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Experience in Modelling Nuclear Energy Systems with MESSAGE: Country Case Studies

IAEA
International Atomic Energy Agency

EXPERIENCE IN MODELLING NUCLEAR ENERGY SYSTEMS WITH MESSAGE: COUNTRY CASE STUDIES

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FOREWORD

The IAEA's Planning and Economic Studies Section (PESS) assists Member States in capacity building in national and regional energy system analysis and planning, and in the evaluation of long range energy strategies and the potential role of nuclear energy in a country's future energy mix. In response to the need to model future nuclear power scenarios and to develop strategies for sustainable nuclear energy systems, PESS has developed the analytical tool Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE).

Established in 2000, the focus of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is on global sustainability of nuclear energy and development of long term nuclear energy strategies. With the help of MESSAGE, the IAEA, through PESS and INPRO, has analysed regional, national and global nuclear energy scenarios to model sustainable nuclear energy systems. This publication is the result of these joint efforts and documents the experience gained using the MESSAGE code in various case studies performed by the participating Member States.

This publication explores the experience gained in modelling national and global nuclear energy systems, with a focus on specific aspects of collaboration among technology holder and user countries and the introduction of innovative nuclear technologies. The feedback from the case studies demonstrates the analytical capabilities of MESSAGE and highlights the path forward for further advancements in the MESSAGE code and nuclear energy system modelling. This publication will facilitate the use of MESSAGE in modelling technical and economic aspects of nuclear energy systems targeting enhanced nuclear energy sustainability.

The IAEA gratefully acknowledges the valuable contributions of all those who assisted in the drafting and review of this publication. The IAEA officers responsible for this publication were A. Jalal, G. Fesenko and V. Kuznetsov of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

One of the objectives of IAEA is to provide integrated services to support Member States in national energy planning and nuclear energy system (NES) analysis and assessment, taking into account the need for sustainable development. The sustainability of a NES is understood as a capability of the system to comply with the INPRO basic principles, followed by user requirements, and criteria developed by qualified experts – representatives of the IAEA Member States – INPRO Members in line with the United Nations concept of sustainable development [1]. Technological and institutional innovations in nuclear reactors and nuclear fuel cycles, as well as cooperation among countries, are the instruments for NES sustainability enhancement. Several IAEA Member States have expressed interest in modelling nuclear energy evolution scenarios leading to enhanced sustainability of nuclear energy.

Responding to Member State requests the IAEA Planning and Economic Study Section (PESS) and the International Project on Innovative Reactors and Fuel Cycles (INPRO) have jointly developed A Users' Guide on Modelling Nuclear Energy Systems using IAEA tool MESSAGE that supports energy analysis and planning and nuclear energy system modelling in Member States [2].

MESSAGE User's Guide included guidance on building mathematical models for dynamic mass flow calculations, preparing input data for the variety of facilities, and addressing the specifics of NES modelling with MESSAGE. The outputs of the MESSAGE code were explained for three demonstration cases, including the results in economics. The major assumptions and boundary conditions for NESs, as well as data for thermal and fast NPPs (including their respective fuel cycles) were based on the GAINS analytical framework [3] developed by INPRO. Major elements of the GAINS analytical framework include: scenarios for long term nuclear power evolution based on projections of international energy organizations; a heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle; metrics and tools to assess the sustainability of scenarios for a dynamic NES; an international database of best-estimate characteristics of existing and future innovative nuclear reactors and associated nuclear fuel cycles, for material flow analysis, and findings from analyses of scenarios of a transition from present day nuclear reactors and fuel cycles to future NES architectures with innovative technological solutions.

The Users' Guide was used in a number of training courses, conducted jointly by INPRO and PESS, for providing training on the use of the MESSAGE tool for evaluation of different NES options toward sustainability within a framework of the overall energy system analysis and planning. Research teams in several Member States have been using the MESSAGE model and the above mentioned Users' Guide for their national studies. In these activities, valuable experience has been accumulated which can be shared with other Member States interested in exploring the long term strategies for sustainable nuclear energy.

Global studies under the INPRO projects "Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle" (GAINS) [3] and "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES) [4] also used the MESSAGE model for developing long term scenarios reflecting different conditions for cooperation among countries. Additionally, INPRO studies also illustrated the potential role of thorium in supplementing the uranium–plutonium fuel cycle and possible contribution of innovative technologies [5] employing *inter alia* minor actinide (MA) utilization for a transition to future sustainable nuclear energy systems.

Minor actinide transmutation in an advanced fuel cycle with innovative reactor technologies that could reduce the volume of long-lived radioactive waste destined for repositories and increase the efficiency of natural resource utilization. Reactor and fuel cycle options for actinide recycling could include fast spectrum reactors and accelerator driven systems.

The use of thorium also provides a number of opportunities: potentially, the reduction of ^{235}U enrichment, the reduction of long-lived radioactive waste inventories by diminishing the production of plutonium and minor actinides, as well as the advantages from increasing the world's fissile resources by breeding ^{233}U from thorium. Three variants of thorium fuel introduction were considered in the document: (1) once-through fuel cycle based on thermal reactors utilizing thorium without spent fuel reprocessing; (2) closed fuel cycle based on thermal reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and ^{233}U (as well as Pu) recycling; (3) closed fuel cycle based on thermal and fast reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and recycling of ^{233}U and Pu.

Describing the experience on modelling approaches in these studies and in country case studies would be useful for both, future investigations of NES and future refinement of the MESSAGE code.

1.2. OBJECTIVE

The main objective of the document is to share the experience in the use of MESSAGE code for modelling nuclear energy systems and provide detailed guidance on how to build mathematical models representing complex nuclear energy systems to the level of detail as necessary for the evaluation of different innovative nuclear energy systems.

The specific objective is to facilitate application of MESSAGE for modelling of technical and economic features of nuclear energy systems by presenting the examples of case studies. The document includes country cases studies covering a variety of nuclear energy systems based on a once-through fuel cycle and on a closed fuel cycle with thermal reactors, fast reactors and advanced systems. It also provides guidance for preparation of the input data for all facilities in an NES as needed to calculate dynamic nuclear material mass flows, nuclear reactor build-up, resource usage, wastes produced, etc. The studies are presented as examples illustrating how to use the MESSAGE code for a case study. Another specific objective of the document is to identify directions for further improvement of the MESSAGE model.

The targeted users are engineers and economists working at nuclear energy departments, electric utilities, energy ministries and/or R&D institutions, including technical universities, who are interested in using MESSAGE for modelling of the entire nuclear energy system with all the technical details to explore alternatives supporting the formulation of long term nuclear energy strategies in countries or regions. The document assumes the users are familiar with the basic approach, functionality description and application of MESSAGE.

1.3. SCOPE

This document includes guidance on building mathematical models for dynamic mass flow calculations, preparation of input data for the variety of facilities and also addresses the specifics of NES modelling with MESSAGE. The document presents country cases studies covering a variety of nuclear energy systems based on a once-through fuel cycle and a closed fuel cycle for thermal reactors, fast reactors and advanced systems. In particular, the document describes modelling of a heterogeneous world nuclear energy system with the Multi-regional MESSAGE model, as well as modelling of nuclear energy systems based on thorium fuel cycle and minor actinide transmutation.

1.4. STRUCTURE

Excluding the Introduction presented in the current Section 1, this document is divided into three sections.

Section 2 describes the application of MESSAGE code in modelling of specific nuclear energy systems as addressed in the case studies performed by the participating Member States. Different aspects of scenarios and parameters for national or regional nuclear energy systems are modelled in five case studies performed by Argentina, China, Romania, the Russian Federation and Ukraine. The findings and feedback from individual studies suggest the directions for further elaboration of the models and analysis tools.

Section 3 presents the use of MESSAGE for simulation of innovative NES options supporting the global vision of nuclear energy sustainability, on an example of the case studies performed by IAEA. Presented are sample case studies performed in the GAINS and SYNERGIES projects to simulate heterogeneous global nuclear energy systems based on grouping of the countries having different strategies for the back end of the nuclear fuel cycle. The role of thorium fuel for enhancing nuclear energy sustainability is modelled and analyzed for transition scenarios to future NESs. This section also describes INPRO case studies for modelling different fuel cycle system scenarios based on innovative technologies for minor actinide transmutation considered for minimizing the radioactive waste load in support of enhanced sustainability.

Section 4 titled "Feedback and conclusions from case studies" provides a detailed discussion of the results from the case studies described in previous sections, particularly, exploring the extent of usefulness of the MESSAGE code for supporting the technological, collaboration and economic aspects in sustainability analysis of different nuclear energy system scenarios. The section also highlights what needs to be improved in the model to make further studies more efficient.

A list of important abbreviations used in the document is provided in the end.

2. MESSAGE APPLICATION TO NUCLEAR ENERGY SYSTEMS MODELLING

2.1. ARGENTINE CASE STUDY ON MODELLING OF THE NUCLEAR FUEL CYCLE

2.1.1. Introduction

2.1.1.1. Current state of the electricity sector

In Argentina, total energy demand was 59 918 ktoe ktep by 2014 [6]. Nearly 18.2% of the total energy demand is met by electricity generation, of which 64.8% [7] is generated through thermal technologies burning fossil fuels, showing the high dependence of Argentina on these fuels as energy sources. The rest of the electricity generation is distributed among the following technologies: nuclear power (4.3%), hydropower (30.4%) and other variable renewables, including wind and solar power (0.5%).

Since 2004, a State policy has been established in Argentina to diversify the electricity generation mix and promote a higher share of nuclear power, hydropower and other variable renewables. A number of laws have been passed in order to decrease the use of fossil fuels and to promote the rational and efficient use of energy. This also includes reactivation of various nuclear projects aimed at increasing the portfolio of nuclear power in the national energy mix.

Regarding the nuclear power industry, a reactivation of the nuclear R&D and NPP projects was started on 23 August 2006. Later, National Law No. 26566 was passed on 25 November 2009 and enacted on 17 December 2009. This law, regulating nuclear R&D and nuclear projects, aims to:

— Boost uranium mining in order to allow prospecting in the whole country;

— Resume enrichment activities at the Pilcaniyeu Technological Complex;

— Extend the operating licence of the Embalse NPP (Central Nuclear Embalse (CNE)) and undertake the necessary tasks for CNE plant life extension (PLEX);

— Continue previous studies to define Atucha I NPP (Central Nuclear Atucha I (CNA I)) PLEX;

— Undertake works to complete construction of Atucha II NPP (Central Nuclear Atucha II (CNA II)), to commission it and to operate it;

— Start up the heavy water industrial plant;

— Commence preliminary feasibility studies to build a fourth nuclear power plant in one or two modules;

— Design, execute and commission the CAREM 25 NPP under the Argentine Atomic Energy Agency (Comisión Nacional de Energía Atómica (CNEA)) responsibility.

Regarding renewables, the main promulgated laws are the ones on solar and wind energy promotion (No. 25019), the one to promote and to provide sustainable use of biofuels (No. 26093) and the one on national support for the use of renewable sources for electricity generation in order to reach, gradually, a minimum 20% of share by 2025 (No. 27191).

2.1.1.2. Nuclear programme

Argentina is actively engaged in several front end and back end stages of the open nuclear fuel cycle.

Uranium exploration activities in Argentina started in 1952. Currently prospecting in 74 areas is ongoing to increase reasonably assured resources: six sites in Chubut, one in Salta and 67 in search areas showing evidence of uranium mineralization. Production of uranium from 1952 to 1995 totalled 2581.7 tU. After 1995, local uranium production ceased and natural and low enriched uranium up to 3.5% is being imported.

At the Pilcaniyeu Technological Complex, uranium enrichment is being carried out by gaseous diffusion in a pilot plant. Moreover, R&D activities to develop ultra-centrifuge and laser technologies for uranium enrichment are being undertaken.

Argentina currently manufactures fuel assemblies for its three nuclear power plants in operation and has designed the one corresponding to the CAREM 25 facility. Argentina also designs and fabricates fuel assemblies for research and radioisotope production reactors for both local and export markets.

Since 1996, low enriched uranium (LEU) has been used in CNA I with 0.85% of the ^{235}U isotope. The same strategy has been set for CNA II, which currently operates with natural uranium and has a projected conversion of its fuel assemblies into LEU by 2021.

The three operational NPPs in Argentina are CNA I, commissioned in 1974, CNE in 1984 and CNA II in 2015. In January 2016, CNE ended the first operational cycle starting the final stage of the PLEX project. The objective of this project is to extend its lifetime for 30 years of operation and increase electrical power of the NPP by 35 MW(e) by 2018.

The first Argentine SMR CAREM 25 plant has been under construction since February 2015 and was completely designed in Argentina.

There are two planned nuclear power projects: a CANDU 6 NPP (740 MW(e)), which will start its construction in 2017 and a PWR (1100 MW(e)) due to start in 2019 in accordance with a Memorandum of Understanding signed between the National Energy Administration of the People's Republic of China and the Ministry of Energy and Mining of the Argentine Republic.

There are ongoing negotiations with possible suppliers from different countries to add new NPPs to the electricity generating system.

Regarding the back end of nuclear fuel cycle (NFC), Argentina is currently placing spent fuel in both dry and wet storage facilities at NPP sites. A decision will be made in 2030 about whether fuels will be reprocessed or whether they will be sent to a repository for final disposal. If the option of reprocessing is not chosen, the place for final disposal of spent fuel should be indicated in order that its construction be started by 2050 and to have the geological repository in operation by 2060.

Radioactive waste management activities are currently undertaken according to the National Programme of Radioactive Waste Management and reprocessing on a laboratory scale is being researched and developed.

In the CNEA, there have been ongoing activities developed in terms of nuclear forecasting and planning for the short, mid- and long terms since 1964.

2.1.2. Objective of the study and presentation of the problem

This study entails the analysis of the growth of the Argentine nuclear system based on the diversification of the electricity mix in the long term and considering a larger share of nuclear, hydropower and other variable renewables by using the MESSAGE model.

The period 2015–2050 was defined and two scenarios were projected which corresponded to high and low nuclear share. The base year was 2015. In the following paragraphs, the key objectives are listed for each stage of the nuclear fuel cycle.

Front end:

— Quantification of requirements of natural uranium and enriched uranium for current NPPs for both ongoing projects and candidates;

— Identification of needs for yellow cake production;

— Evaluation of the strategy for local uranium enrichment to 3.5%.

NPPs:

— Quantification of the shares for nuclear, hydropower and other variable renewables by 2050 in installed capacity and in electricity generation, as opposed to thermal technologies burning fossil fuels.

Back end:

— Quantification of spent fuel inventory accumulated by 2050 and generated by current and future NPPs;

— Quantification of the needs for wet and dry storage of spent fuel.

Economics:

— Extraction of data from MESSAGE by post processing of the solution (so called *cin file*) in order to obtain the following economic results:

a. Annual investment in future NPPs;

b. Annual expenditure on total fuel cycle and on operations and maintenance (O&M) of NPPs;

c. Levelized unit amortization cost and levelized unit operation and maintenance cost (LUAC and LUOM).

2.1.3. Model description and input data

2.1.3.1. Energy demand and nuclear share

Final electricity demand by 2050 is considered to be 14 524.3 MW·year. Taking into account scenarios of high, mid and low projections of electricity demand of the Electrical Energy Secretariat in the modelling, there is an average annual growth of 3.2%. Moreover, it is divided into five sectors of consumption presented in the following paragraphs with its value by 2015, by 2050 and whether there is a related load curve or not, as shown in Table 1.

TABLE 1. ELECTRICITY DEMAND PER SECTOR

Sector	Electricity demand (MW·year)		Details
	2015	2050	
Household	5160.8	13 112.3	Annual load curve
Commercial and public	3466.2	12 658.3	Annual load curve
Transport	73.8	190.7	-
Industry	5701.8	17 288.1	-
Agricultural	121.7	520.6	-

In particular, natural gas demand is modelled as it represents 69% of fossil fuels used in the electricity generation mix.

In Argentina, natural gas dispatch has the following priority order: household, commercial and public, transport, exports, industry and electric power plants. In winter, natural gas for heating purposes is used in the household and the public and commercial sector. As a result, its use is limited in industry and in thermal power plants during the winter season. There are also restrictions on infrastructure in gas transport. Therefore, natural gas demand is divided into four sectors as shown in Table 2.

TABLE 2. NATURAL GAS DEMAND PER SECTOR

Sector	Natural gas demand (MW·year)		Details
	2015	2050	
Household	12 644.0	32 676.9	Annual load curve
Commercial and public	2 020.4	4 327.3	Annual load curve
Transport	3 154.4	4 256.8	-
Industry	10 070.9	21 569.9	-

Losses in transport and distribution of electricity have been taken into account and these represent 15% of total supplied energy.

In order to meet the demand, Argentina has a thermal power generating system with the following technologies: thermal using fossil fuels, hydropower, nuclear and other variable renewables. The total and thermal installed capacities per type of technology as on 31 December 2015 are presented in Tables 3 and 4, respectively.

TABLE 3. TOTAL INSTALLED CAPACITY BY 2015 PER TYPE OF TECHNOLOGY

	Thermal	Hydro	Nuclear	Wind	Solar (photovoltaic)	Total
Total installed capacity (MW)	19 500.7	11 107.9	1755.0	187.4	8.2	32 559.2
Share (%)	59.9	34.1	5.4	0.6	0.03	-

TABLE 4. THERMAL INSTALLED CAPACITY BY 2015 PER TYPE OF TECHNOLOGY

	ST	GT	CC	DI	BG	Total
Total installed capacity (MW)	4451.2	4022.4	9227.1	1783.4	16.6	19 500.7
Share (%)	22.8	20.6	47.4	9.1	0.1	100.0

Technologies: ST: Steam Turbine; GT: Gas Turbine; CC: Combined Cycle; DI: Diesel; BG: Biogas.

Electricity generation equipment items from both, the fixed system projects and candidates are modelled in the following way:

— Thermal power plants: These are grouped according to technology and used fuel;

— Hydropower plants: run-of-river, reservoir and pump;

— Nuclear: pressurized heavy water reactor (PHWR) with natural uranium and LEU, PWR with uranium enriched to 3.1%, 4.45% and 4.8%;

— Other renewables: solar, wind, biogas, biomass and small hydropower (hydropower plants with an installed capacity of less than 50 MW, hereafter referred to as MiniHydro).

Uranium, oil, natural gas and coal resources were modelled at a local level with respect to domestic reserves. Uranium and natural gas extraction were also represented and imports of each energy source were taken into account.

2.1.3.2. Description of low and high nuclear share scenarios

Scenarios of high and low nuclear share have common traits in terms of start-ups and decommissioning (Table 5).

TABLE 5. INSTALLED, UNDER CONSTRUCTION AND PROJECTED NUCLEAR POWER PLANTS

NPP	Gross power per unit (MW)	Description	Year
CNE	648	Shutdown for PLEX	2016–2017
	683	Start-up and full power operation for 30 years	2018
CNA I	362	Shutdown for PLEX	2019–2020
		Start-up and full power operation for 10 years	2021
		Shutdown	2032
CAREM 25	32	Start-up	2020
CNA II	745	Conversion of natural uranium to LEU	2021
4th NPP	740	Start-up PHWR — CANDU 6	2023
5th NPP	1150	Start-up PWR — HPR1000	2024

Table 6 shows the nuclear technology projects at various nuclear generating stations (NGS) and the schedule for introduction for both high and low scenarios.

TABLE 6. SCHEDULE FOR INTRODUCTION OF NUCLEAR POWER PLANTS PER SCENARIO

NPP	Gross power per unit (MW)	Description	High	Low
CAREM 120	120	First NGS — Unit I (FOAK SMR)	2025	2027
		First NGS — Unit II	2027	2031
		First NGS — Unit III	2029	2033
		First NGS — Unit IV	2031	2035
		Second NGS — Unit I	2036	2042
		Second NGS — Unit II	2037	2044
		Second NGS — Unit III	2038	2046
		Second NGS — Unit IV	2039	2048
		Third NGS — Unit I	2044	-
		Third NGS — Unit II	2045	-
		Third NGS — Unit III	2046	-
		Third NGS — Unit IV	2047	-
Other PWRs	1200	PWR (HPR1000 or WWER) Unit I	2027	2031
		PWR (HPR1000 or WWER) Unit II	2029	2033
	1060	First NGS — Generic PWR Unit I	2033	2039
		First NGS — Generic PWR Unit II	2034	2041
		Second NGS — Generic PWR Unit III	2039	2047
		Second NGS — Generic PWR Unit IV	2040	2049
		Third NGS — Generic PWR Unit V	2045	-
		Third NGS — Generic PWR Unit VI	2046	-

2.1.3.3. Fuel cycle option

The two nuclear share scenarios are based on an open fuel cycle. The data considered in the case study appear in the following paragraphs.

Technical data for power reactors and fuel cycle

The technical parameters of modelled NPPs and nuclear fuel cycle are presented in Table 7.

Economic parameters of reactors and its fuel cycle

Economic parameters of modelled and related NPPs are provided in the Table 8 and the economic parameters of the fuel cycle are provided in the Table 9.

TABLE 7. TECHNICAL DATA FOR REACTOR TECHNOLOGIES AND NUCLEAR FUEL CYCLE

Item	Unit	CNA I	CNA II natU/LEU	CNE	CAREM 25	CAREM 120	CANDU 6	PWR HPR1000	PWR WWER	PWR Generic
Nuclear capacity	MW	362	745	648	32	120	740	1150	1200	1060
Load factor	n.a.[a]	0.75	0.88	0.85	0.8	0.9	0.85	0.85	0.9	0.93
Thermal efficiency	%	31	34	31	32	32	33	38	33	32
Discharge burnup	GW·d/t HM	10.7	7.5/10.7	7.2	18	31.5	7.5	45	55.5	60
Residence time	EFPD	456	301/456	335	840	1710	335	1620	1620	1620
Enrichment of fresh fuel	n.a.	0.085	0.007 14/0.085	0.007 14	0.031	0.031	0.007 14	0.0445	0.048	0.0445
Tails assay	n.a.	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Minimum cooling time	year	5	5	5	5	5	5	5	5	5

a. n.a.: not applicable.

TABLE 8. ECONOMIC PARAMETERS FOR REACTOR TECHNOLOGIES

Item	Unit	CNA I[a]	CNA II* natU/LEU	CNE[a]	CAREM 25	CAREM 120	CANDU 6	PWR HPR1000	PWR WWER	PWR Generic
Investment cost	US $/kW(e)	-	-	-	7125	5700	7665	6993	7000	6500
Fixed O&M cost	US $/kW·year	86	86	86	50	50	86	50	50	50
Variable O&M cost	US $/kW·year	1.52	1.10	1.62	10	10	1.62	10	10	10
Lifetime	Year	30	30	30	40	40	35	60	60	60
PLEX	Year	10[b]	-	30[b]	-	-	-	-	-	-
Construction time	Year	-	-	-	5	5	8	7	5	5
Fuel fabrication cost	US $/kg HM·year	650.8	425.1/604.8	216.0	1000	1000	216.0	1000	1000	1000

a. CAMMESA (Compañia Administradora del Mercado Mayorista Eléctrico Sociedad Anónima) data.
b. Lifetime to full power.

TABLE 9. ECONOMIC PARAMETERS OF NUCLEAR FUEL CYCLE

Item	Unit	Value
Nuclear uranium cost:		
Local natural uranium	US $/kg	a
Imported natural uranium	US $/kg	108
Imported UO_2 up to 3.5%	US $/kg	900
Imported UO_2 up to 4.8%	US $/kg	1134
Yellowcake conversion	US $/kg HM	49.9
UF_6 conversion	US $/kg HM	10
Enrichment	US $/kg HM	55–110
Cooling storage	US $/kg HM·year	5
Interim storage	US $/kg HM	4

a Costs and resources are taken from data in Ref. [8].

Analytical mass flow calculation for open fuel cycle

Table 10 provides parameters of the associated mass balance for each considered reactor technology.

TABLE 10. ANALYTICAL MASS BALANCE FOR THE REACTOR TECHNOLOGIES

Item	Unit	CNA I LEU	CNA II natU/ LEU	CNE	CAREM 25	CAREM 120	CANDU 6	PWR HPR1000	PWR WWER	PWR Generic
Fresh fuel	t HM	30.14	92.55/ 64.84	90.92	1.62	3.92	92.76	21.03	21.33	18.74
Fuel in core	t HM	50.21	86.73/ 92.05	98.18	4.67	20.38	100.16	109.80	105.19	89.44
Spent fuel discharged	t HM + t FP	30.14	92.55/ 64.84	90.92	1.62	3.92	92.76	21.03	21.33	18.74

2.1.3.4. Important assumptions and boundary conditions

Front end assumptions

Exploration: In the modelling, reasonably assured resources (RAR), inferred resources (IR) and prognosticated resources (PR) were obtained from Ref. [8] for Argentina and are listed in Table 11.

TABLE 11. URANIUM RESOURCES AND COSTS

Value (US $/kgU)	RAR (tU)	IR (tU)	PR (tU)
<80	5130	8432	n.a.[a]
<130	8599	9932	13 810
<260	8599	10 982	13 810

a. n.a.: not applicable.

Production: Argentina has a uranium production plant with an annual capacity of 400 t (appearing as Yellow_Cake_400), although it ceased operating in 1996 owing to environmental and political considerations. During the modelling, it was assumed that such a plant would resume operation by 2020.

Moreover, in order to quantify the projections for future local production, the technology of a new candidate uranium production plant (Yellow_Cake_CAN) was implemented, which will have the same installed capacity and is expected to be in operation from 2024. Table 12 provides economic parameters for both plants.

TABLE 12. YELLOW CAKE COSTS

	Unit	Yellow_Cake_400	Yellow_Cake_CAN
Investment cost	US $/kg	-	50
Fixed O&M cost	US $/kg·year	6.81	6.81
Variable O&M cost	US $/kg	16.18	16.18

Imports: Argentina currently imports natural uranium as well as uranium enriched to 3.5%. From 2020, the imports of natural uranium will be gradually replaced with local production, and by 2025 the uranium production will be enriched to 3.5% to meet the necessary shortfall.

Also, uranium enriched to 4.8% will be imported as PWR reactors are incorporated into the system.

Fuel mix: Three technologies are modelled with the fuel mix for different reactors, as shown in Table 13.

TABLE 13. FUEL MIX

	Unit	Natural_U	U_3.5%	U_4.8%
Mix_LEU	kg/t	772.91	227.09	-
Mix_3.1	kg/t	116.67	883.33	-
Mix_4.45	kg/t	74.02	-	925.98

Enrichment: By 2020, Argentina will have to decide, which type of enrichment technology is to be used on an industrial scale. By allowing seven years for engineering and construction, it was modelled to start operation in 2027 with uranium enriched to 3.5%.

Fuel fabrication: A technology for each line of fuel fabrication was modelled.

Back end assumptions

For current NPPs, the historical amount of dry and wet storage capacity for spent fuel assemblies was considered up to 2015. In addition, all of the maximum storage capacities were calculated for each NPP in operation.

As of 2019, CNA I will have vertical dry silos for the interim storage of spent fuel, and 5000 fuel assemblies will be placed in CNA II pools, as a result of saturation of the wet storage capacity of CNA I. In the case of CNE, dry storage has been in operation since 1993, thus being represented with an initial volume.

For project and candidate NPPs, the volume of each wet storage unit was modelled with a design capacity equivalent to 10 operating years.

Modelling was based on an open fuel cycle during the whole period of study (2015–2050) because no formal decision on fuel recycling has been made yet.

2.1.4. Modelling of selected NES elements with MESSAGE and schemes

2.1.4.1. Modelling of PWRs and PHWRs

In operation: In the case of CNA I, it was considered that this plant would be shut down for its PLEX in 2018–2019. In the case of CNA II, it was anticipated that, by 2020, it will be converted from natural uranium to LEU. CNE would be shut down for PLEX in 2016–2017.

Projects: CAREM 25 would start operation by 2020. In the case of CAREM 120, it was considered that modules of four units would be built. The construction of the first NGS will be accomplished over a lengthier period than the second and/or third NGS, whose plants will be built over shorter periods. The CANDU 6 and PWR HPR1000 units would start operation in 2023 and 2024, respectively.

Candidates: For the candidate NPPs, there is no identification of the supplier, a decision on which could take into account that a PWR HPR1000 reactor has been represented, and the WWER and Generic PWR have been modelled in order to compare the results among them.

2.1.4.2. Modelling of once-through nuclear fuel cycle

Figure 1 shows the scheme of modelling of the Argentine nuclear fuel cycle. The technologies that still do not exist but will be installed in the future are represented by dotted elements.

2.1.4.3. Specifics of NES modelling in the national energy system

The modelling scheme of the Argentine energy system is shown in Fig. 2.

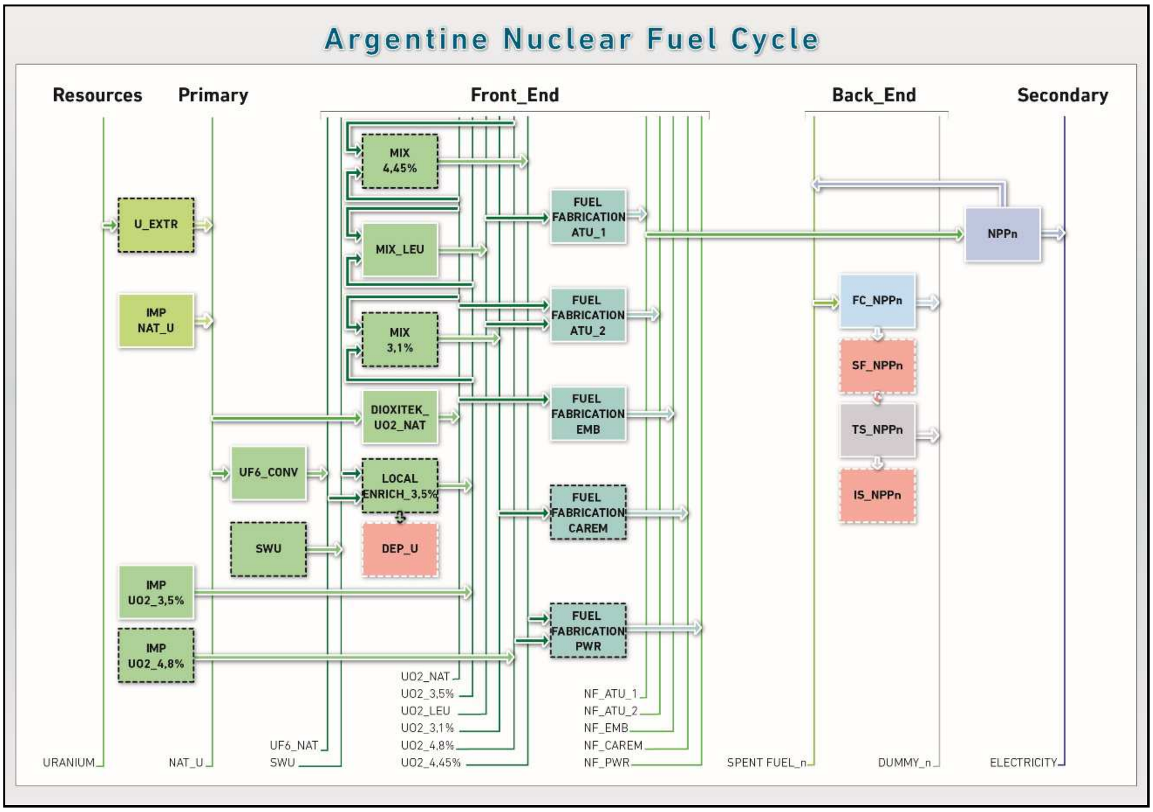


FIG. 1. Argentine nuclear fuel cycle scheme.

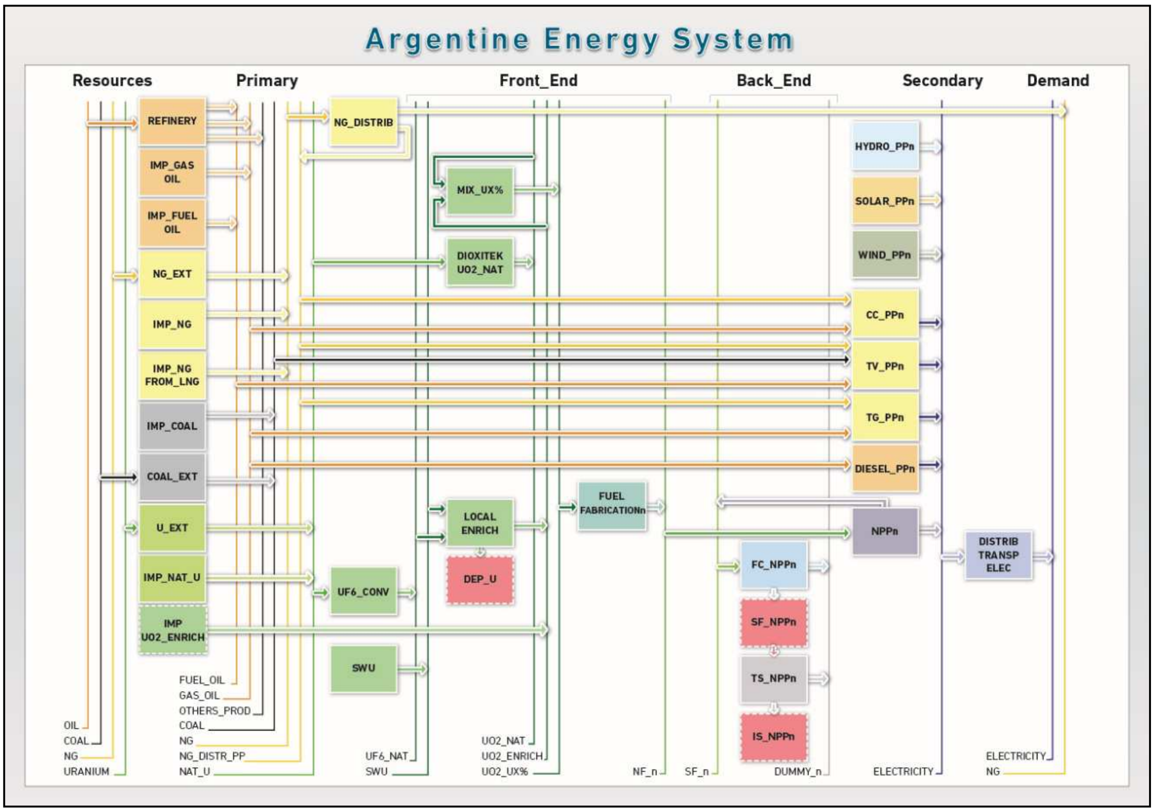


FIG. 2. Argentine energy system scheme.

Table 14 provides the modelled capacities of the thermal fixed system as per type of technology and fuel.

TABLE 14. THERMAL POWER PLANTS OF THE FIXED SYSTEM MODELLED

Fixed system (MW)	NG	NG + GO	GO	NG + FO	FO	Coal	Biogas	Total
CC_PP	3262.6	5964.4						9227.0
GT_PP	1156.9	2688.5	177.0				16.6	4039.0
ST_PP				3924.2	27.0	500.0		4451.2
DI_PP			1783.4					1783.4

Technologies: CC: Combined Cycle; GT: Gas Turbine; ST: Steam Turbine; DI: Diesel Fossil Fuels; NG: Natural Gas; GO: Gas Oil; FO: Fuel Oil.

For the candidate thermal generation, a technology per type of equipment was added, together with the modules of installed capacities shown in Table 15.

TABLE 15. ECONOMIC PARAMETERS OF THERMAL CANDIDATES IN THE VARIABLE SYSTEM MODELLED

Candidates	Capacity (MW)	Investment cost (US $/kW)	Fuel type
CAN_CC	800	1100	NG/GO
CAN_TG	200	700	NG/GO
CAN_TV	240	2100	Coal

Technologies: CC: Combined Cycle; TG: Gas Turbine; TV: Steam Turbine.

The installed capacity of the fixed generating system, the projects and candidates for hydropower plants are presented in Table 16, together with the investment costs.

TABLE 16. HYDROPOWER PLANTS OF THE FIXED AND VARIABLE SYSTEMS MODELLED

Fixed system	Capacity (MW)
HI_PP_ROR_1	2745
HI_PP_ROR_2	945
HI_PP_ROR_3	107
HI_PP_STO_1_South	5211
HI_PP_STO_2_Others	1350
HI_PP_PUMPSTO	750

Projects and candidates	Capacity (MW)	Investment cost (US $/kW)	Details
PROJ_HI	8007	2050	18 local projects
CAN_HI	1440	4000	1 binational project
CAN_HI_2	1000	2400	1 binational project

In terms of the technologies named as other variable renewables, Table 17 presents the installed capacity both, for the fixed system and for the projects and candidate power plants with associated investment costs.

TABLE 17. POWER PLANTS OF THE FIXED AND VARIABLE SYSTEMS INCLUDED IN OTHER VARIABLE RENEWABLES MODELLED

Fixed system	Capacity (MW)
WIND_PP_South	136.7
WIND_PP_Others	50.7
SOLAR_PP_PV	8.2

Projects	Capacity (MW)	Investment cost (US $/kW)	Details
PROJ_MiniHydro	500	2000	17 modules of 20–30 MW
PROJ_WIND	22 200	1800	37 modules of 600 MW
PROJ_PV	3600	4000	12 modules of 300 MW
PROJ_BIOGAS	585	2350	39 modules of 15 MW
PROJ_BIOMASS	2 340	3350	39 modules of 60 MW

Regarding nuclear technologies, Table 18 presents the installed capacity both for the fixed system and for the projects and candidate power plants investment costs.

TABLE 18. NUCLEAR POWER PLANTS OF THE FIXED AND VARIABLE SYSTEMS MODELLED

Fixed system	Capacity (MW)
CNA_I_NPP	362
CNA_II_NPP	745
CNE_NPP	648

Projects and candidates	Capacity per unit (MW)	Investment cost (US $/kW)	Number of units
PROJ_CAREM_25_NPP	32	7125	1
PROJ_CAREM_120_NGS _I/II/III	120	5700	4
PROJ_CANDU_6_NPP	740	7665	1
PROJ_HPR1000_NPP	1150	6993	1
CAN_WWER_NGS	1200	7000	2
CAN_Generic_NGS_I/II/III	1060	6500	2

2.1.5. Scope of results and findings of the case study

2.1.5.1. Main outputs calculated with MESSAGE

Results for front end fuel cycle

Uranium requirements

Figure 3 shows the annual requirements of imported natural uranium (import_Unat), natural uranium extracted in the country (local_Unat), imported uranium enriched to 3.5% (import_3.5) and imported uranium enriched to 4.8% (import_4.8) for the fabrication of fuel assemblies in both scenarios.

Currently, natural uranium is being imported and it will continue to be imported until the domestic extraction plant starts to produce uranium once again. At that time, the model will cease to import any natural uranium until 2035 (for high scenario) and 2038 (for low scenario) and will only import it in small quantities until the end of the period of study, since it is cheaper to import than to install a new candidate.

Uranium requirements - Local Production and Imports [in tons]
Region: HIGH_SCENARIO_AFC, Scenario: adb

	import_Unat	local_Unat	import_3.5	import_4.8
2015	103.77	0.00	6.02	0.00
2016	115.84	0.00	6.85	0.00
2017	115.84	0.00	6.85	0.00
2018	212.06	0.00	6.85	0.00
2019	188.37	0.00	0.00	0.00
2020	0.00	188.92	4.12	0.00
2021	0.00	190.46	29.18	0.00
2022	0.00	169.43	23.00	0.00
2023	0.00	269.59	23.00	0.00
2024	0.00	270.31	23.00	101.67
2025	0.00	266.12	41.01	19.47
2026	0.00	264.20	26.46	19.47
2027	0.00	302.44	39.86	124.66
2028	0.00	300.52	25.31	40.80
2029	0.00	338.77	38.70	145.98
2030	0.00	336.85	24.16	62.13
2031	0.00	375.09	37.55	62.13
2032	0.00	373.17	23.00	62.13
2033	0.00	392.36	11.55	144.94
2034	0.00	393.75	11.55	162.30
2035	24.38	400.00	6.94	96.83
2036	26.76	400.00	24.94	96.83
2037	63.08	400.00	23.79	96.83
2038	63.54	400.00	27.25	96.83
2039	70.62	400.00	30.71	179.65
2040	70.08	400.00	16.16	197.00
2041	64.85	400.00	16.16	131.54
2042	64.85	400.00	16.16	131.54
2043	64.85	400.00	16.16	131.54
2044	67.23	400.00	34.17	131.54
2045	74.30	400.00	37.63	214.35
2046	72.33	400.00	38.58	231.70
2047	71.37	400.00	44.54	166.24
2048	69.45	400.00	30.00	166.24
2049	69.45	400.00	30.00	166.24
2050	69.45	400.00	30.00	166.24

Uranium requirements - Local Production and Imports [in tons]
Region: LOW_SCENARIO_AFC, Scenario: adb

	import_Unat	local_Unat	import_3.5	import_4.8
2015	103.77	0.00	6.02	0.00
2016	115.84	0.00	6.85	0.00
2017	115.84	0.00	6.85	0.00
2018	212.06	0.00	6.85	0.00
2019	188.37	0.00	0.00	0.00
2020	0.00	188.92	4.12	0.00
2021	0.00	190.46	29.18	0.00
2022	0.00	169.43	23.00	0.00
2023	0.00	269.59	23.00	0.00
2024	0.00	270.31	23.00	101.67
2025	0.00	263.74	23.00	19.47
2026	0.00	263.74	23.00	19.47
2027	0.00	266.12	41.01	19.47
2028	0.00	264.20	26.46	19.47
2029	0.00	264.20	26.46	19.47
2030	0.00	300.07	21.85	19.47
2031	0.00	302.44	39.86	124.66
2032	0.00	336.39	20.70	40.80
2033	0.00	315.47	31.86	145.98
2034	0.00	349.42	12.70	62.13
2035	0.00	351.79	30.71	62.13
2036	0.00	385.74	11.55	62.13
2037	0.00	385.74	11.55	62.13
2038	21.61	400.00	6.94	62.13
2039	28.23	400.00	6.94	144.94
2040	22.99	400.00	6.94	79.48
2041	29.61	400.00	6.94	162.30
2042	26.76	400.00	24.94	96.83
2043	24.84	400.00	10.40	96.83
2044	27.22	400.00	28.40	96.83
2045	25.29	400.00	13.85	96.83
2046	27.67	400.00	31.86	96.83
2047	32.37	400.00	17.31	179.65
2048	29.52	400.00	35.32	114.18
2049	34.21	400.00	20.77	197.00
2050	28.98	400.00	20.77	131.54

FIG. 3. Uranium requirements: local production and imports.

Currently, uranium enriched to 3.5% is imported in order to fabricate LEU fuel for CNA I. During 2019 and 2020, CNA I PLEX will be carried out. CNA II U_nat would be replaced by LEU by 2020. Both CNA NPPs would then use LEU until 2032 when CNA I will cease operation, leaving only CNA II using this type of fuel.

Both CAREM (25 and 120) NPPs use uranium enriched to 3.1%. This is produced by mixing uranium enriched to 3.5% with natural uranium and the requirements change annually according to each created scenario.

Uranium enriched to 4.8% (imported during the whole period of study) will be used for PWR WWER NPPs. In the case of the PWR, both Generic and HPR1000, a fuel mix will be made which will require enrichment of 4.45%.

Each time a new NPP is included in the NGS, there is a higher uranium requirement as a result of the first load (fuel in core) as opposed to regular fresh fuel requirements.

Figure 4 shows the quantification of resources for each production line in more detail.

Uranium Fuel Production Lines [in tons]
Region: HIGH_SCENARIO_AFC, Scenario: adb

	U_Nat	LEU	U_3.1	U_4.45	U_4.8
2015	83.27	26.53	0.00	0.00	0.00
2016	92.54	30.14	0.00	0.00	0.00
2017	92.54	30.14	0.00	0.00	0.00
2018	188.76	30.14	0.00	0.00	0.00
2019	188.37	0.00	0.00	0.00	0.00
2020	188.37	0.00	4.67	0.00	0.00
2021	95.83	122.19	1.62	0.00	0.00
2022	95.83	94.98	1.62	0.00	0.00
2023	195.99	94.98	1.62	0.00	0.00
2024	188.59	94.98	1.62	109.80	0.00
2025	188.59	94.98	22.01	21.03	0.00
2026	188.59	94.98	5.54	21.03	0.00
2027	188.59	94.98	25.92	21.03	105.19
2028	188.59	94.98	9.45	21.03	21.33
2029	188.59	94.98	29.84	21.03	126.51
2030	188.59	94.98	13.37	21.03	42.66
2031	188.59	94.98	33.75	21.03	42.66
2032	188.59	94.98	17.28	21.03	42.66
2033	188.59	64.84	17.28	110.46	42.66
2034	188.59	64.84	17.28	129.20	42.66
2035	188.59	64.84	17.28	58.51	42.66
2036	188.59	64.84	33.75	58.51	42.66
2037	188.59	64.84	33.75	58.51	42.66
2038	188.59	64.84	33.75	58.51	42.66
2039	188.59	64.84	33.75	129.20	42.66
2040	188.59	64.84	17.28	129.20	42.66
2041	188.59	64.84	17.28	58.51	42.66
2042	188.59	64.84	17.28	58.51	42.66
2043	188.59	64.84	17.28	58.51	42.66
2044	188.59	64.84	17.28	58.51	42.66
2045	188.59	64.84	17.28	58.51	42.66
2046	188.59	60.14	15.66	58.51	42.66
2047	188.59	64.84	17.28	58.51	42.66
2048	188.59	64.84	17.28	58.51	42.66
2049	188.59	64.84	17.28	58.51	42.66
2050	188.59	64.84	17.28	58.51	42.66

Uranium Fuel Production Lines [in tons]
Region: LOW_SCENARIO_AFC, Scenario: adb

	U_Nat	LEU	U_3.1	U_4.45	U_4.8
2015	83.27	26.53	0.00	0.00	0.00
2016	92.54	30.14	0.00	0.00	0.00
2017	92.54	30.14	0.00	0.00	0.00
2018	188.76	30.14	0.00	0.00	0.00
2019	188.37	0.00	0.00	0.00	0.00
2020	188.37	0.00	4.67	0.00	0.00
2021	95.83	122.19	1.62	0.00	0.00
2022	95.83	94.98	1.62	0.00	0.00
2023	195.99	94.98	1.62	0.00	0.00
2024	188.59	94.98	1.62	109.80	0.00
2025	188.59	94.98	1.62	21.03	0.00
2026	188.59	94.98	1.62	21.03	0.00
2027	188.59	94.98	22.01	21.03	0.00
2028	188.59	94.98	5.54	21.03	0.00
2029	188.59	94.98	5.54	21.03	0.00
2030	188.59	94.98	5.54	21.03	0.00
2031	188.59	94.98	25.92	21.03	105.19
2032	188.59	94.98	9.45	21.03	21.33
2033	188.59	64.84	29.84	21.03	126.51
2034	188.59	64.84	13.37	21.03	42.66
2035	188.59	64.84	33.75	21.03	42.66
2036	188.59	64.84	17.28	21.03	42.66
2037	188.59	64.84	17.28	21.03	42.66
2038	188.59	64.84	17.28	21.03	42.66
2039	188.59	64.84	17.28	110.46	42.66
2040	188.59	64.84	17.28	39.77	42.66
2041	188.59	64.84	17.28	129.20	42.66
2042	188.59	64.84	33.75	58.51	42.66
2043	188.59	64.84	17.28	58.51	42.66
2044	188.59	64.84	33.75	58.51	42.66
2045	188.59	64.84	17.28	58.51	42.66
2046	188.59	64.84	33.75	58.51	42.66
2047	188.59	64.84	17.28	129.20	42.66
2048	188.59	64.84	33.75	58.51	42.66
2049	188.59	64.84	17.28	129.20	42.66
2050	188.59	64.84	17.28	58.51	42.66

FIG. 4. Uranium fuel production lines.

Local uranium enrichment to 3.5%

Figures 5 and 6 present all of the separative work unit (SWU) requirements to obtain uranium enriched to 3.5% which is necessary to supply current and future NPPs for high and low scenarios. As the technology and its associated costs have not been defined yet, as it is a strategic decision for Argentina, modelling was undertaken using typical costs (Table 9) in order to evaluate requirements of enrichment capacity and replacement of imports.

It was considered that, in the future, imports will be gradually and partially replaced. Argentina will choose which type of uranium enrichment technology will be used by 2020, although it is assumed that the enrichment plant would have modules with an installed capacity of 20 000 SWU.

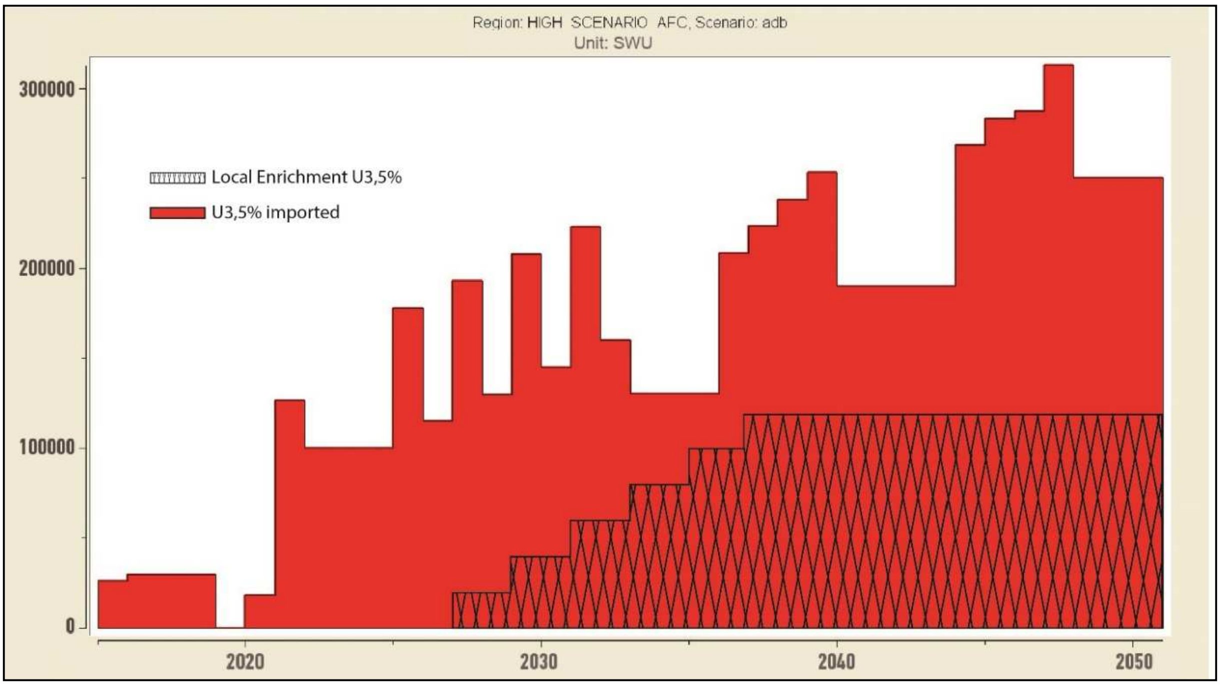


FIG. 5. SWU requirements for the high scenario.

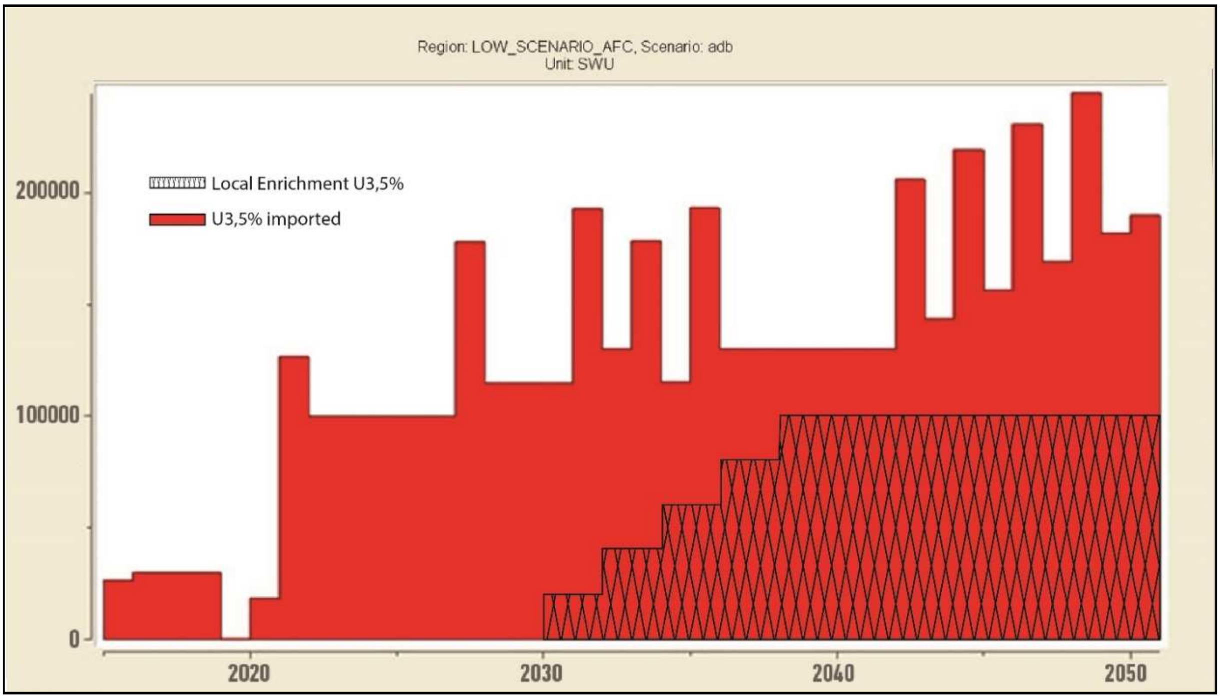


FIG. 6. SWU requirements for the low scenario.

A replacement strategy can be derived from Fig. 5 for the staggered high nuclear share scenario for every two years starting from 2027 until 120 000 SWU have been reached, while in the low nuclear share scenario local enrichment will be started in 2030 and 100 000 SWU level would be reached in stages as depicted by Fig. 6. The spikes in the graph represent the reactor first loading. The strategy would enable the decision makers to evaluate both the capacity of the future enrichment plants and the foreign currency savings that would accrue once the technology has been selected.

NPP participation in the electricity energy mix

The evolution of share per type of reactor technology is presented in Figs 7 and 8 in terms of generation which verifies the change of the electricity mix by 2050 in GW·h.

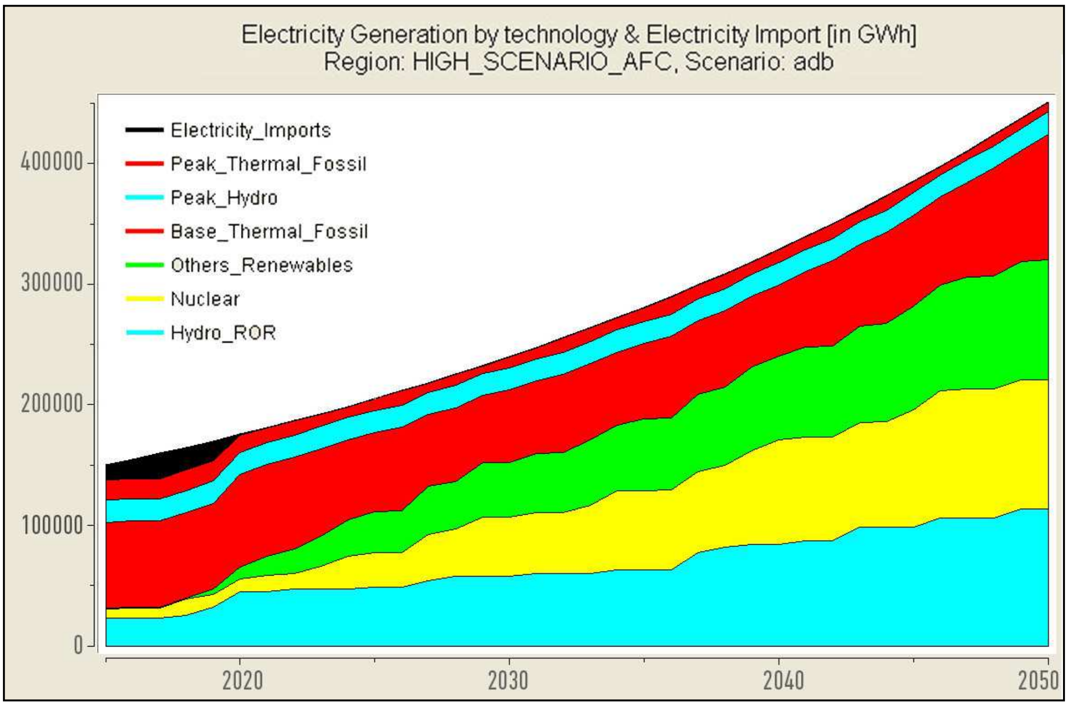


FIG. 7. Electricity generation by technology type for the high scenario.

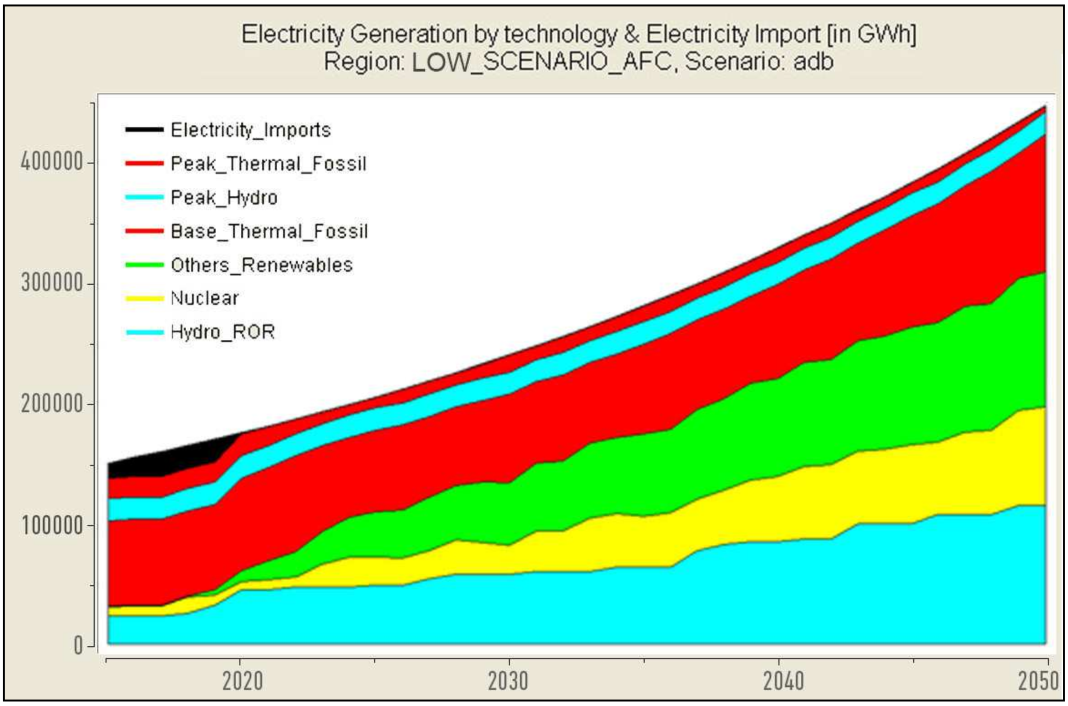


FIG. 8. Electricity generation by technology type for the low scenario.

In the high nuclear share scenario, nuclear power generation by 2050 reaches 12 238.3 GW·h, with an installed capacity of 13 508 MW while for the low nuclear share scenario is 9834.9 GW·h with a capacity of 10 908 MW. This reduction in nuclear power generation in the low nuclear share scenario is compensated for by the thermal and other renewables generation candidates, as shown in Fig. 9.

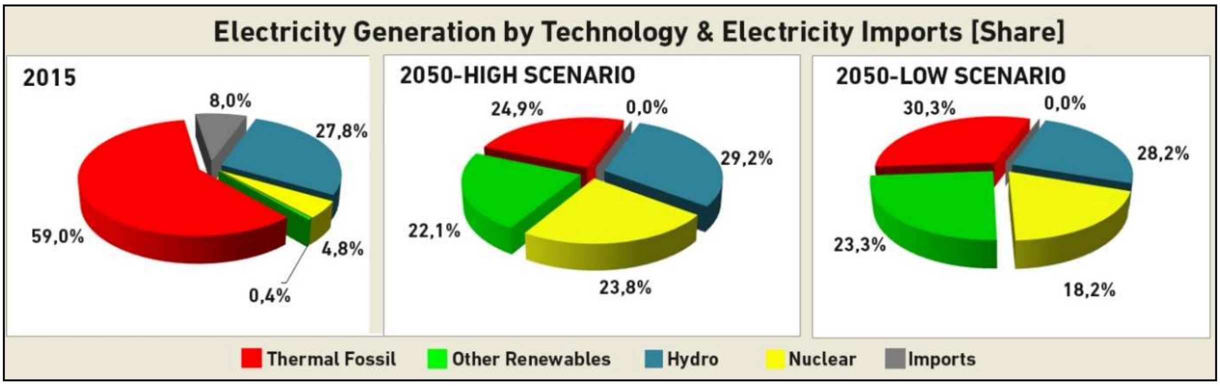


FIG. 9. Comparison for electricity generation per type of technology between 2015 and 2050.

By 2015, the nuclear share was 4.8% and its values in high and low scenarios are 23.8% and 18.2%, respectively. In terms of hydropower, the base year share is 27.8% and for the high and low scenarios it reaches 29.2% and 28.2%, respectively, by 2050, thus maintaining its share. The other variable renewables start from a value of 0.4% in 2015, reaching 22.1% in the high scenario and 23.3% for the low scenario and in line with Law No. 27191, which promotes the use of renewables.

Regarding imports, these will disappear after the first few years and thermal generation burning fossil fuels will decrease by around 50% in the low scenario and above that in the high scenario.

The comparison of total installed capacity per technology for the base year and for the two scenarios is presented in Fig. 10.

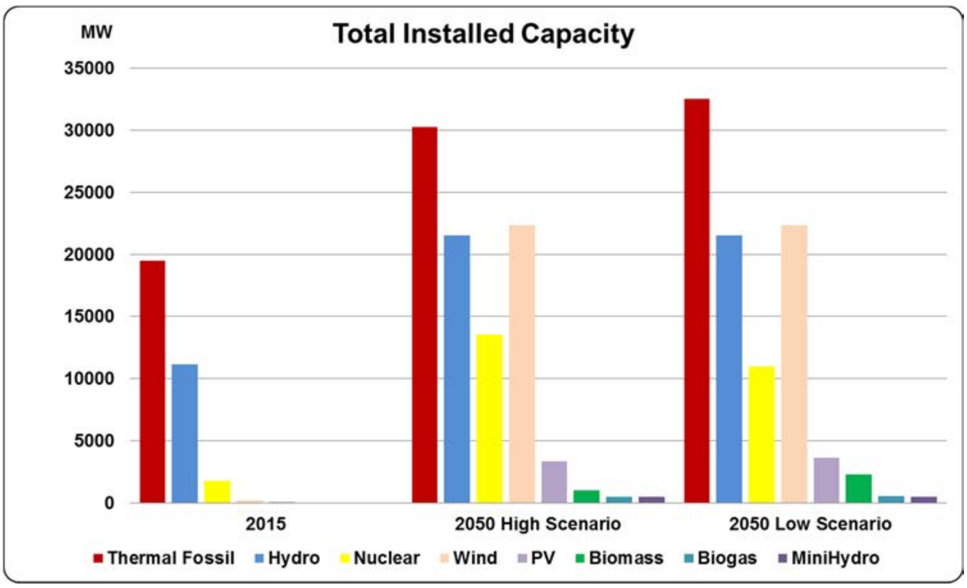


FIG. 10. Comparison for total installed capacity per type of technology between 2015 and 2050.

Results of back end fuel cycle

The evolution of stock for both wet and dry storage for NPPs operating in the base year is provided in the Figs 11(a)–(f).

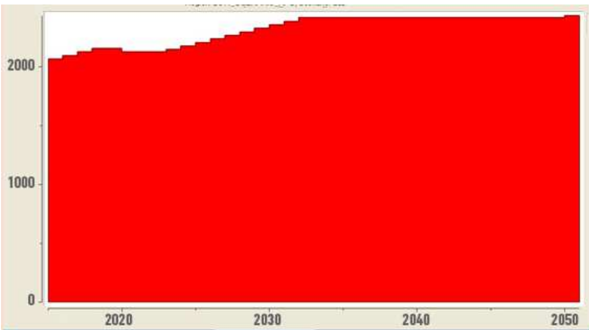


FIG. 11(a). SNF accumulation (in tons) from CNA I (NPP in operation) in wet storage.

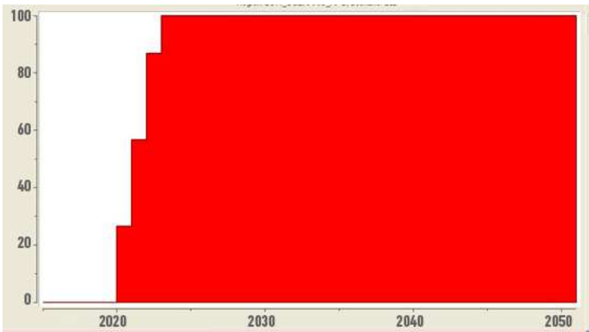


FIG. 11(b). SNF accumulation (in tons) from CNA I (NPP in operation) in dry storage.

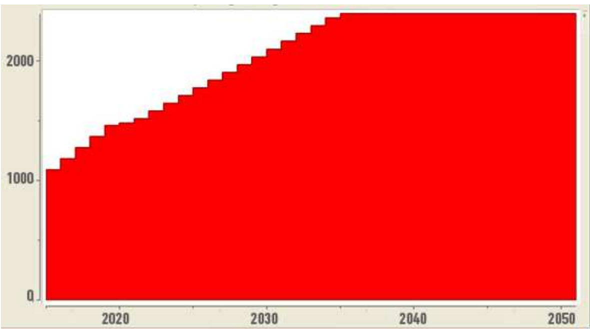


FIG. 11(c). SNF accumulation (in tons) from CNA II (NPP in operation) in wet storage.

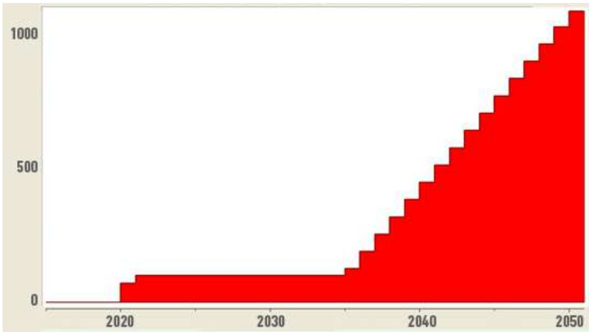


FIG. 11(d). SNF accumulation (in tons) from CNA II (NPP in operation) in dry storage.

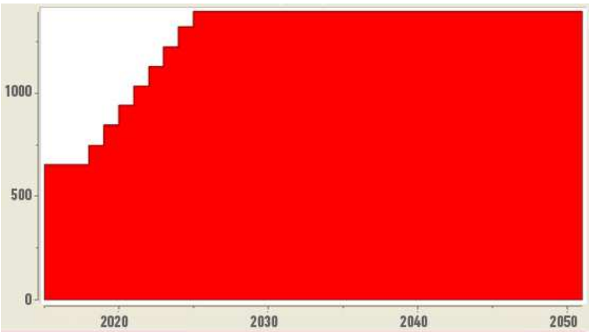


FIG. 11(e). SNF accumulation (in tons) from CNE (NPP in operation) in wet storage.

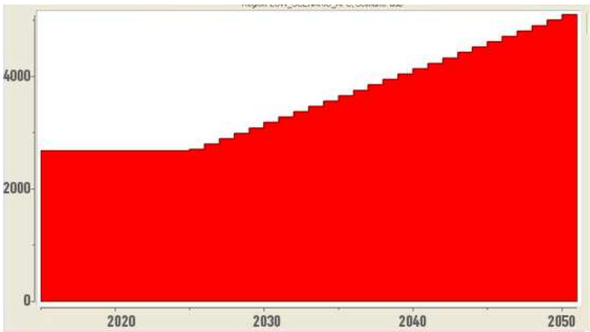


FIG. 11(f). SNF accumulation (in tons) from CNE (NPP in operation) in dry storage.

In the particular case of NPPs in operation in the base year, wet storage has an initial volume regarding its historic production. In the case of CNA II wet storage, which started in February 2015, there is a higher volume than it should have according to its operation. This is the result of 5000 spent fuel assemblies from CNA I wet storage being transferred to CNA II wet storage to make space for the remaining operational time, including the PLEX of 10 years. In CNA I, dry storage is being built with a design capacity of 2880 fuel assemblies to transfer those elements.

Regarding CNE, by the time the dry storage facility for spent fuel is built; there will be 216 dry storage facilities and 32 under construction. These 216 dry storage facilities will accommodate 116 640 fuel assemblies, and the additional 32 facilities under construction will store 17 280 fuel assemblies.

The evolution of stock both in wet and in dry storage is presented in the Figs 12(a)–(l) for nuclear projects related to the high nuclear share scenario.

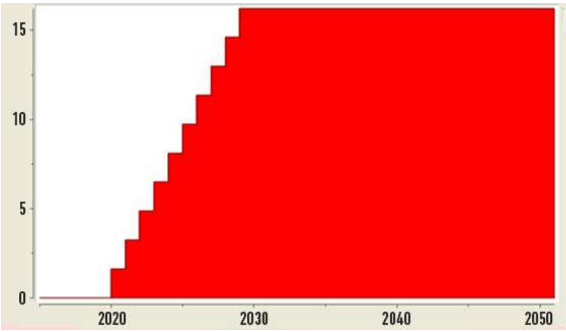


FIG. 12(a). SNF accumulation (in tons) from CAREM 25 (project NPP) in wet storage for high scenario.

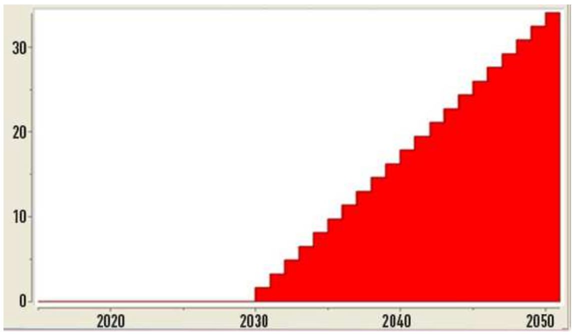


FIG. 12(b). SNF accumulation (in tons) from CAREM 25 (project NPP) in dry storage for high scenario.

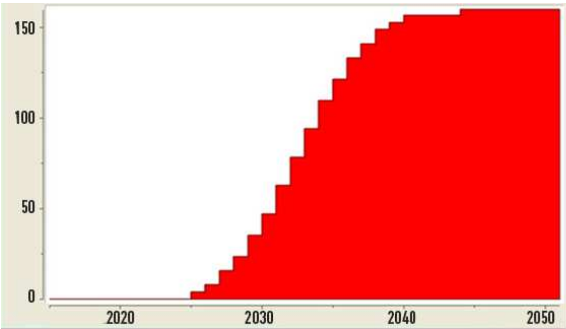


FIG. 12(c). SNF accumulation (in tons) from CAREM 120 NGS I (project NPP) in wet storage for high scenario.

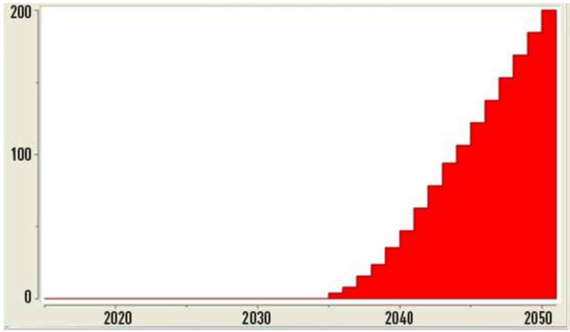


FIG. 12(d). SNF accumulation (in tons) from CAREM 120 NGS I (project NPP) in dry storage for high scenario.

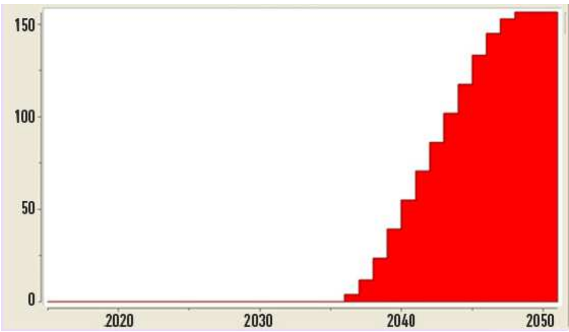


FIG. 12(e). SNF accumulation (in tons) from CAREM 120 NGS II (project NPP) in wet storage for high scenario.

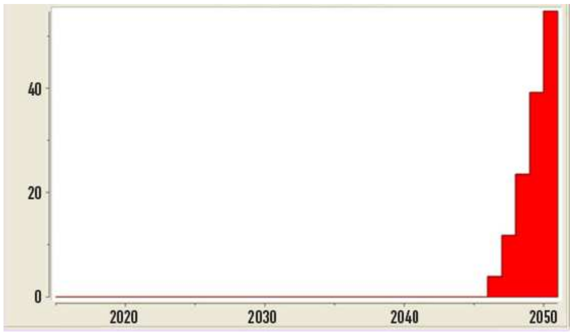


FIG. 12(f). SNF accumulation (in tons) from CAREM 120 NGS II (project NPP) in dry storage for high scenario.

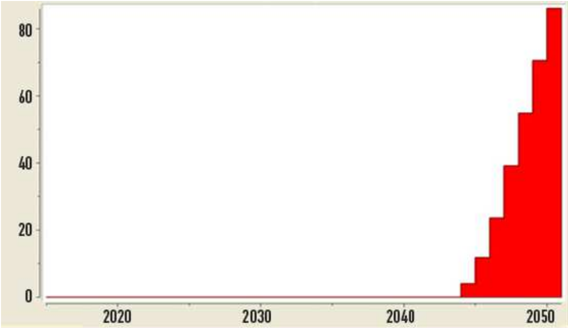


FIG. 12(g). SNF accumulation (in tons) from CAREM 120 NGS III (project NPP) in wet storage for high scenario.

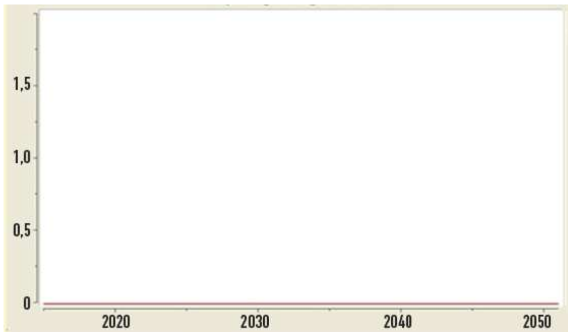


FIG. 12(h). SNF accumulation (in tons) from CAREM 120 NGS III (project NPP) in dry storage for high scenario.

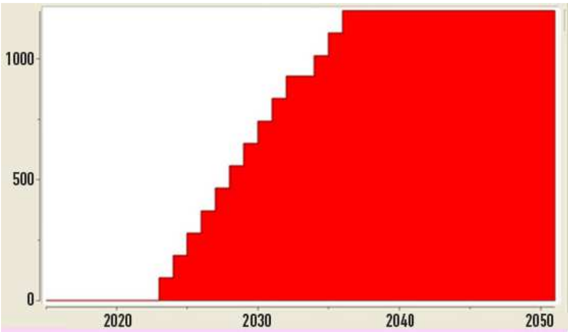


FIG. 12(i). SNF accumulation (in tons) from CANDU 6 (project NPP) in wet storage for high scenario.

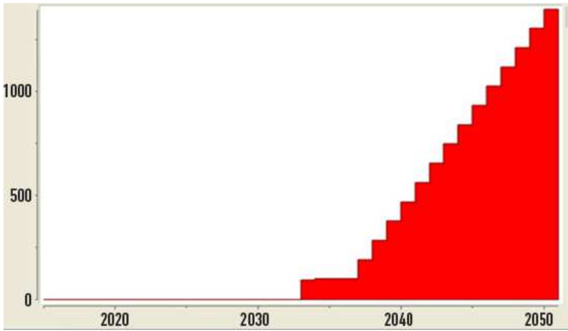


FIG. 12(j). SNF accumulation (in tons) from CANDU 6 (project NPP) in dry storage for high scenario.

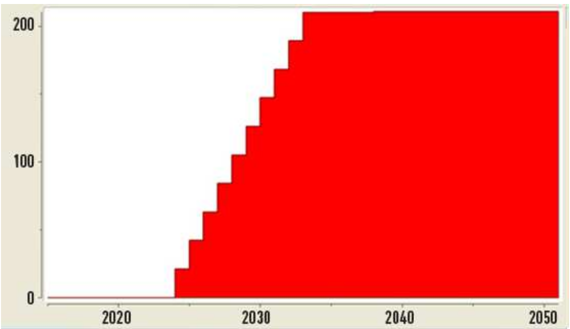


FIG. 12(k). SNF accumulation (in tons) from HPR1000 (project NPP) in wet storage for high scenario.

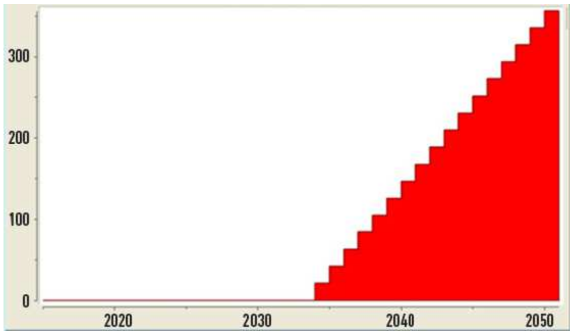


FIG. 12(l). SNF accumulation (in tons) from HPR1000 (project NPP) in dry storage for high scenario.

Stored spent fuel in CAREM 25 NPP is 1.62 t HM/year and in each CAREM 120 unit is 9.92 t HM/year. The spent fuel storage requirement is 92.6 t HM/year and 21.6 t HM/year for CANDU 6 and HPR1000 NPPs, respectively. In every case, the transfer of the spent fuel into the silos is carried out after 10 years of wet storage.

In the case of CAREM 120 NGS III, the model did not install a dry storage facility, since its construction is close to the final year of study (2050).

The evolution of wet and dry storage facilities for the candidate NPPs related to the high nuclear share scenario is provided in Figs 13(a)–(h). It shows that stored spent fuel in each WWER unit is 21.33 t HM/year and in each PWR Generic unit is 18.74 t HM/year. In every case, the transfer of spent fuel into the silos is carried out after 10 years of wet storage. The result of the dry storage facility of the PWR Generic NGS III technology presented in the model is the same as the technology in CAREM 120 NGS III.

The evolution of stock both in wet and in dry storage facilities related to the low nuclear share scenario are presented in the Figs 14(a)–(j) and 15(a)–(f) for the project and candidate NPPs, respectively. The results show that the amount of stock is the same as shown in the high nuclear share scenario (owing to each technology inserted parameters), but a difference lies in the years where the data are shown.

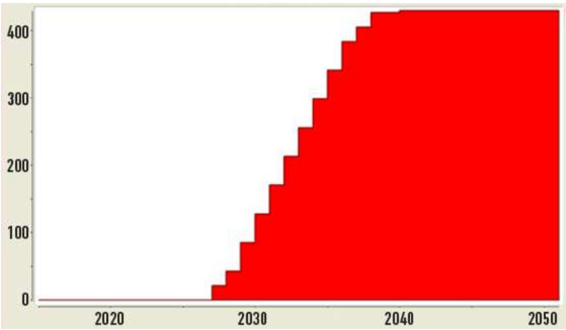


FIG. 13(a). SNF accumulation (in tons) from WWER (candidate NPP) in wet storage for high scenario.

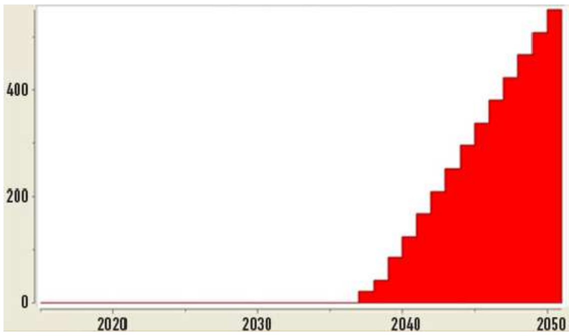


FIG. 13(b). SNF accumulation (in tons) from WWER (candidate NPP) in dry storage for high scenario.

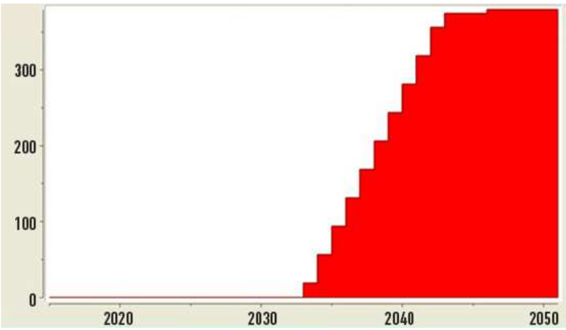


FIG. 13(c). SNF accumulation (in tons) from PWR Generic NGS I (candidate NPP) in wet storage for high scenario.

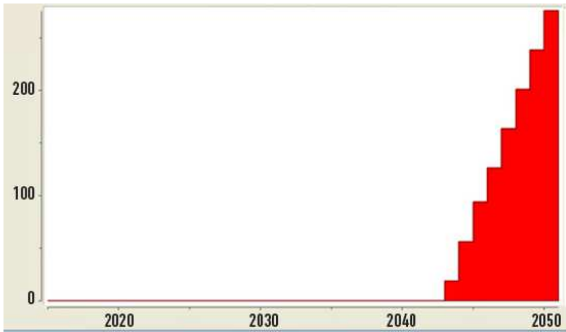


FIG. 13(d). SNF accumulation (in tons) from PWR Generic NGS I (candidate NPP) in dry storage for high scenario.

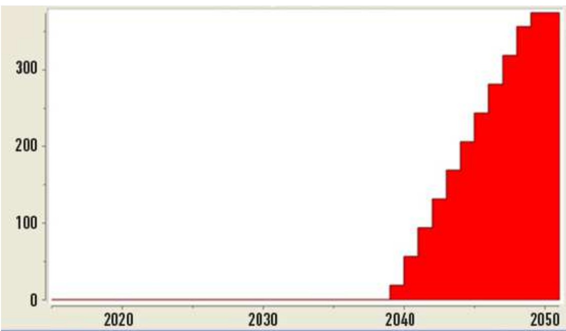


FIG. 13(e). SNF accumulation (in tons) from PWR Generic NGS II (candidate NPP) in wet storage for high scenario.

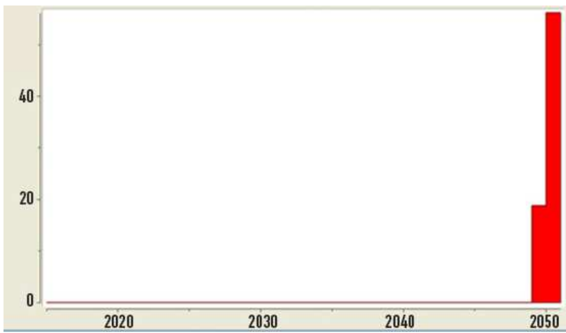


FIG. 13(f). SNF accumulation (in tons) from PWR Generic NGS II (candidate NPP) in dry storage for high scenario.

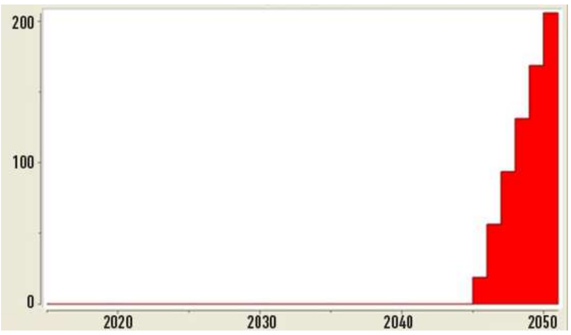


FIG. 13(g). SNF accumulation (in tons) from PWR Generic NGS III (candidate NPP) in wet storage for high scenario.

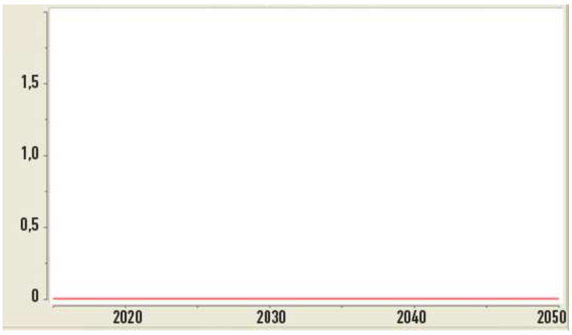


FIG. 13(h). SNF accumulation (in tons) from PWR Generic NGS III (candidate NPP) in dry storage for high scenario.

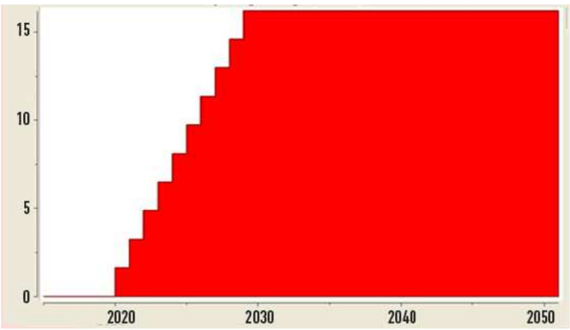


FIG. 14(a). SNF accumulation (in tons) from CAREM 25 (project NPP) in wet storage for low scenario.

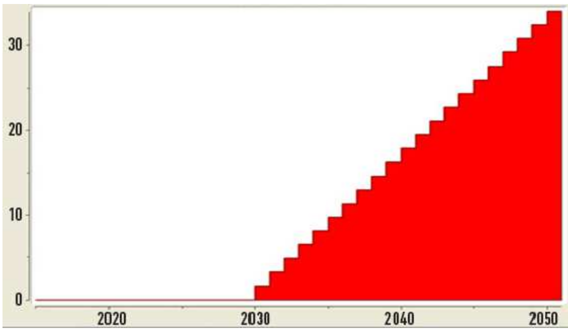


FIG. 14(b). SNF accumulation (in tons) from CAREM 25 (project NPP) in dry storage for low scenario.

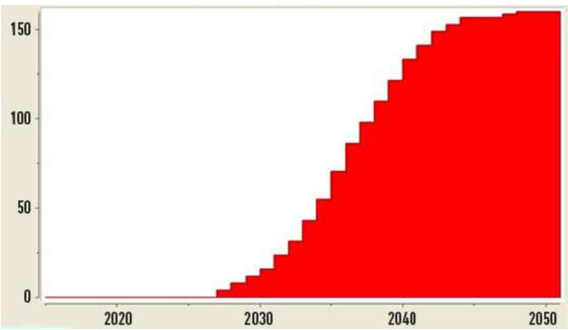


FIG. 14(c). SNF accumulation (in tons) from CAREM 120 NGS I (project NPP) in wet storage for low scenario.

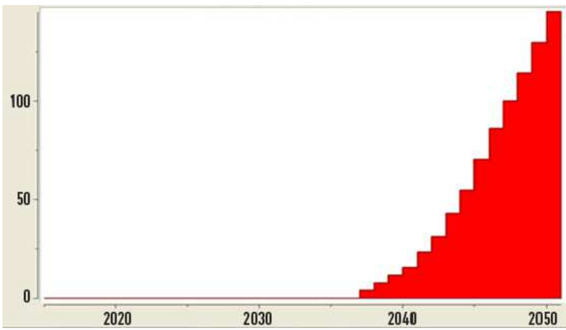


FIG. 14(d). SNF accumulation (in tons) from CAREM 120 NGS I (project NPP) in dry storage for low scenario.

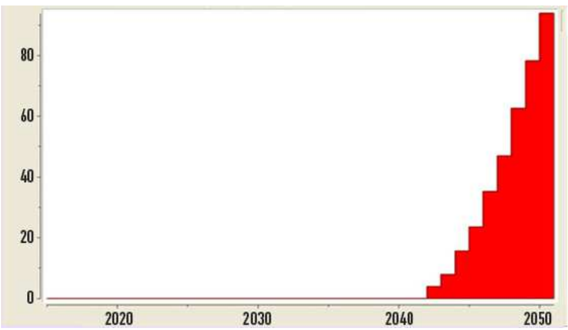


FIG. 14(e). SNF accumulation (in tons) from CAREM 120 NGS II (project NPP) in wet storage for low scenario.

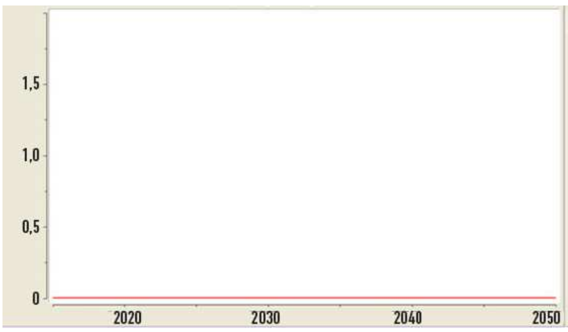


FIG. 14(f). SNF accumulation (in tons) from CAREM 120 NGS II (project NPP) in dry storage for low scenario.

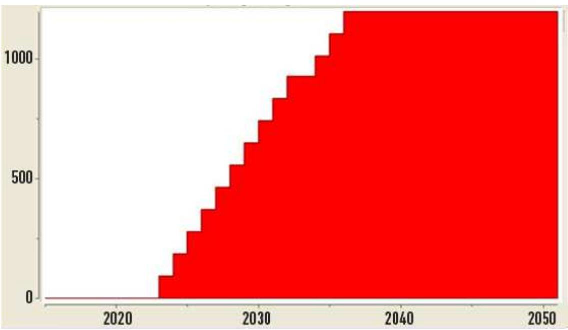


FIG. 14(g). SNF accumulation (in tons) from CANDU 6 (project NPP) in wet storage for low scenario.

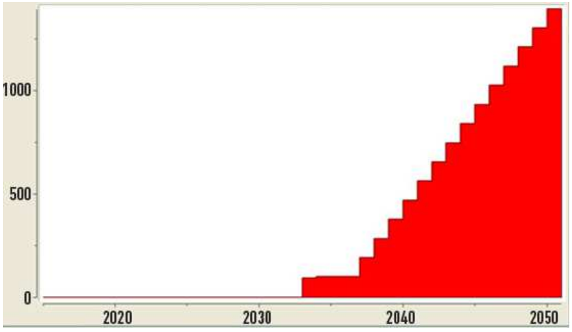


FIG. 14(h). SNF accumulation (in tons) from CANDU 6 (project NPP) in dry storage for low scenario.

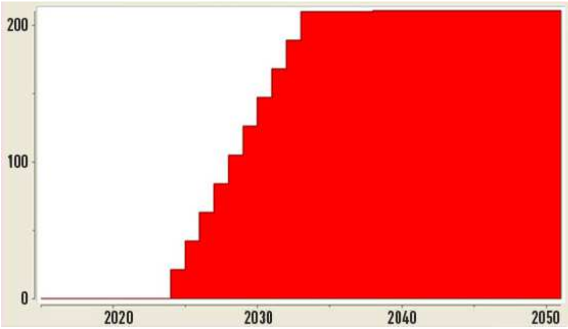


FIG. 14(i). SNF accumulation (in tons) from HPR1000 (project NPP) in wet storage for low scenario.

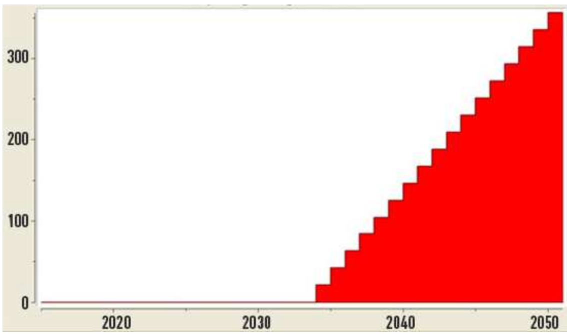


FIG. 14(j). SNF accumulation (in tons) from HPR1000 (project NPP) in dry storage for low scenario.

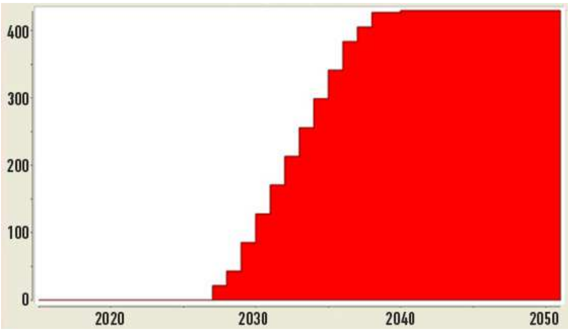


FIG. 15(a). SNF accumulation (in tons) from WWER (candidate NPP) in wet storage for low scenario.

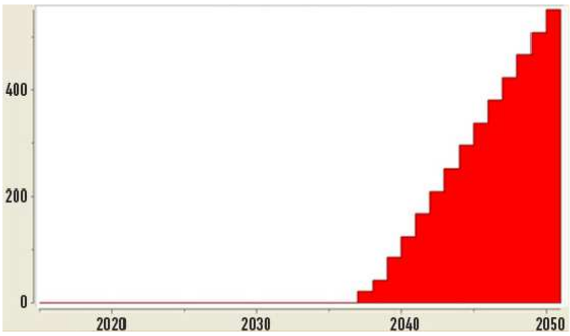


FIG. 15(b). SNF accumulation (in tons) from WWER (candidate NPP) in dry storage for low scenario.

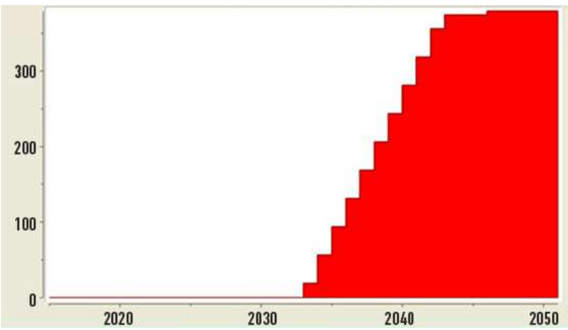


FIG. 15(c). SNF accumulation (in tons) from PWR Generic NGS I (candidate NPP) in wet storage for low scenario.

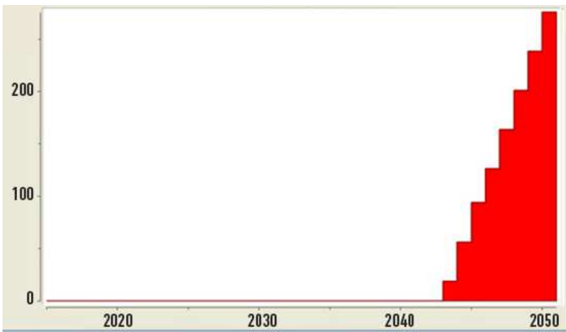


FIG. 15(d). SNF accumulation (in tons) from PWR Generic NGS I (candidate NPP) in dry storage for low scenario.

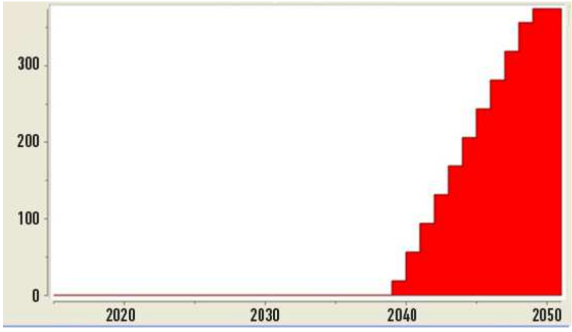


FIG. 15(e). SNF accumulation (in tons) from PWR Generic NGS II (candidate NPP) in wet storage for low scenario.

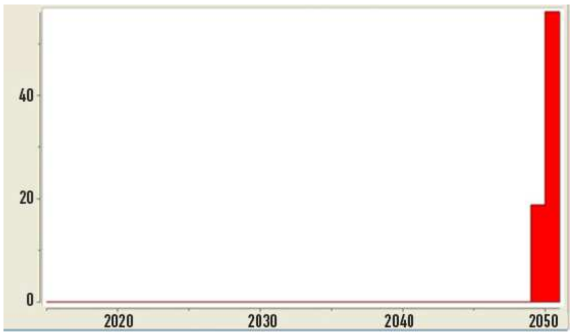


FIG. 15(f). SNF accumulation (in tons) from PWR Generic NGS II (candidate NPP) in dry storage for low scenario.

Results of economic analysis

<u>Annual investment in future NPPs</u>

Total overnight investments per type of technology of candidates and projects are presented in Figs 16 and 17 for the two modelled scenarios. A schedule for particular investments per type of technology was considered for both scenarios.

Costs of investment would reach their highest peak in the high nuclear share scenario in 2043 and in the low nuclear share scenario in 2028 and 2029. In both scenarios, these peaks are below US $4500 million. If the average annual investment per scenario is analysed, the high nuclear share scenario will be around US $2400 million and the low nuclear share scenario will be approximately US $1700 million.

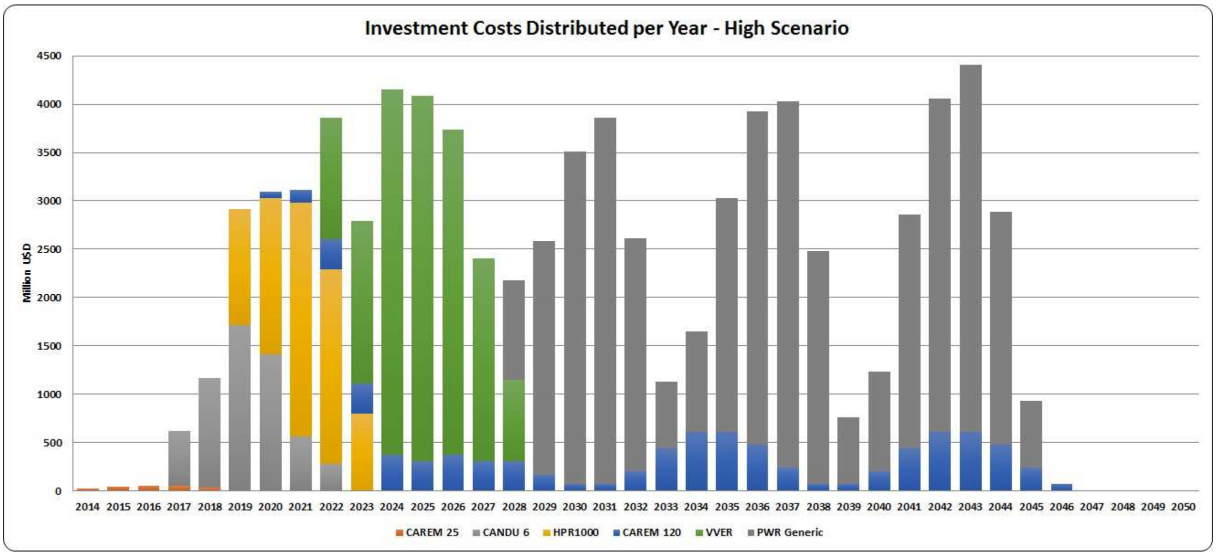


FIG. 16. Investment costs distributed annually in the high scenario.

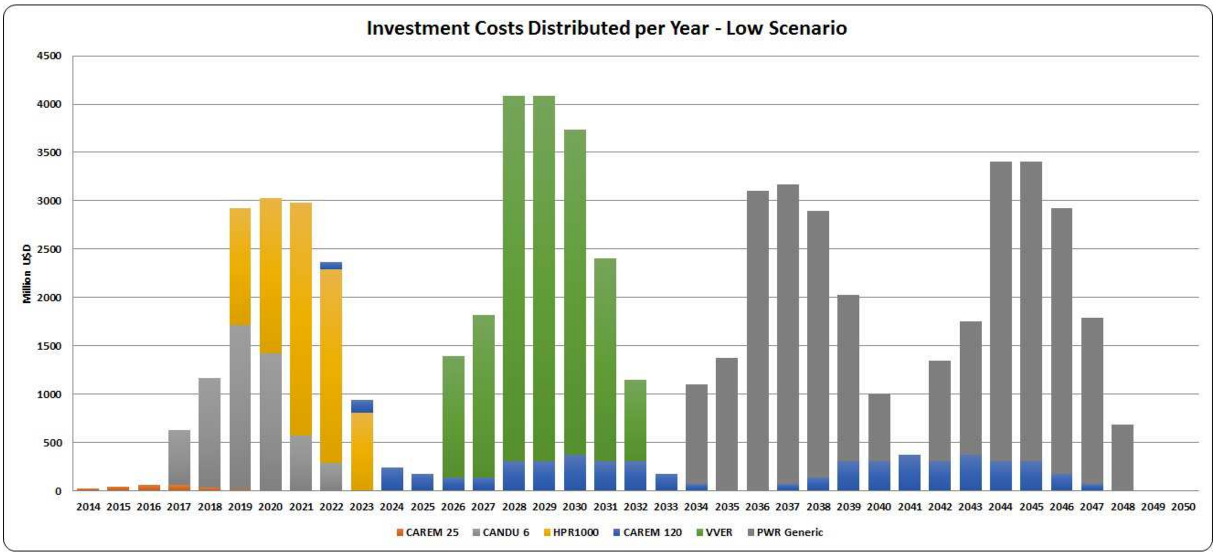


FIG. 17. Investment costs distributed annually in the low scenario.

Investment costs (in million dollars) for each NPP are presented in Figs 18 and 19 according to the MESSAGE schedule for the high and low nuclear share scenarios, respectively. The bar colour coding in the figures show equal units of NPPs, such as two HPR1000 PWRs or modules of NPPs, such as CAREM 120 I / II / III.

The results do not show information on the investment schedule for each NPP but the total amount of investment by the first operational year of the NPP. Investment is made during the construction period of five to six years prior to the beginning of operation.

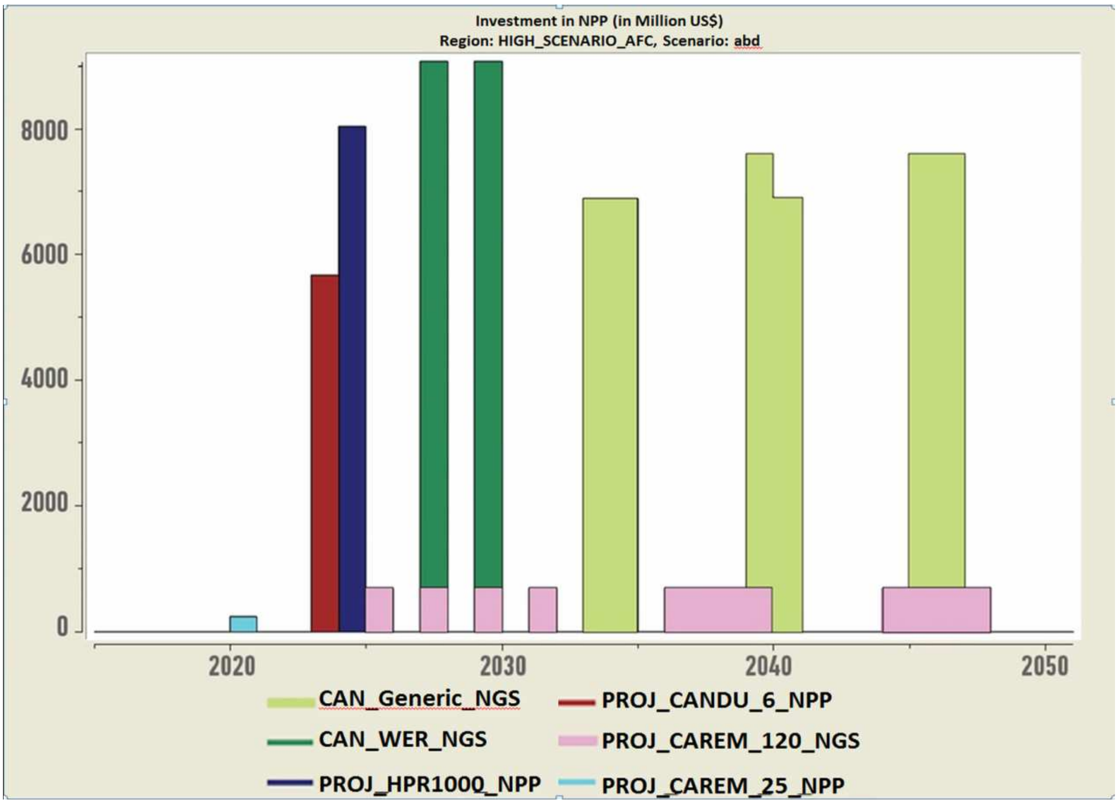


FIG. 18. Investment costs for future NPPs in the high scenario.

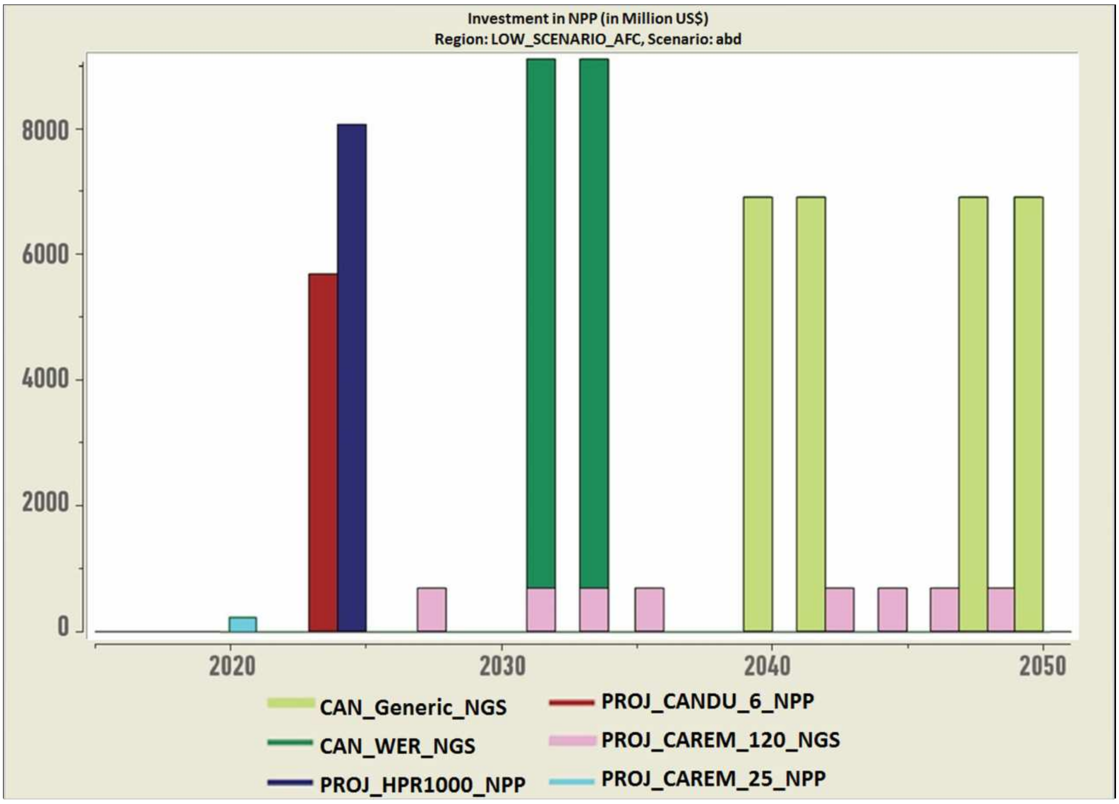


FIG. 19. Investment costs for future NPPs in the low scenario.

Annual expenditure on total fuel cycle and O&M of NPPs

Total annual costs of the nuclear fuel cycle and O&M of nuclear power plants are presented in Figures 20 and 21 for the high and low scenarios, respectively. For the calculations, it was considered that uranium enriched to 3.5% was imported because the enrichment technology and costs are not defined for local production.

Expenditure on total FC and O&M of NPP [in USD]
Region: HIGH_SCENARIO_AFC, Scenario: adb

	resources	Uranium_Import	yellow_cake	fuel_fabrication	wet_storage	dry_storage	NPP_O&M
2015	0.0	16629.1	2724.8	49863.4	19049.0	10720.0	151967.9
2016	0.0	18671.4	2724.8	58960.3	19662.4	10720.0	152062.7
2017	0.0	18671.4	2724.8	58960.3	20275.8	10720.0	152062.7
2018	0.0	29063.3	2724.8	79744.1	21368.4	10720.0	153000.7
2019	0.0	20344.2	2724.8	60041.5	22310.3	10720.0	152588.4
2020	12279.6	3709.9	5781.5	64708.1	22778.2	11105.6	154444.4
2021	12380.0	26263.0	5806.5	41939.3	23439.0	11346.7	218926.7
2022	11012.9	20701.5	5466.2	41939.3	24250.5	11467.3	218926.7
2023	17523.0	20701.5	7086.7	63573.1	25610.5	11520.0	283583.0
2024	17570.3	135997.2	7098.4	171773.5	27141.5	11520.0	350857.4
2025	17297.8	58986.4	7030.6	103385.6	28592.0	11600.1	357937.3
2026	17172.9	45894.0	6999.5	86917.2	29663.5	11983.5	357937.3
2027	17327.5	181379.2	7038.0	212486.3	30861.3	12366.8	435816.6
2028	17202.6	73193.1	7006.9	112161.1	32059.0	12750.1	435816.6
2029	17357.2	208678.4	7045.4	237730.2	33382.9	13133.4	513695.9
2030	17232.3	100492.3	7014.3	137405.0	34698.7	13523.2	513695.9
2031	17386.9	116697.7	7052.8	157789.1	36034.1	13913.0	520775.8
2032	17262.0	103605.2	7021.7	141320.7	37369.6	14302.8	520775.8
2033	16177.9	191358.5	6751.9	211139.0	38184.2	15063.7	583220.9
2034	16268.1	211035.9	6774.3	229878.4	39414.9	15566.5	646078.3
2035	15927.9	136799.5	6689.6	159181.4	40536.6	16156.6	646078.3
2036	16082.5	153004.9	6728.1	175649.8	41479.4	16905.5	646078.3
2037	16112.2	156117.9	6735.5	175649.8	41858.8	18120.8	646078.3
2038	16141.9	159230.9	6742.9	175649.8	42254.4	19338.8	646078.3
2039	16601.9	256257.7	6857.4	246346.8	42633.4	20660.7	708935.7
2040	16985.2	262842.8	6848.8	229878.4	43123.3	21968.8	771793.2
2041	17475.3	188606.4	6764.1	159181.4	43576.4	23306.4	771793.2
2042	17475.3	188606.4	6764.1	159181.4	44029.5	24644.0	771793.2
2043	17475.3	188606.4	6764.1	159181.4	44388.9	26056.5	771793.2
2044	17641.7	204811.8	6802.6	159181.4	44691.0	27530.5	778873.1
2045	18137.1	301838.7	6917.1	159181.4	44995.9	29018.0	848810.4
2046	17998.7	322379.3	6885.1	157559.2	45318.7	30481.4	918439.6
2047	17931.8	253505.8	6869.6	159181.4	45623.6	32000.2	925827.7
2048	17797.4	240413.4	6838.5	159181.4	45908.8	33534.7	925827.7
2049	17797.4	240413.4	6838.5	159181.4	46080.8	35159.8	925827.7
2050	17797.4	240413.4	6838.5	159181.4	46259.5	36865.6	925827.7

FIG. 20. Expenditure on total fixed and O&M costs of NPPs in the high scenario.

Expenditure on total FC and O&M of NPP [in USD]
Region: LOW_SCENARIO_AFC, Scenario: adb

	resources	Uranium_Import	yellow_cake	fuel_fabrication	wet_storage	dry_storage	NPP_O&M
2015	0.0	16629.1	2724.8	49863.4	19049.0	10720.0	151967.9
2016	0.0	18671.4	2724.8	58960.3	19662.4	10720.0	152062.7
2017	0.0	18671.4	2724.8	58960.3	20275.8	10720.0	152062.7
2018	0.0	29063.3	2724.8	79744.1	21368.4	10720.0	153000.7
2019	0.0	20344.2	2724.8	60041.5	22310.3	10720.0	152588.4
2020	12279.6	3709.9	5781.5	64708.1	22778.2	11105.6	154444.4
2021	12380.0	26263.0	5806.5	41939.3	23439.0	11346.7	218926.7
2022	11012.9	20701.5	5466.2	41939.3	24250.5	11467.3	218926.7
2023	17523.0	20701.5	7086.7	63573.1	25610.5	11520.0	283583.0
2024	17570.3	135997.2	7098.4	171773.5	27141.5	11520.0	350857.4
2025	17143.2	42781.0	6992.1	83001.5	28572.5	11600.1	350857.4
2026	17143.2	42781.0	6992.1	83001.5	29624.4	11983.5	350857.4
2027	17297.8	58986.4	7030.6	103385.6	30695.9	12366.8	357937.3
2028	17172.9	45894.0	6999.5	86917.2	31767.4	12750.1	357937.3
2029	17172.9	45894.0	6999.5	86917.2	32838.9	13133.4	357937.3
2030	17172.9	45894.0	6999.5	86917.2	33902.3	13523.2	357937.3
2031	17327.5	181379.2	7038.0	212486.3	35091.9	13913.0	435816.6
2032	17202.6	73193.1	7006.9	112161.1	36281.5	14302.8	435816.6
2033	15842.8	202517.7	6668.4	218112.3	36982.8	15063.7	513283.6
2034	15717.9	94331.6	6637.4	117787.0	38006.6	15566.5	513283.6
2035	15872.5	110537.0	6675.8	138171.1	38960.5	16141.0	520363.5
2036	15747.6	97444.6	6644.8	121702.7	39715.9	16874.2	520363.5
2037	15747.6	97444.6	6644.8	121702.7	39995.0	17988.5	520363.5
2038	15747.6	97444.6	6644.8	121702.7	40270.7	19105.5	520363.5
2039	16177.9	191358.5	6751.9	211139.0	40636.4	20225.5	583220.9
2040	15964.0	117122.1	6667.2	140442.0	41002.1	21345.4	583220.9
2041	17519.5	211035.9	6774.3	229878.4	41335.3	22566.3	646078.3
2042	17319.6	153004.9	6728.1	175649.8	41688.0	23787.3	646078.3
2043	17185.1	139912.5	6697.0	159181.4	41914.6	25109.2	646078.3
2044	17351.6	156117.9	6735.5	175649.8	42177.9	26417.3	646078.3
2045	17217.1	143025.5	6704.4	159181.4	42404.4	27754.9	646078.3
2046	17383.6	159230.9	6742.9	175649.8	42650.6	29092.4	646078.3
2047	17712.5	240052.3	6818.9	229878.4	42999.4	30422.8	708935.7
2048	17512.7	182021.5	6772.7	175649.8	43366.7	31754.1	708935.7
2049	17841.6	262842.8	6848.8	229878.4	43726.1	33166.6	771793.2
2050	17475.3	188606.4	6764.1	159181.4	44185.8	34584.8	771793.2

FIG. 21. Expenditure on total fixed and O&M costs of NPPs in the low scenario.

<u>LUAC and LUOM</u>

Regarding the annual generation and costs for each type of technology, generation costs in US $/MW·h for projects and candidates were calculated and are presented in Fig. 22.

The value of the cost of electricity from the CAREM 25 NPP is high as this reactor is an originally designed prototype and, consequently, a first of a kind (FOAK) reactor. Since the CAREM 25 prototype would already be developed, built and operational, a further development on a larger scale at a lower general cost will be possible for the CAREM 120 NPP.

Regarding the remaining larger sized NPPs, these are within the international standard ranges of US $100/MW·h with a variation of ±10%.

LUAC & LUOM [in U$S/MWh]
Region: LUAC_LUOM_LOW_2, Scenario: adb

	PROJ_CAREM_25_NPF	PROJ_CAREM_120_NGS_I	PROJ_CANDU_6_NPF	PROJ_HRP1000_N	CAN_VVER_NGS	CAN_Generic_NGS_I
2015	112.29	81.45	118.52	102.12	96.60	87.36
2050	112.29	81.45	118.52	102.12	96.60	87.36

FIG. 22. LUAC and LUOM in both high and low scenarios.

2.1.6. Feedback from the case study on NES modelling with the MESSAGE tool

2.1.6.1. Main conclusions and findings of the case study

Nuclear fuel cycle modelling has addressed the key objectives of the study for NPPs as well as for the front end and back end of the nuclear fuel cycle stages listed in Section 2.1.

From an economic analysis viewpoint, similar results have been obtained in previous studies by applying INPRO Methodology for the economics. Nuclear power is competitive in Argentina because even though local natural gas is more economic, it is insufficient to meet all of the local demands necessitating import of higher priced natural gas, LNG and other liquid fuels.

The necessary requirements in terms of natural and enriched uranium for both scenarios were quantified regarding the front end of the nuclear fuel cycle. The replacement of imports of natural and enriched uranium was evaluated. The analysis of the SWU requirements assisted the formulation of a strategy which envisaged installation of a local enrichment plant, thus partially replacing imports of 3.5% enriched uranium during the period of study.

Regarding electricity generation, an analysis was performed taking into account a modified energy mix with a higher share of hydropower, nuclear power and other variable renewables, resulting in a reduction of thermal generation through burning fossil fuels of approximately 50% by 2050 in each scenario analyzed.

Spent fuel, both in wet and dry storage, has been quantified regarding the back end of the nuclear fuel cycle.

In conclusion, this work is considered to be highly significant as it will enable decision makers to have additional information to define a path for the Nuclear Plan of the Argentine Republic. From this study, it will be possible to conduct sensitivity analysis, taking into account different variables which may be modified at future dates.

2.1.6.2. Discussion about aspects in which the MESSAGE model was useful in this study

The MESSAGE model was very useful for the case study since it was possible to achieve comprehensive modelling of the Argentine open nuclear fuel cycle. All the details of nuclear material flows were represented in the MESSAGE model. The materials and infrastructure facilities, conversion, enrichment and fuel fabrication services, etc., needed for future nuclear power development, were quantified and assessed. MESSAGE helped to optimize the electricity generation system and identify potential contribution of the nuclear power including the front end and the back end of the open (once-through) nuclear fuel cycle.

2.2. CHINA DEMO-SCENARIO WITH PLUTONIUM MULTI-RECYCLING BASED ON FBR AND CNFC TECHNOLOGY

2.2.1. Introduction (general information)

China is striving to achieve sustainable environmental development for the future. Developing nuclear power is one of the important options for China's energy supply structure optimization.

The Government of China has consistently advocated the development of nuclear power on the basis of nuclear safety. The Qinshan Nuclear Power Plant was the first nuclear power plant established in China and was put into operation in 1991. Since then 28 units had been put into commercial operation by the end of 2015, bringing the total installed nuclear capacity to 26.42 GW(e). Twenty four of these units are based on PWR technology, corresponding to 24.98 GW(e) in terms of power production.

China has a far-reaching nuclear power development vision. In the next five years, about 30 GW(e) of nuclear capacity will be put into operation and more than 30 GW(e) capacity will be under construction. The nuclear power capacity is estimated to be 58 GW(e) by 2020. The top level scenario of China's nuclear power development is a three-step strategy of 'thermal reactor–fast reactor–fusion reactor' which was adopted in the 1990s.

China has long been focusing on the development of nuclear power technology. The Generation III nuclear power technologies, for example HPR1000 and CAP1400, have been developed domestically. Significant R&D efforts have also been put into developing the technology of Generation IV nuclear energy systems, such as fast reactor with sodium coolant (SFR), molten salt reactor (MSR), etc. China will become a technology exporting country and will contribute to the development of global nuclear energy in the future.

2.2.2. Objectives and problem resolution

China needs large scale development of nuclear power, but it has limited uranium resources which is detrimental to its ambitious nuclear development plan. In order to ensure the effective utilization of nuclear resources and the effective disposal of high level long lived radioactive waste (spent fuel containing Pu, minor actinides and long lived fission products) produced by nuclear power plants, China insists on using the closed nuclear fuel cycle strategy to ensure the sustainable development of fission nuclear energy. China has carried out considerable research on the fast breeder reactor and on the closed nuclear fuel cycle (CNFC) technology. China has completed the construction of the China Experimental Fast Reactor (CEFR) of 20 MW(e) and the China Spent Fuel Reprocessing Pilot Plant (CRPP) which has a capacity of 50 t HM/year. The China Demonstration Fast Reactor of 600 MW(e) and the China Industrial Demonstration Reprocessing Plant with capacity of 200 t HM/year are in the design stage.

In view of China's nuclear strategy, this case study attempts to evaluate the development scenarios based on fast breeder reactor (FBR) and CNFC technologies, and uses the MESSAGE program to model optimization options for these nuclear energy systems.

The specific objectives of this 'demo-scenario' study are:

— To investigate the coupling development of FBR and PWR NPPs;

— To investigate the uranium resource demand in order to support the development of nuclear power;

— To investigate the reprocessing capacity demand for FBR plutonium recycling;

— To analyze the sensitivity of the whole nuclear energy system to economic implications of CNFC options, such as natural uranium cost.

2.2.3. Model description and input data

With the rapid development of China's economy and society in recent decades, the demand for energy is also increasing rapidly. Electricity is the most important part of energy for social development. At the end of 2015, China's power generation capacity reached 1.53 billion kW. The whole society is expected to consume 6.8–7.2 trillion kW in 2020, with an average annual growth rate of 3.6–4.8%. The national installed capacity of power generation is 2 billion kW, close to the level of a typical medium developed country. The objective of optimizing the energy structure is to reduce the proportion of coal and gas and to increase the proportion of wind, hydro and nuclear, to ensure energy security and to reduce environmental stress.

Nuclear power has many advantages, such as possibility of large scale deployment, high efficiency, lack of climate restrictions, etc. Therefore, the Government changed the nuclear energy policy from moderate to positive in 2005 and incorporated nuclear power into the national electricity development strategy. On 22 March 2006, the State Council adopted the 'Nuclear power middle–long term development programme of China (2005–2020)'. The nuclear power ratio will be increased step by step over the coming years, and nuclear generating capacity will be 40 GW(e), with a further 18 GW(e) of nuclear units being under construction by 2020 [9]. It is also possible that this plan will be changed to a more aggressive one. The 40 GW(e) may be increased to about 60 GW(e) in 2020. The general target for nuclear generation capacity is 160 GW(e) and 250 GW(e) for 2030 and 2050 respectively. In this study, according to the results of the China nuclear energy development studies by the Chinese Academy of Engineering [10], it is assumed that the NPP capacity will achieve the scale of 300 GW(e) by 2050.

2.2.4. Modelling of selected NES elements with MESSAGE

On the basis of China's circumstances, a simplified scenario model is studied. In this case, two reactor technologies are considered, one being a typical 1000 MW scale PWR with UOX fuel and the other an 800 MW scale FBR with MOX fuel.

The NES adopts closed nuclear fuel cycle technology. The system mass flow is shown in Fig. 23. The light water reactor (LWR) needs the manufacture of uniform fuel assemblies, whereas the fast reactor needs the manufacture of assemblies containing radial and axial blankets. Reprocessing will be divided into: recovery of uranium, plutonium, fission products and minor actinides. The plutonium will be recycled in the system.

The main parameters of the two types of reactor technology are listed in Table 19. The enrichment of LWR fresh fuel is about 4wt% by weight. The plutonium content of fast reactor (FR) MOX fuel is about 22wt%. The material of the FR blanket zone is depleted uranium. The spent fuel cooling time of LWR and FR fuel is 5 and 2 years, respectively.

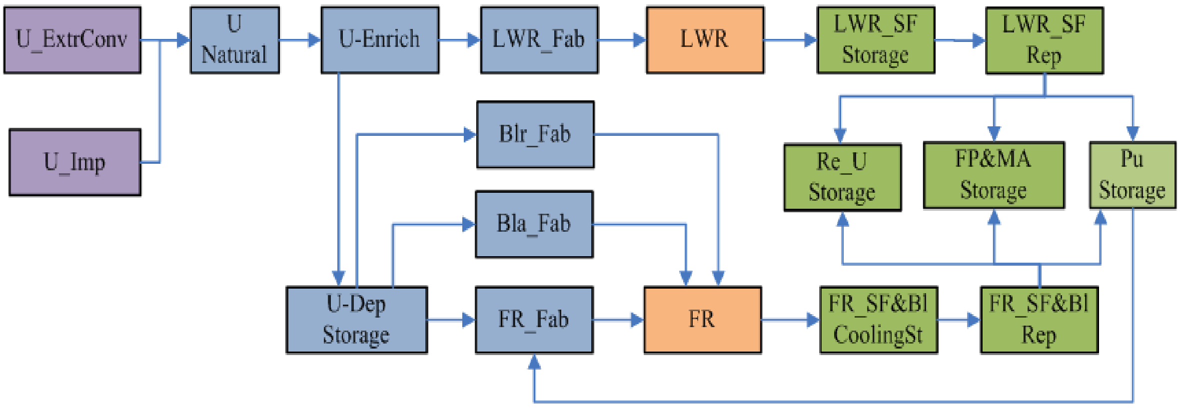


FIG. 23. System mass flow chart.

TABLE 19. MAIN PARAMETERS OF REACTOR TECHNOLOGIES

Item	**Unit**	**LWR**	**FR**		
Nuclear capacity	GW(e)	1	0.87		
Load factor	n.a.	0.8	0.85		
Thermal efficiency	%	33	41.43		
Enrichment of fresh fuel	n.a.	0.04	-		
Tails assay	n.a.	0.003			
Cooling time	year	5	2		
			Core	Axial blanket	Radial blanket
Fuel residence time	EFPD	1168	420	420	490
Discharged burnup	GW·d/t HM	45	65.9	4.8	4.2
First loading	t HM		12.6	5.5	6.2
Pu content	%		21.8	Dep U	Dep U

The NES mass flow parameters are listed in the Table 20.

TABLE 20. MAIN PARAMETERS OF MASS FLOW CALCULATIONS

Annual output parameters	**Unit**	**LWR**	**FR**
Fresh fuel/fuel zone	t HM	19.66	9.31
Fresh fuel/axial blanket	t HM	-	4.06
Fresh fuel/radial blanket	t HM	-	3.93
Fuel in core	t HM	78.65	-
Natural U	t HM	176.85	-
Conversion	t HM	176.85	-
SWU	t SWU	103.70	-
Depleted U	t HM	157.18	-
Spent fuel discharged	t HM + t FP	19.66	17.30
Reprocessed Pu used	t HM	-	2.03
Spent fuel reprocessing	t HM + t FP	-	17.19
Reprocessed Pu	t HM	-	2.03
Pu losses	t HM	-	0.02
Minor actinides	t HM	-	0.04
Fission products	t FP	-	0.66

The main economic data for the case study are shown in Table 21, which includes data on the fuel supply and fuel cycle, using the data adopted in the MESSAGE template rather than real data.

TABLE 21. MAIN ECONOMIC DATA OF NES

Item	Unit	LWR	FR-MOX
Reactor economic data			
Investment cost	US $/kW(e)	3000	3500
Fixed O&M cost	US $/kW·year	55	55
Variable O&M cost	US $/kW·year	10	50
Lifetime	year	40	60
Construction time	year	5	5
Conversion	US $/kg HM	8	-
Enrichment	US $/kg HM	110	-
Fuel fabrication	US $/kg HM	275	1500
Blanket fuel fabrication	US $/kg HM	-	300
Cooling storage	US $/kg HM·year	5	7.5
Interim storage	US $/kg HM·year	4	7
Natural uranium cost	US $/kg HM	40	-
Reprocessing	US $/kg HM	-	1500
Separated plutonium	US $/kg HM	-	2000
Cooling time for mixed spent fuel	year	-	2
Reprocessing time	year	-	1
Fuel cycle economic data			
Capacity	t HM/year	1000	1000
Capacity factor of use	%	100	100
Construction time	year	5	5
Operational life	year	60	60
Reprocessing time	year	1	1
Investment cost	US $/kg HM	5000	5000
Annual operational cost	US $/kg HM·year	400	1000
Total service cost	US $/kg HM	650	1250
Reprocessing losses	%	≤1 (0.755)	≤1 (0.755)

The energy levels and forms are established on the basis of the system mass flow, as shown in Fig. 24, in accordance with the MESSAGE User's Guide [2].

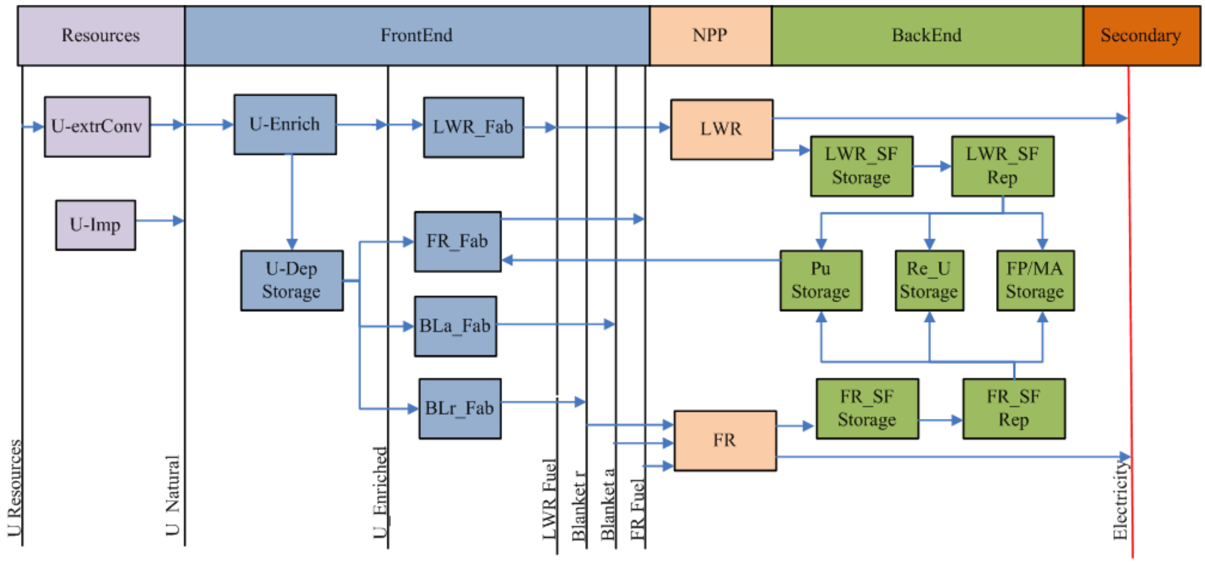


FIG. 24. General schemes of material flows in the NES.

After creating a new case for study in MESSAGE, the editing of relevant information ‘application db(adb)’ is started. In ‘General Info’ tab as shown in Fig. 25, a ‘discount rate (drate)’ is identified, which is assumed according to the regional long term condition. The analysis time span in this case is a century period from 2001 to 2100.

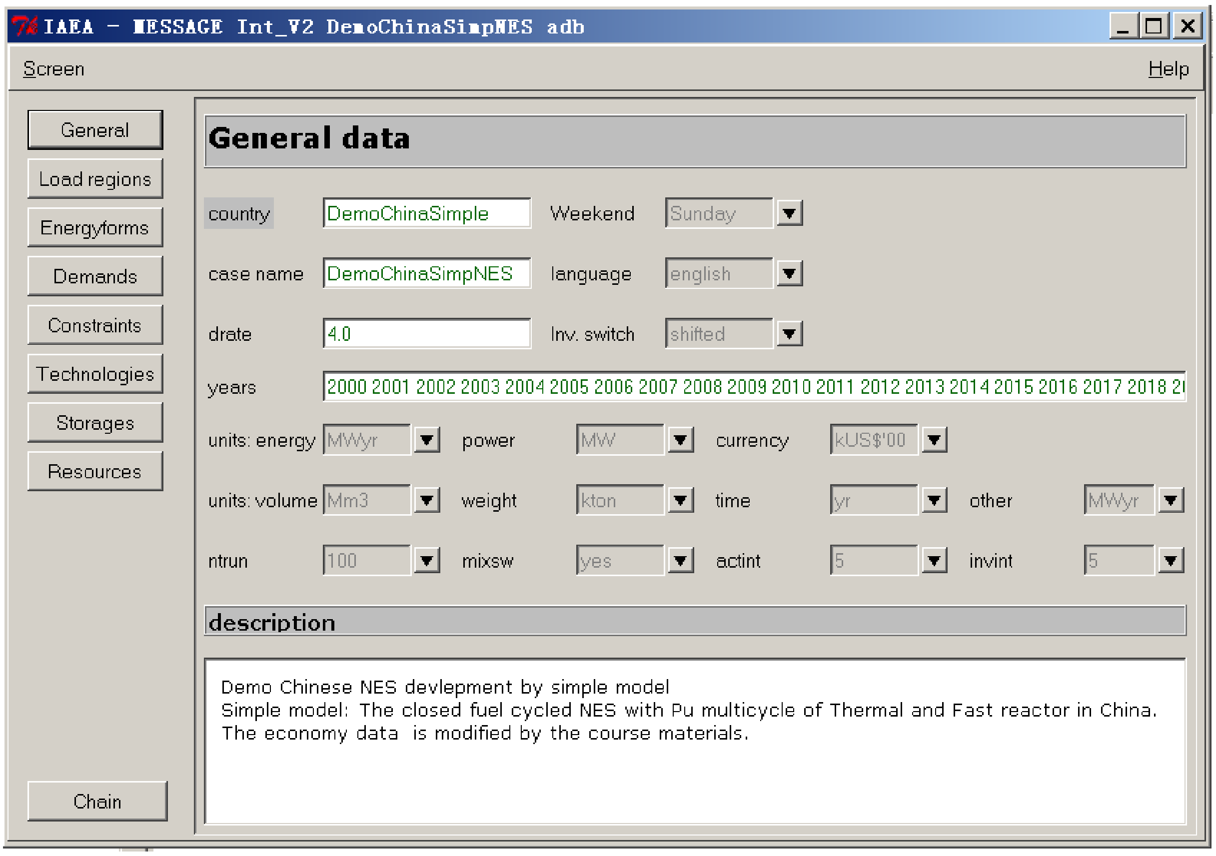


FIG. 25. Editing Interface of ‘General Info’.

In this case study, it is assumed that a natural uranium resource of about 2 Mt is available, which can support the development of PWR to 200 GW. The import of uranium is a realistic option but was not considered in this demo-scenario analysis. The total capacity requirement is 300 GW and therefore the balance of 100 GW capacity needs to be supplied by FR technology. The ‘Demand’ interface edited in this case is shown in Fig. 26.

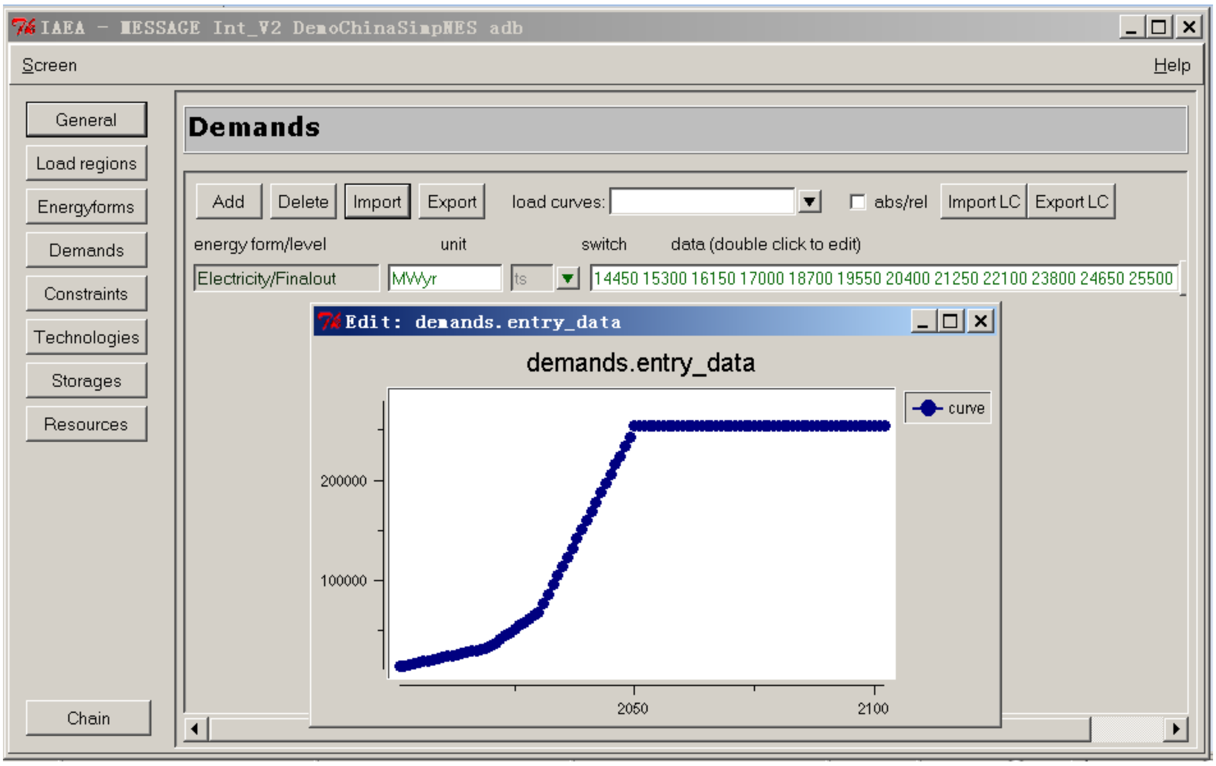


FIG. 26. *Editing interface of ‘Demands’.*

In accordance with the chart of energy levels and forms, the ‘Energy Forms’ and ‘Technology Chain’ are edited and the data completed, as shown in Figs 27 and 28. When editing the technology chain, the logic of all levels should be emphasized.

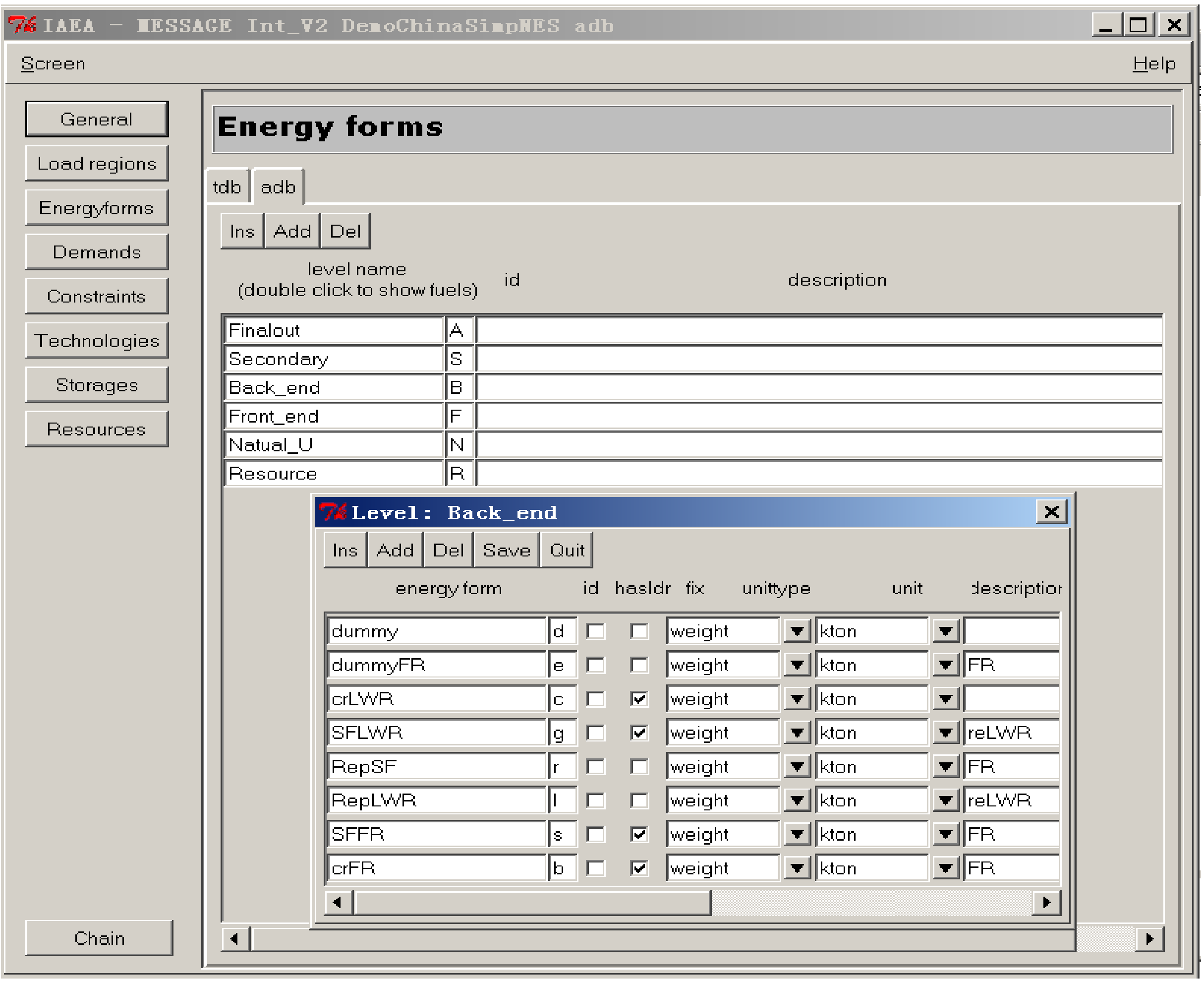


FIG. 27. Editing interface of 'Energy Forms'.

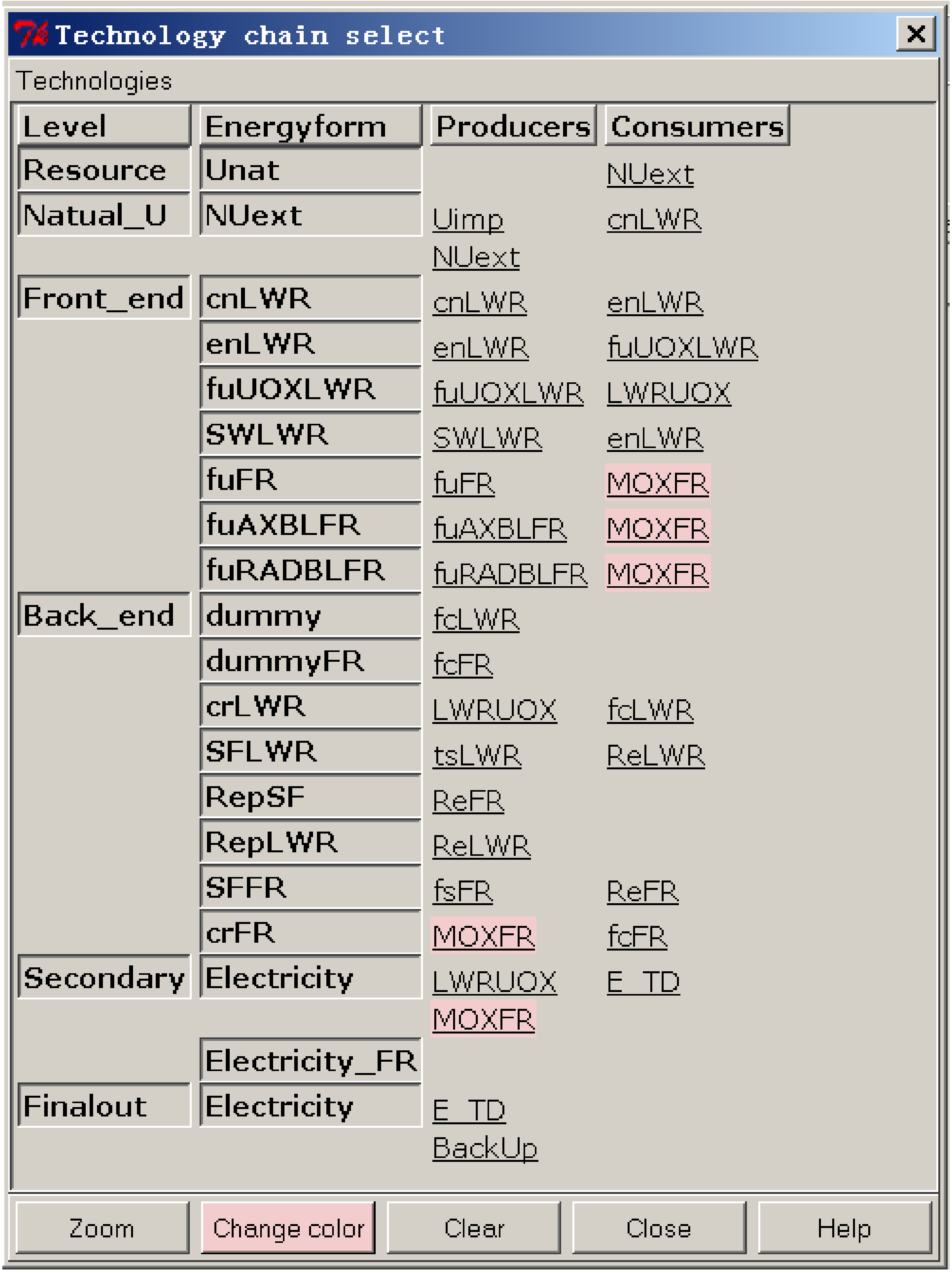


FIG. 28. Editing interface of 'Technology Chain'.

According to the sketch of the chain, the 'Technologies' interface is shown in Fig. 29. Each technology is edited at all levels and the relevant parameters of the 'input', 'output' and necessary data of costs are provided. When editing one 'Technologies', the description of the technical constraints would be needed. For the property 'Activity', it is set via the 'bda' (bounds on activity) button, and for the property ‘Capacity’, it is set via the ‘bdi’ (bounds on total installed capacity) button, and the setting options include the upper limit (up), lower limit (low), and fixed value (fx). The technology MOX FR is selected as an example and the editing interfaces are shown in Figs 30 and 31. The total capacity of one FR NPP is calculated as 870 × 0.85 = 739.5 MW·year. Regarding the front end of fuel cycle, input parameters are calculated for the axial blanket as fuAXBLFR = 4.06/(1000 × 739.5) = 0.000005493979 kt/MW·year, the radial blanket as fuRADBLFR = 3.93/(1000 × 739.5) = 0.000005308468 kt/MW·year and the fuel zone as fuFR = 9.31/(1000 × 739.5) = 0.000012586207 kt/MW·year. Regarding the back end of fuel cycle, the discharged spent fuel parameter is calculated as fuFR = 17.30/(1000 × 739.5) = 0.000023388654 kt/MW·year.

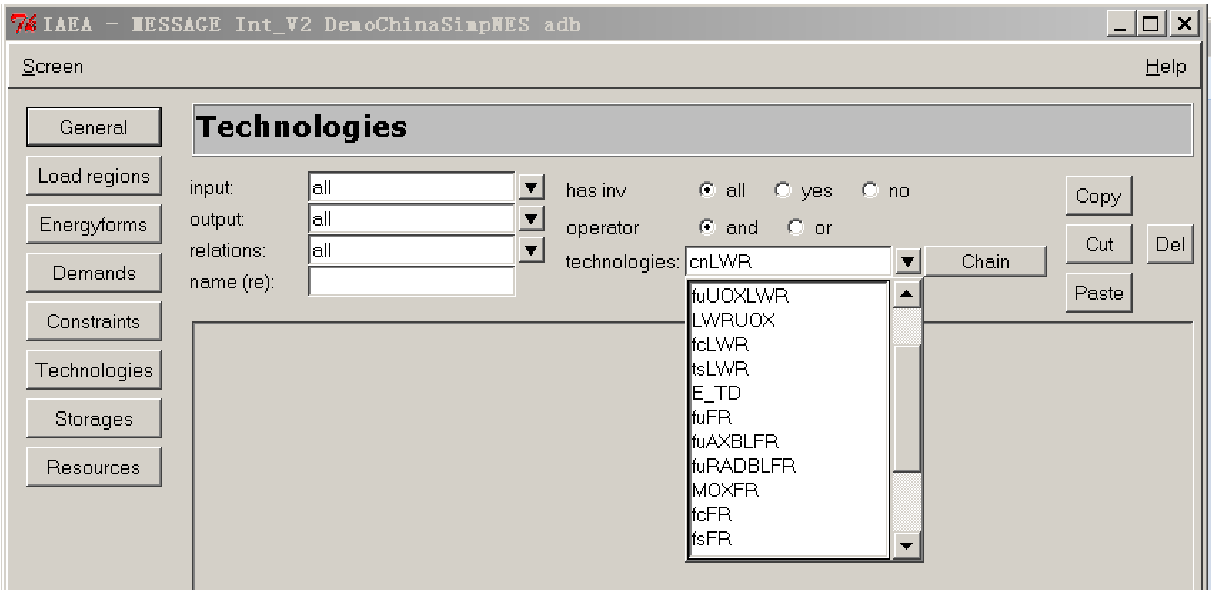


FIG. 29. Editing interface of ‘Technologies’.

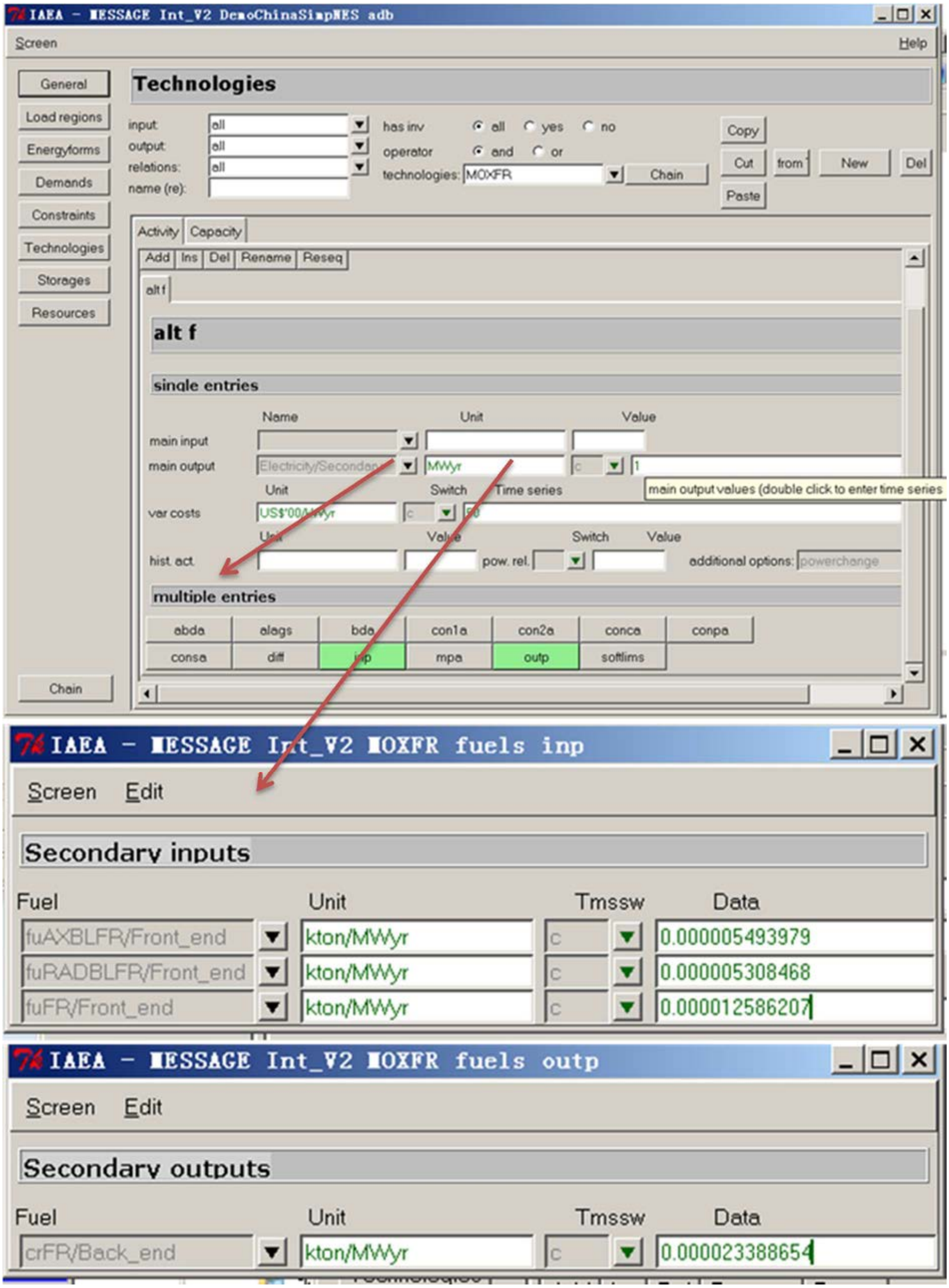


FIG. 30. Editing interface of 'Activity' of MOX FR.

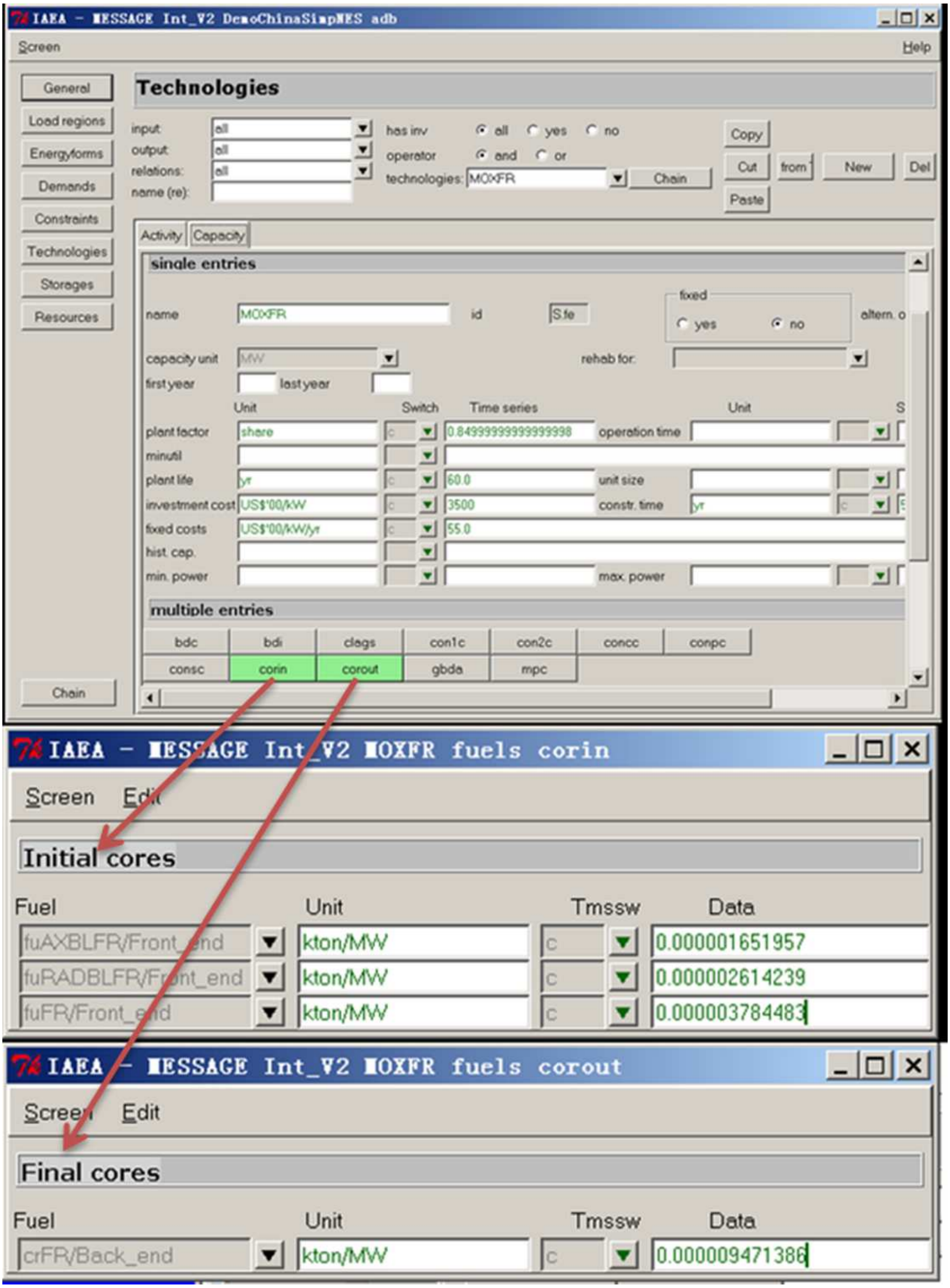


FIG. 31. Editing interface of 'Capacity' of MOX FR.

The technology ReFR is selected as another example illustrated by Fig. 32. The description of its parameters has some particular features.

The 'Storage' in the energy levels and forms chart is edited as shown in the Fig. 33.

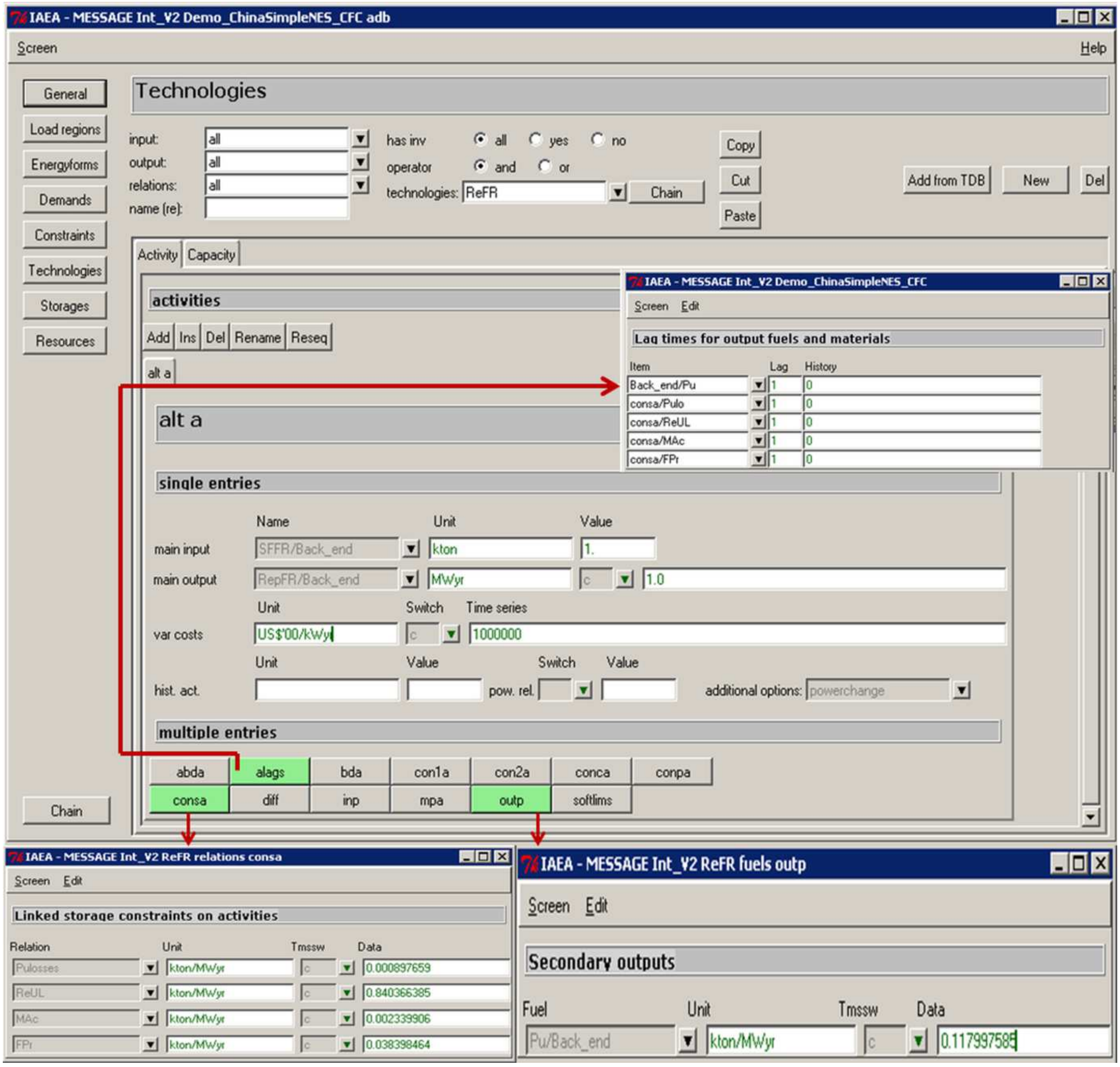


FIG. 32. Editing interface of ReFR 'Technology'.

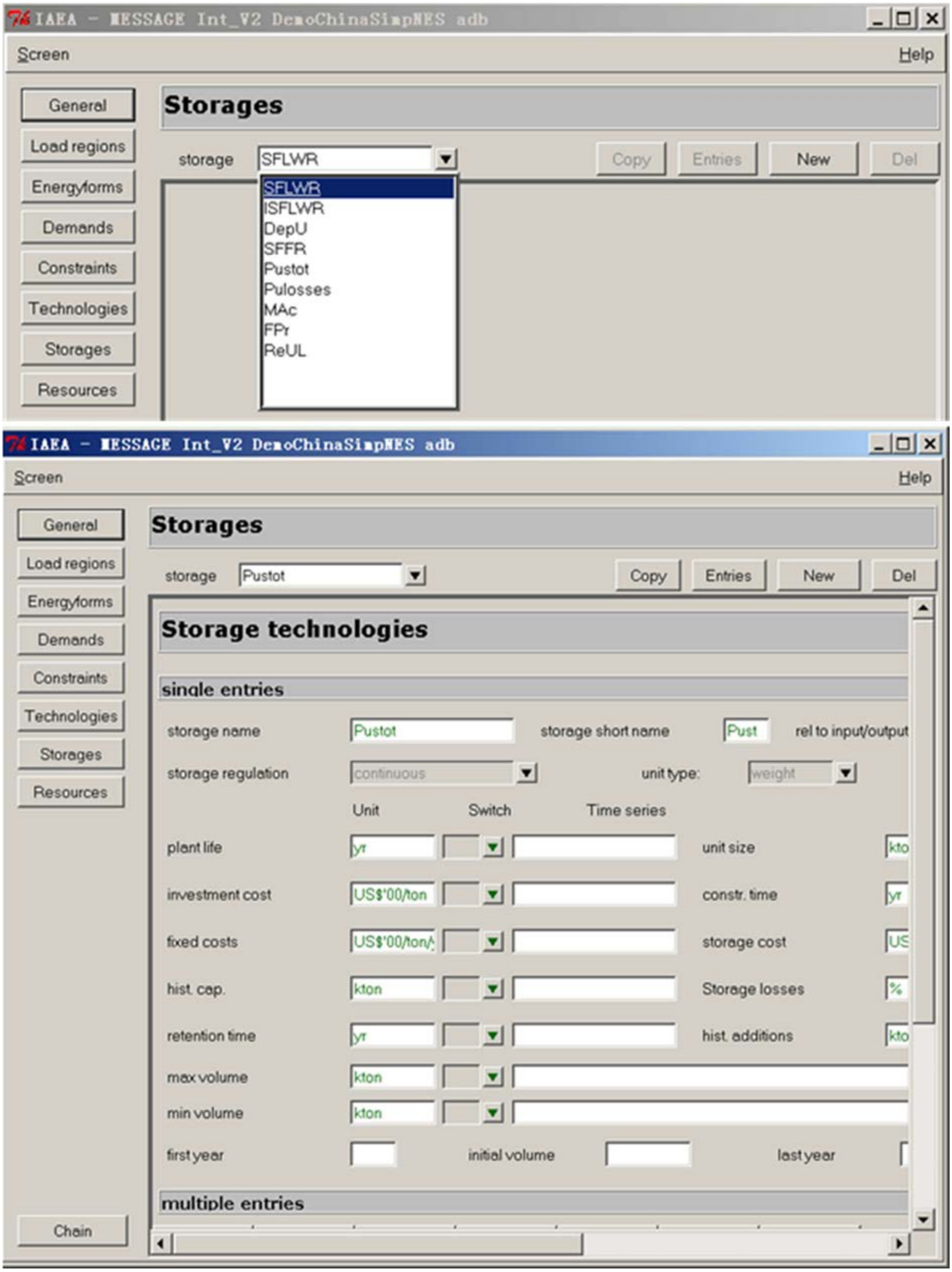


FIG. 33. Editing interface of 'Storages'.

Of particular note is that special attention has to be paid to the parameters' unit conversion in the MESSAGE technical model editing. There are some data entries that may require conversion between MWyr and MW accordingly.

By editing all the technical data and boundary conditions one by one, the analyses can be optimized for calculation.

2.2.5. Scope of the results and findings of the case study

The results of the calculation and analysis of the case study are discussed below.

Figure 34 shows the contribution of the two reactor technologies to the power output. By the end of this century, the major part of the fission nuclear energy supply could be from fast reactor technology after the depletion of natural uranium resources.

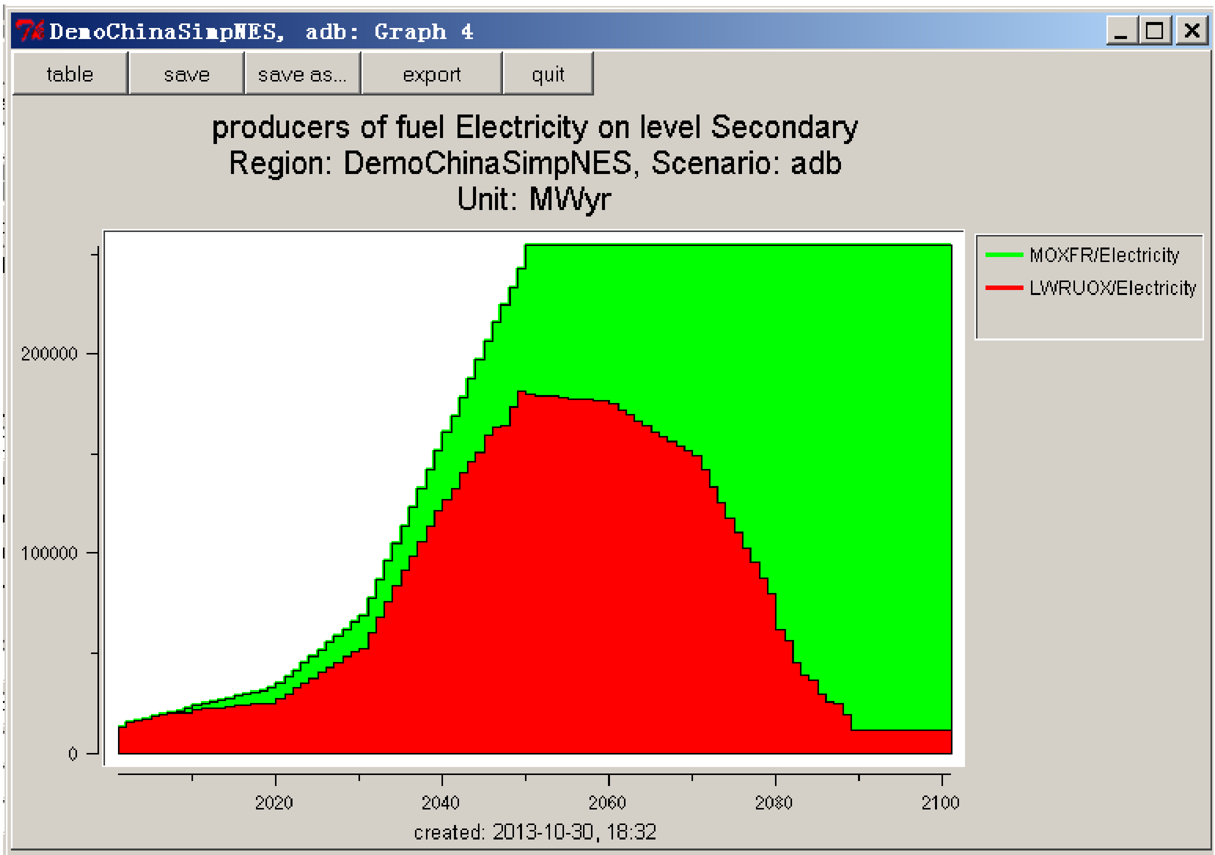


FIG. 34. Electricity product balance.

Figure 35 shows annual consumption of natural uranium resources. This corresponds to the scale of PWR development. The spikes in the graph are due to the reactor first loading.

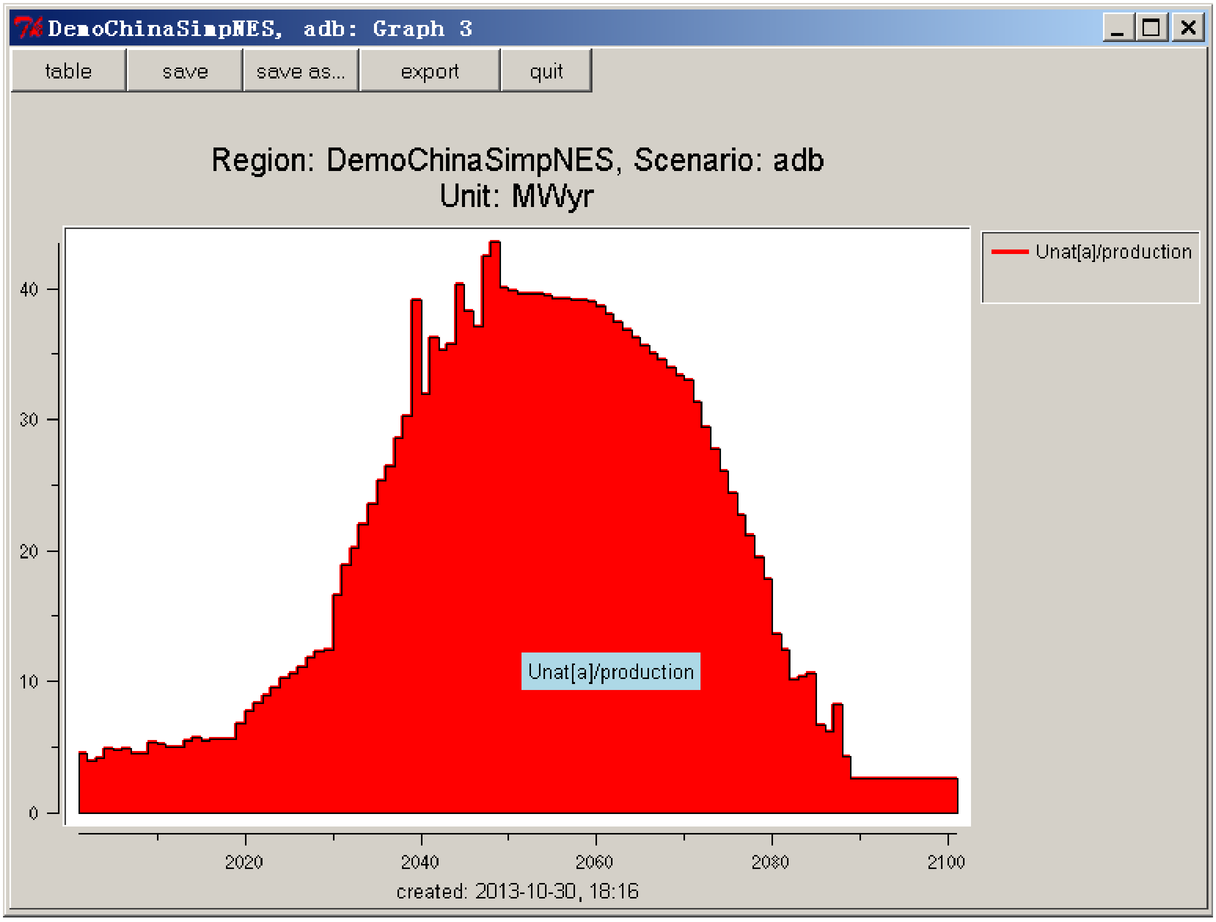


FIG. 35. Natural uranium consumption.

The amount of spent fuel produced by the two types of reactor is shown in Fig. 36. The spikes in the graph are explained by the boundary effect in code calculation and should be ignored. It can be seen that the spent fuel accumulation is more pronounced for PWR per unit of installed capacity.

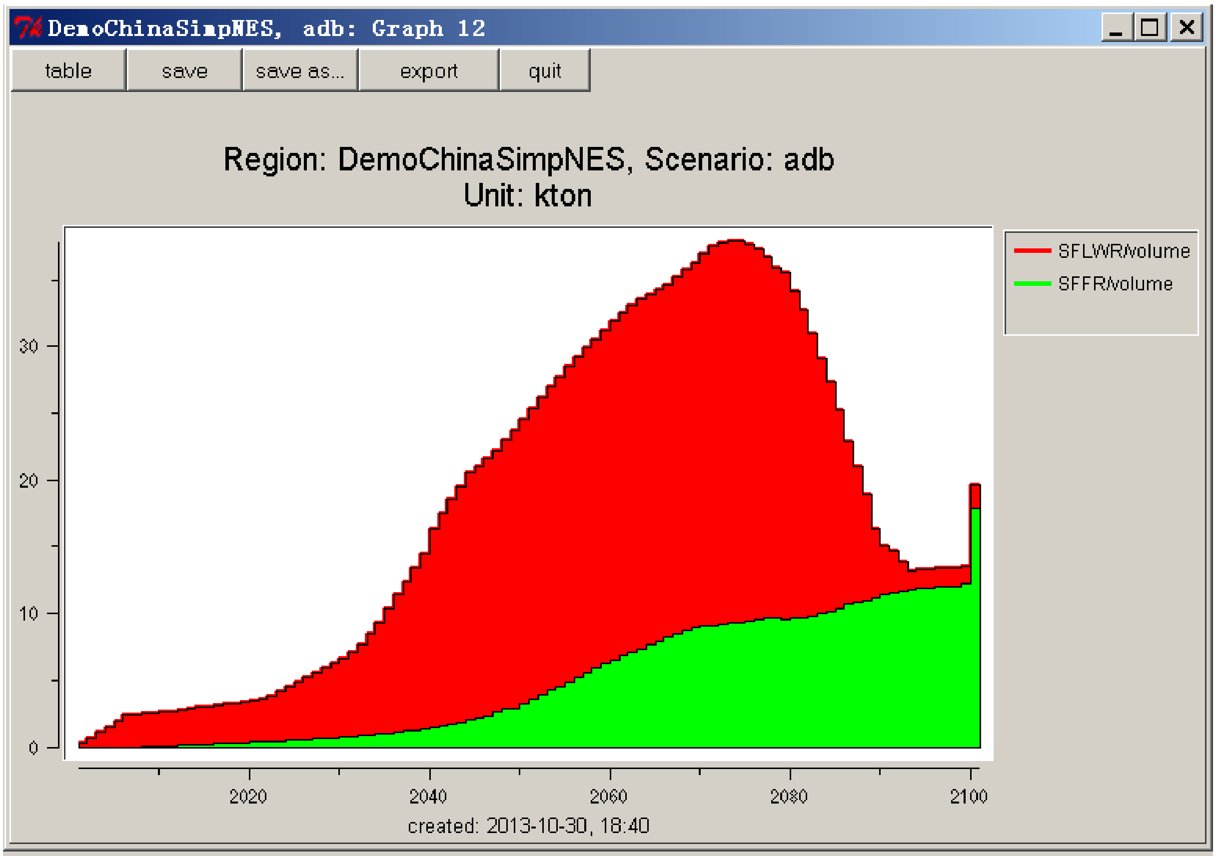


FIG. 36. Spent fuel accumulation of LWR & FR.

Figure 37 shows the storage requirements for fission products and minor actinides of the considered NES. Plutonium is not accumulated in the stocks because it is used in the fast reactors in this case. The stocks of fission products and minor actinides show the amount of high level radioactive waste that needs to be disposed of. These results are similar to those obtained from the simulation exercise using the DESEA code [11].

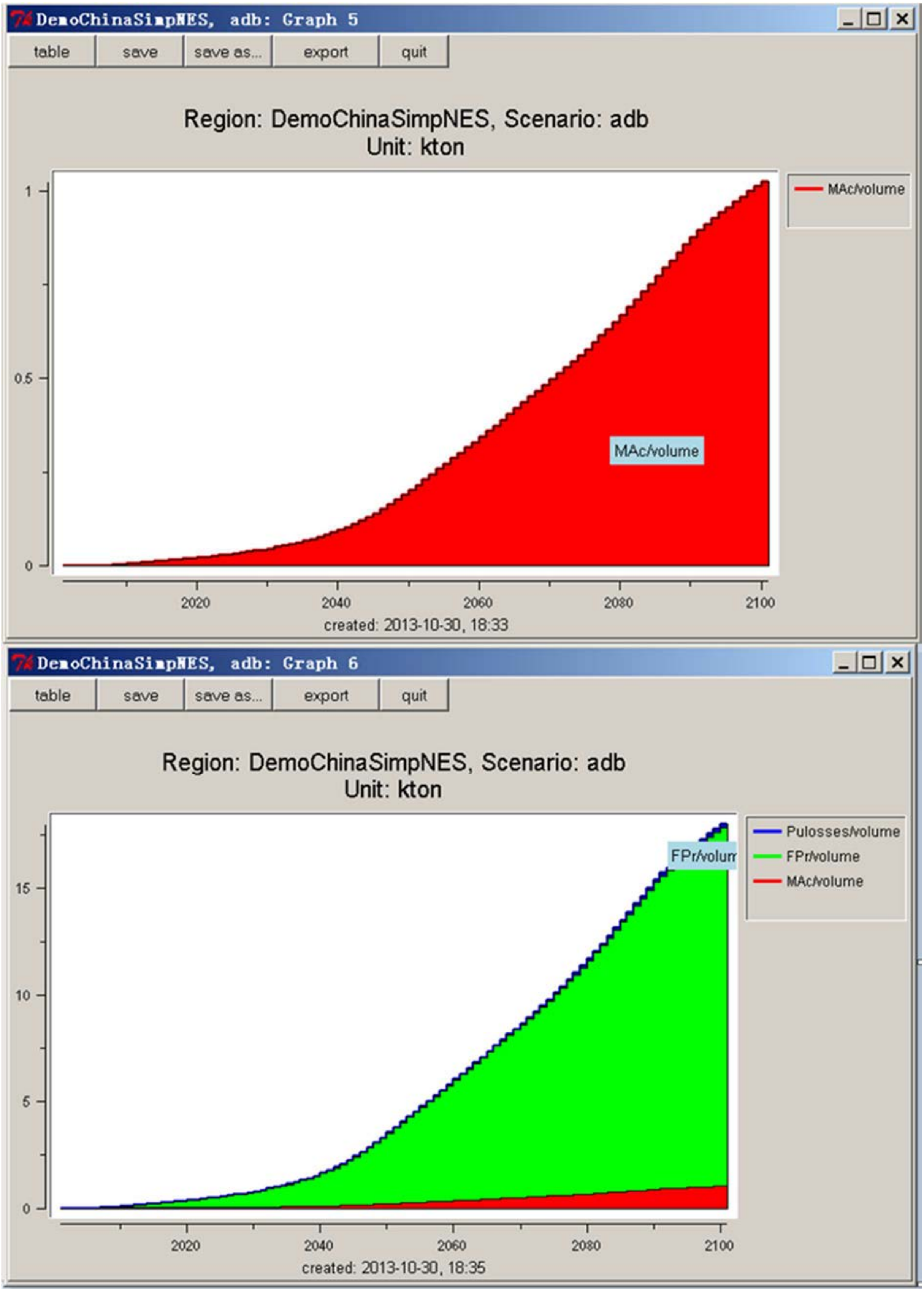


FIG. 37. Minor actinide/fission produce/(Pu_loss) storages.

The impact of changes in the cost of natural uranium on the nuclear energy mix and reactor development plans is shown in Figs 38 and 39. It can be seen that the cost of uranium resources has great impact on the development of fast reactors. The reduction in natural uranium costs suppresses the development of fast reactors and pushes their deployment further into the future.

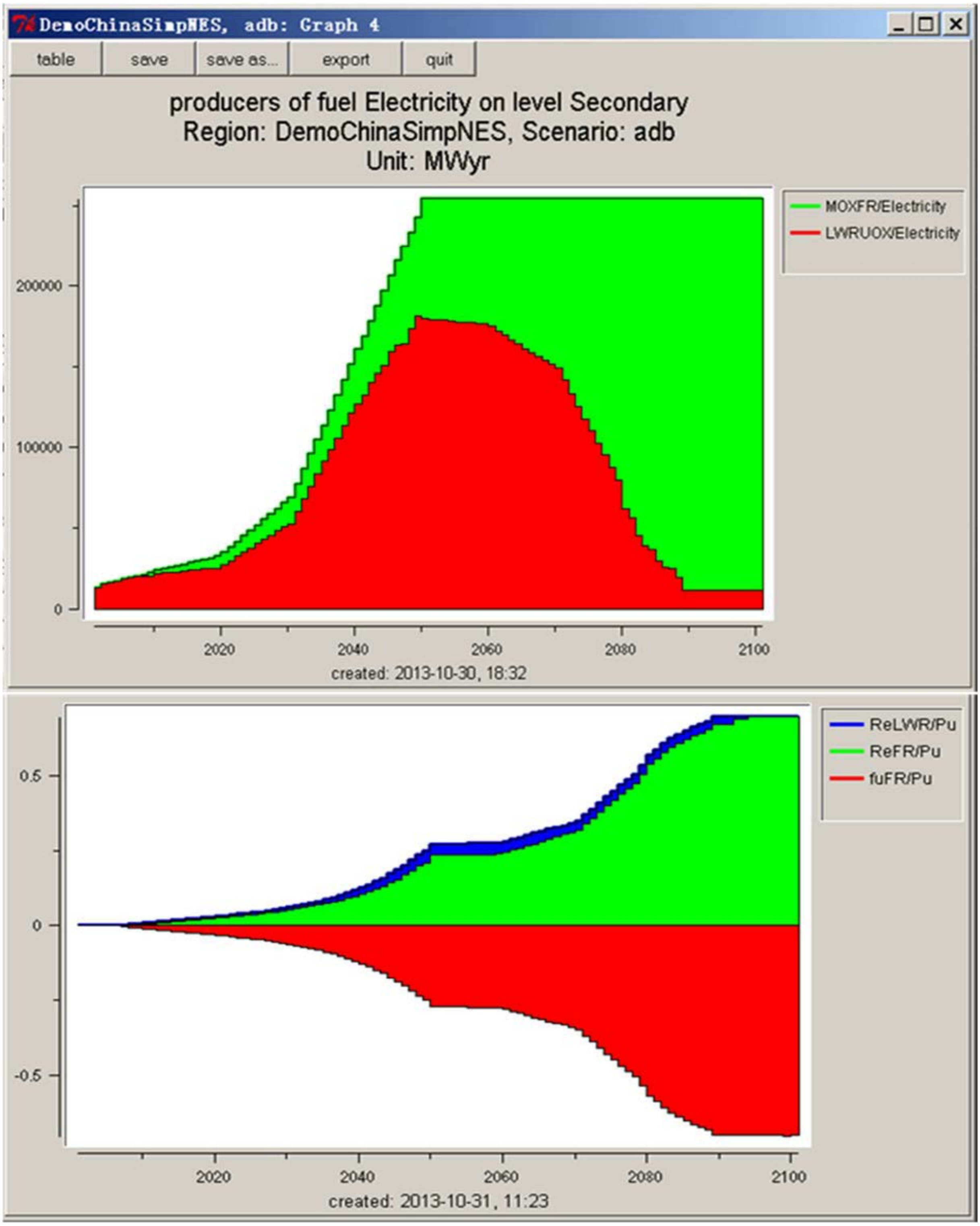


FIG. 38. Electricity production (top) and plutonium balance (bottom) in the high cost uranium case (NatU Cost US $400/kg).

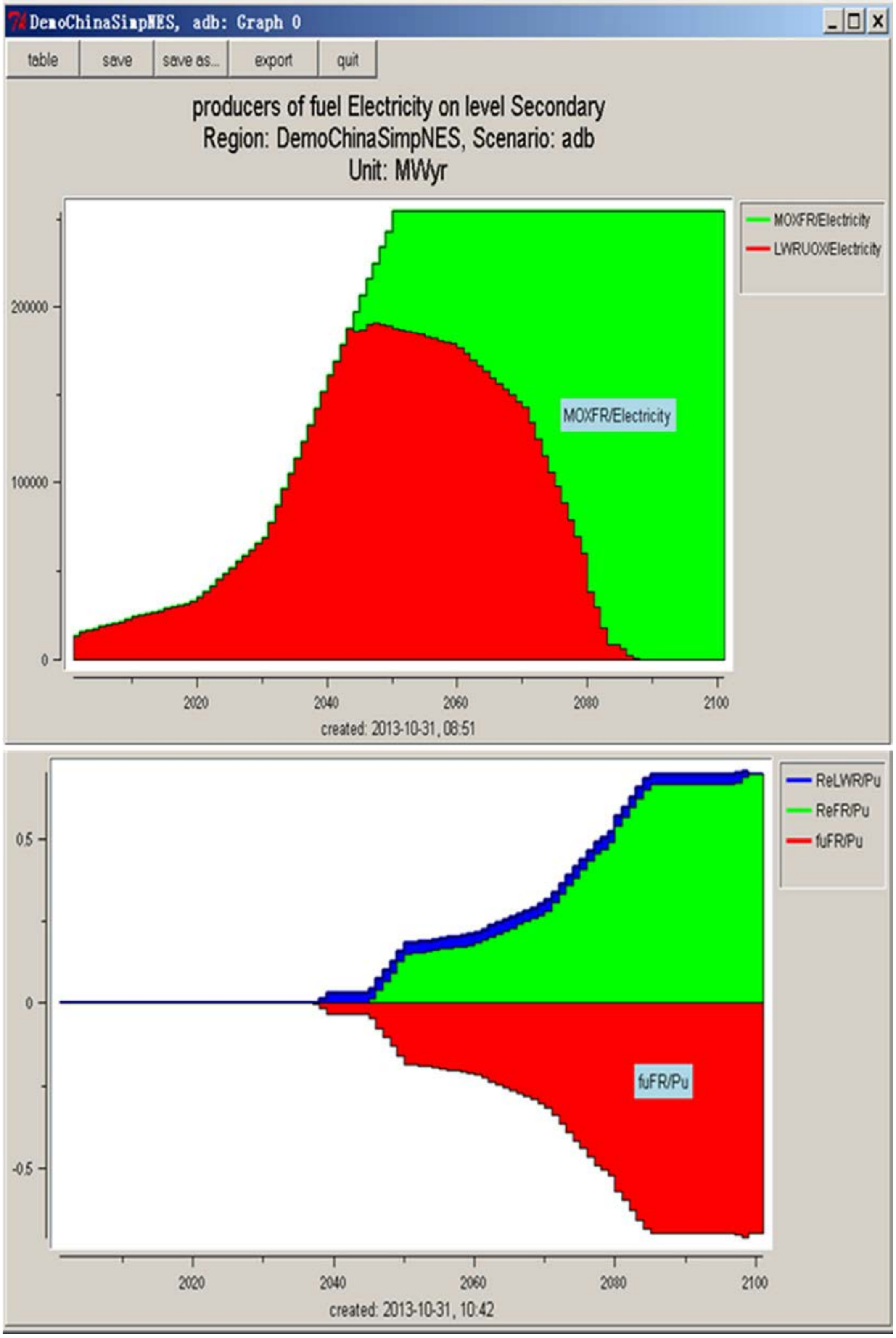


FIG. 39. Electricity production (top) and plutonium balance (bottom) in the low cost uranium case (NatU Cost US $40/kg).

In future studies, the sensitivity of the economic parameters in the nuclear fuel cycle important to the development of nuclear energy will be carefully investigated.

2.2.6. Feedback from the case study on NES modelling with the MESSAGE tool

The MESSAGE code has the advantages of simple operation and a ‘friendly’ interface. For a closed nuclear fuel cycle, it reflects the important logistics and economy of each step, and the optimization goal is simple and clear. It is very important to make a technical decision after gaining a thorough understanding following detailed study while using the MESSAGE tool.

When MESSAGE is used in nuclear energy systems, in addition to technical processes, the analyses are particularly dependent on the data used for technical and economic parameters which are deficient in many cases. In order to ensure the effectiveness of nuclear energy applications of MESSAGE, it is important to collect reliable technical and economic data related to all the nuclear fuel cycle steps included in the system. These data should be updated periodically.

In addition, the role of nuclear energy is increasingly dependent on the economic environment of energy markets and the competitiveness of the alternative energy technologies. As such, the entire energy/electricity market should be modelled and the role of nuclear energy in the entire system setting should be assessed. However, using MESSAGE for the entire electricity market in China would be very challenging owing to the size and complexity of the market.

MESSAGE needs some adaptations for nuclear energy professionals. It is useful to consider details of MESSAGE application for the analysis and calculation of the ‘bulk management’ mass balance model of nuclear material in the high temperature gas cooled reactor and for the mass flow and economic calculations of the innovative concept of long refuelling cycle fast reactor (travelling wave reactor) with ‘once–through’ fuel cycle strategy. Moreover, it is expected that a Chinese language version could be developed.

2.3. ROMANIAN EXPERIENCE IN NUCLEAR ENERGY SYSTEM MODELLING WITH MESSAGE

2.3.1. Introduction

Romania has actively participated in the INPRO activities in support of the sustainability of nuclear energy since 2007. This section presents the case study on assessment of national nuclear energy development using the IAEA MESSAGE tool. It is based on the previous experience gained in modelling the possible scenarios for nuclear energy transitions developed in the INPRO SYNERGIES project by participating experts from Technologies for Nuclear Energy State Owned Company, Institute for Nuclear Research Pitesti, (RATEN ICN Pitesti) [4].

The current case study analyzes sustainable development of nuclear capacity and its growth in the national energy mix by overcoming short and medium term challenges to sustainability using existing infrastructure, near term projected technologies and collaboration in the nuclear fuel cycle based on a ‘win–win approach. The case study also encompasses economic evaluation for comparing nuclear energy with other competing technologies from the national energy mix.

The national vision for nuclear energy (including nuclear power) in Romania is linked to the European Union (EU) Energy Policy, global climate actions, national and regional legislation, treaties and regulatory provisions [12]. The Romanian Energy Policy [13] for the period 2015–2035 is, in effect, strategically directed towards energy security, sustainability and economic competitiveness in line with the EU Energy Policy. The policy states that “Romania must have a diverse, balanced energy mix together with the efficient utilization of the national primary energy sources and modern technologies allowing long term utilization of fossil fuels with low greenhouse gas emissions, renewable energy sources and nuclear energy” [14].

The Romanian energy mix comprises a balanced portfolio of electricity generation from hydro, nuclear, coal and gas powered plants. Renewable energy is currently a small but rapidly growing electricity generation sector in the country. Nuclear power corresponds to 20% of national electricity capacity, generated by Cernavoda nuclear power plant, which has two CANDU-6 (PHWR) reactors in operation.

The country’s electricity generation sector is facing significant challenges due to ageing of installed capacities beyond their useful technical age. This will necessitate replacement of ~28% (5.5 GW(e)) of the total installed capacity by 2020 and ~55% (11 GW(e)) by 2035 [14].

2.3.2. Objectives and problem formulation

The study focused on the modelling of national NES development in the short and medium terms by use of the IAEA MESSAGE tool and the recently updated guide for MESSAGE utilization for nuclear energy system modelling [2].

The objective of this study was to model national NES development and growth for a sustainable national energy mix using the MESSAGE tool for short and medium term durations, with due reference to different scenarios of nuclear reactor and fuel cycle conditions. Three scenarios were defined and selected for analysis as options for nuclear energy development and for increasing its contribution in a sustainable national energy mix [4]:

(i) *Reference scenario*: Four PHWR CANDU reactors, of which two have already been operating with high performance indicators since 1996 and 2007, the other two reactors with projected operation after 2020;

(ii) *Pessimistic scenario*: Only already operating CANDU reactors with no further addition of nuclear power;

(iii) *Optimistic scenario*: Reference scenario assumptions with the addition of another advanced PWR or HWR with projected operation after 2035.

The existing NFC infrastructure and provisions of strategic documents in force have been considered, including also the possibility of collaboration related to UO_2 powder/fresh fuel supply and spent fuel storage, in order to consolidate the nuclear energy role and increase its share in the energy sector, with a view to achieving the long term national and regional energy sustainability. The following key questions and issues have been addressed by the case study:

(a) What is the potential for nuclear energy to contribute an important share to the national energy mix, according to the strategic documents in force and regarding cost competitiveness, safety and security of supply, according to existing strategic documents and to projected national electricity demand?

(b) What is the impact of considered NES development scenarios on the national energy mix portfolio of capacities and electricity production?

(c) What is the impact of considered NES development scenarios and supply assumptions on the domestic resources of uranium?

(d) What is the economic projection of considered NES development scenarios in terms of investment costs of new nuclear capacities?

(e) What are the implications of considered NES development scenarios and spent fuel storage assumptions in terms of interim spent fuel (wet and dry) storage?

(f) Is the nuclear energy generation cost competitive when compared with other technologies included in the national energy mix?

(g) What is the impact of various discount rates on the interest parameters?

2.3.3. Model description and input data

Romania's national energy mix was modelled taking into account available data and public information on the technologies participating in national electricity generation (resources, capacities, activities, economic parameters (costs, efficiency, load factors, etc.)), according to the existing legal framework. To compensate for the lack of data, internationally agreed data from studies in the domain have been used.

Romania's energy sector was modelled taking into account existing electricity generating capacities as of 2011, with the time horizon for the performed analysis being 2050. The national energy mix kept its balance characteristics, including the corresponding specific producers of electricity, namely: 'conventional' power plants based on fossil fuels (coal fired plants, gas fired plants and combined cycle plants producing electricity and heat), nuclear power plants and renewable energy plants (including hydropower plants, wind farms and solar photovoltaic stations).

For electricity demand evolution, two scenarios from the Romanian Energy Strategy 2011–2035 have been considered ('Pes1' and 'Pes2'). These scenarios were based on the gross domestic product (GDP) evolution outlooks realized by the National Institute for Economic Studies (2010–2014) and National Commission for Prognoses (2010–2020–2030) and assume a decrease of electricity demand as follows: (a) Pes1: projected annual growth rates of 1.3, 1.6, 1.5, 1.3 and 1.0% for the periods 2011–2014, 2015–2020, 2021–2025, 2026–2030 and 2031–2050, respectively, (b) Pes2: projected annual growth rates of 1.3, 1.1 and 1.0% for 2011–2014, 2015–2020 and 2031–2050, respectively. The third scenario ('NESA' scenario) was established during the IAEA's expert mission to Romania (Nuclear Energy System Assessment in Romania using INPRO Methodology' national project (April 2014)) and assumes annual growth rates of 1.1 and 1.5% for 2011–2020 and 2020–2050, respectively.

The conventional power and district heating sector (thermal power plants) and renewable sector (hydro, wind farms and photovoltaic power plants) were considered according to the optimistic assumptions based on existing public available information [13–21].

The domestic resources of lignite are abundant and national mining capabilities cover the modelled period, the extraction price being considered as US $40/kW per year with a constant annual growth rate of 0.5%. A significant part of Romania's natural gas consumption is sourced from imports (unlimited, but depending on international market prices), the domestic reserves being limited. The extraction price for domestic gas is US $60/kW·year with 0.5% annual constant growth rate; the imported gas price is US $242/kW·year with 0.5% annual constant growth rate. Romanian energy mix includes coal-fired power plants, gas-fired power plants, gas-fired power plants with combined cycle for electricity production and also combined heat and power plants fuelled by coal and natural gas, producing both electricity and heat. The district heat production is assured by old infrastructure with low performance and large losses in transport and distribution system, high costs for thermal energy production and distribution, and low efficiency operation regimes.

The electricity generation sector is facing major challenges as about 30% of the installed generation capacities are already past their useful technical life and must be replaced or upgraded. In these conditions, nuclear power represents a stable component of balanced national energy mix taking into consideration security of supply, reliability, economic efficiency and greenhouse gases (GHG) low emissions [13]. In last 15 years, only about 10% of the installed capacities have been upgraded and equipped with modern facilities for pollution reduction. New capacities addition has been modelled (up to 600 MW per year for power plants fuelled by coal and up to 400 MW per year for power plants fuelled by natural gas) to replace the old capacities, resulting in higher efficiency for classic power plants, reducing losses in electricity and heat transport and distribution and decreased GHG emissions.

The hydro energy potential is very high in Romania (40 TW·h/year, out of which 6 TW·h/year are for small hydro power plants under 10 MW capacity on internal rivers) [16, 17]. In Romania, high potentials also exist for wind energy (23 TW·h/year) and solar photovoltaic energy (1.2 TW·h/year) [16, 17]. The bonds on renewables potential are due to technology limitations, economic efficiency and environmental restrictions. After 2011, according to National Energy Regulatory Authority, reduction in GHG emissions has already been registered due to increasing share of renewable electricity generation.

In Romania, the current policy on NFC is an open NFC, the once-through fuel cycle without reprocessing, characteristic of CANDU reactors [22, 23]. In the model, for the considered time horizon (2050), no changes have been assumed either in the NFC option or in national legislation, which would not support the activities for nuclear fuel enrichment and/or spent fuel reprocessing.

As it was previously mentioned, three NES development scenarios have been considered, namely: (i) reference scenario: four PHWR, CANDU type (existing CANDU U1 and U2 reactors, 700 MW(e) each, in operation, and new CANDU U3 and U4 reactors, 720 MW(e) each, with projected in-service after 2020); (ii) pessimistic (low development) scenario: two PHWR, CANDU type (existing CANDU U1 and U2, in operation); (iii) optimistic (high development) scenario: four PHWR, CANDU type (as in reference scenario) plus another advanced PWR (1000 MW(e)) or advanced PHWR (enhanced CANDU, 720 MW(e)), with projected in-service after 2035.

The front-end activities include: mining and milling of uranium ore, uranium technical concentrates processing/refining and nuclear fuel fabrication.

Formerly there was no uranium market in Romania; the National Uranium Company (CNU) being the sole supplier of UO_2 powder, which is used as the raw material for nuclear fuel fabrication. Uranium technical concentrates for CANDU nuclear fuel fabrication are provided by the Feldioara UO_2 powder plant, a subsidiary of CNU qualified by Atomic Energy of Canada Limited (AECL) as a CANDU UO_2 fuel supplier [22, 23].

The situation changed at the end of 2015, when the national company Nuclearelectrica S.A. signed the contract for UO_2 powder supply with a qualified international supplier (CAMECO, Canada). The contract was renewed in 2016, after completing the public acquisition procedure in which CNU also participated [24]. In the study, both options have been considered for UO_2 powder supply.

The nuclear fuel assemblies for CANDU reactor operation are fabricated by Nuclear Fuel Plant Pitesti (qualified by AECL Canada as a CANDU fuel supplier) [20, 21]. In the study, the same path has been used for the projected CANDU 3 and 4 reactors' nuclear fuel. Nuclear Fuel Plant Pitesti is able to upgrade the fabrication lines in order to increase the annual production from 10 800 bundles/year (actual production of fuel assemblies) to 20 000 fuel bundles/year (ensuring sufficient fuel for all four CANDU reactors), the estimated investment costs being €1–2 million for each 5000 bundles' production upgrade. As for the projected advanced PWR or HWR reactors to be built in Romania after 2035, the nuclear fuel supply is ensured by imports of pre-fabricated fuel assemblies, purchased at international market prices.

The spent fuel discharged from the reactors is cooled down first in the nuclear power plant's spent fuel bay (5 years for advanced PWR and 6 years for HWRs). Intermediate wet cooling continues with intermediate dry storage (50 years for CANDU reactors and advanced HWRs), with the appropriate facilities being built on the nuclear power plant site. As regards the advanced PWR, the spent fuel will be stored in a regional storage facility and will incur the associated costs.

Both technical and economic input data for the reactors and nuclear fuels considered in the study are presented in Table 22, according to Ref. [13].

TABLE 22. TECHNICAL AND ECONOMICAL PARAMETERS OF THE REACTORS CONSIDERED IN THE STUDY

Parameter	**Unit**	**CANDU U1 and U2**	**CANDU U3 and U4**	**Advanced PWR**	**Advanced HWR**
Nuclear capacity	GW	0.700	0.720	1.000	0.720
Load/plant factor	%	95	95	90	90
Availability	%	100	100	100	100
Efficiency	%	33	33	33	33
Discharge burn-up	GW·d/t HM	7.5	7.5	45	15
Operation cycle length[a]	d	346.75	346.75	328.5	328.5
Fuel residence time[b]	d	346.75	346.75	1314	328.5
First load[c]	t HM	98.071	100.873	88.485	47.782
Annual reload[d]	t HM	98.071	100.873	22.121	47.782
SNF discharged[e]	t HM + t FP	98.071	100.873	22.121	47.782
Construction time	year	-	5	6	6
Life time	year	40	40	60	60
Investment costs	US $/kW(e)	500	5820	3400	3000
O&M fixed costs	US $/kW(e)·year	8	8	10	10
O&M variable costs	US $/kW(e)·year	55	55	50	55
Fresh fuel costs[f]	US $/kg U	200	200	520	190
Investment costs for SNF interim dry storage at reactor	US $/kg HM	250	250	-	250
O&M fixed costs for SNF interim dry storage at reactor	US $/kg HM·year	4.2	4.2	-	4.2
SNF dry storage service cost	US $/kg HM	-	-	300	-

[a] 365 d × 95% = 346.75 d; 365 d × 90% = 328.5 d

[b] 346.75 d × 1 refuel batch = 346.75 d; 328.5 d × 4 refuel batches = 1314 d; 328.5 d × 1 refuel batch = 328.5 d

[c] $FF = \frac{365 * NC * Lf}{Eff * Bu}$; where FF: fresh fuel (t HM), NC: nuclear capacity (GW), Lf: load/plant factor (%), Eff: efficiency (%), Bu: Discharge burnup (GW·d/t HM).

365 d × 0.700 GW × 95%/33%/7.5 GW·d/t HM = 98.071 t HM (as example of calculation for CANDU reactors)

First fuel loading is given by the relation: $FuelInCore = \frac{FF * Tr}{365 * Lf}$, where Tr: residence time (d)

98.071 t HM × 346.75 d/365 d/95% = 98.071 t HM (as example of calculation for CANDU reactors)

[d] 365 d × 98.071 t HM × 95%/346.75 d = 98.071 t HM (as example of calculation for CANDU reactors)

[e] SNF discharged= Fresh fuel; 365 d × 1.0 GW × 90%/33%/45 GW·d/t HM = 22.121 t HM + t FP (as example of calculation for advPWR)

[f] Costs include all front end NFC steps.

For each electricity demand evolution scenario, various discount rate values (drate = 5%, 8% and 10%, respectively) were considered. The interest parameters and their evolution during the considered time horizon for the case study were as follows:

- Annual total electricity generation growth, in (GW(e)/year)
- Annual nuclear electricity generation growth, in (GW(e)/year)
- Nuclear new installed capacities, in (GW(e))
- Investments in new nuclear power plants, in (10^9 US$)
- Cumulative uranium consumption, in (kt U)
- Annual UO_2 requirements, in (kt U/year)
- Annual fuel requirements, in (kt HM/year)
- Annual discharged spent fuel (spent fuel in interim wet storages), in (kt HM/year)
- Spent fuel in interim dry storages (kt HM/year)

The case study performed by the Romanian team under IAEA SYNERGIES CP framework included an economic analysis focused on specific economic parameter calculations, such as: levelized unit energy cost (LUEC), internal rate of return (IRR), return on investment (ROI), net present value (NPV) and total investment costs [4].

The main objective of the economic analysis was to assess nuclear energy cost competitiveness compared with other competing technologies for electricity energy generation in Romania, namely, conventional technology represented by coal and gas fired power plants.

The proposed economic analysis has been performed using the IAEA's NEST (NESA economic support tool), available on the IAEA web site, IAEA/INPRO section [25]. Five types of power plant competing in Romania's national energy system for electricity generation were considered, including nuclear technology and conventional fossil fuel technology (coal and natural gas), and using advanced technologies for CO_2 capture.

Sensitivity analyses have been performed, highlighting the effect of various perturbations on LUEC (e.g. discount rate, fixed O&M costs, overnight costs). To confirm the validity of the economic analysis, robustness indices of LUEC were calculated by considering simultaneous variations of several input parameters for the nuclear and alternative source (coal and gas) power plant.

2.3.4. Modelling of selected NES elements with MESSAGE

Figure 40 presents modelling of Romanian energy mix in MESSAGE, based on energy levels and energy forms and highlighting the competing technologies considered for energy generation.

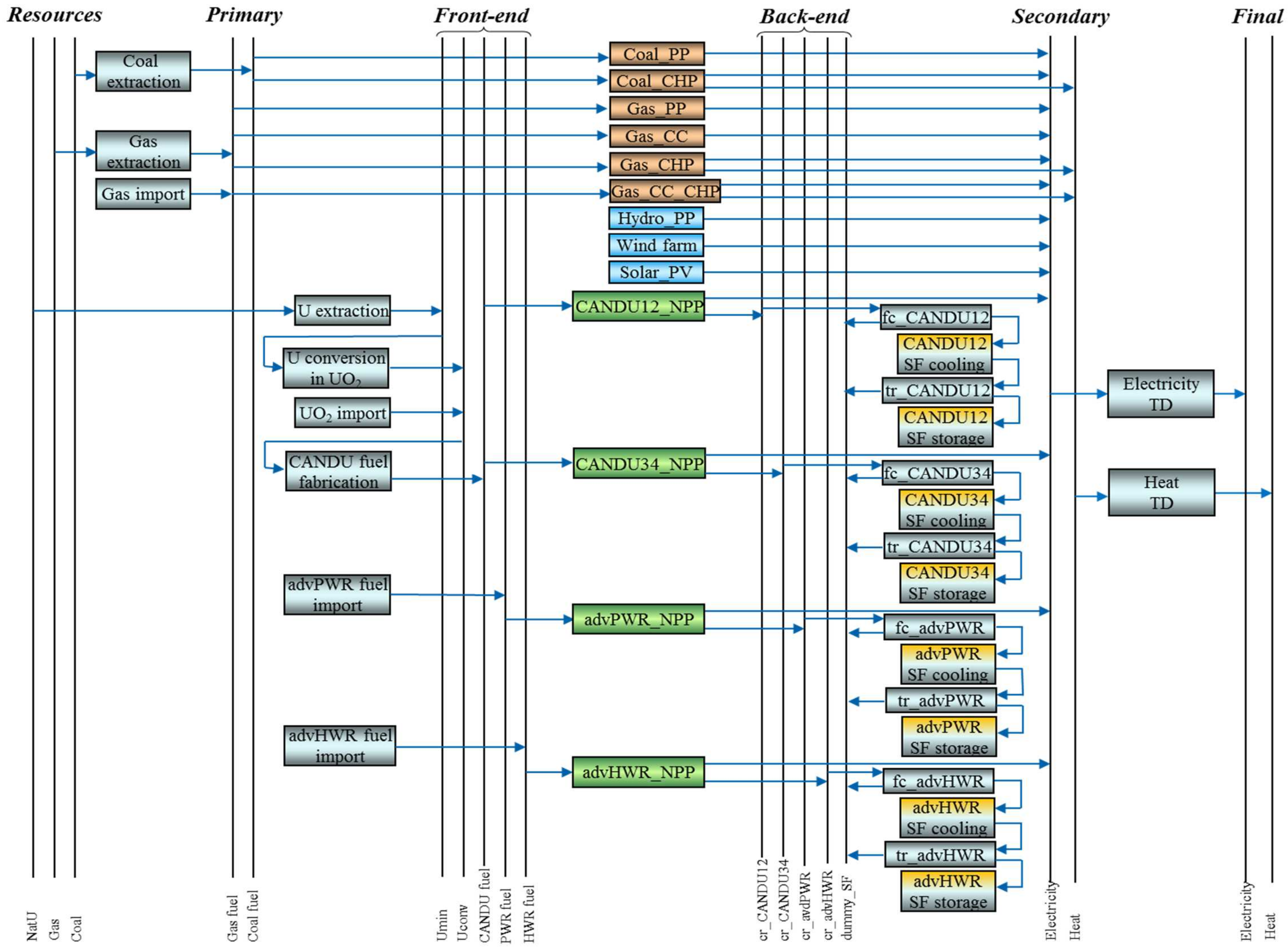
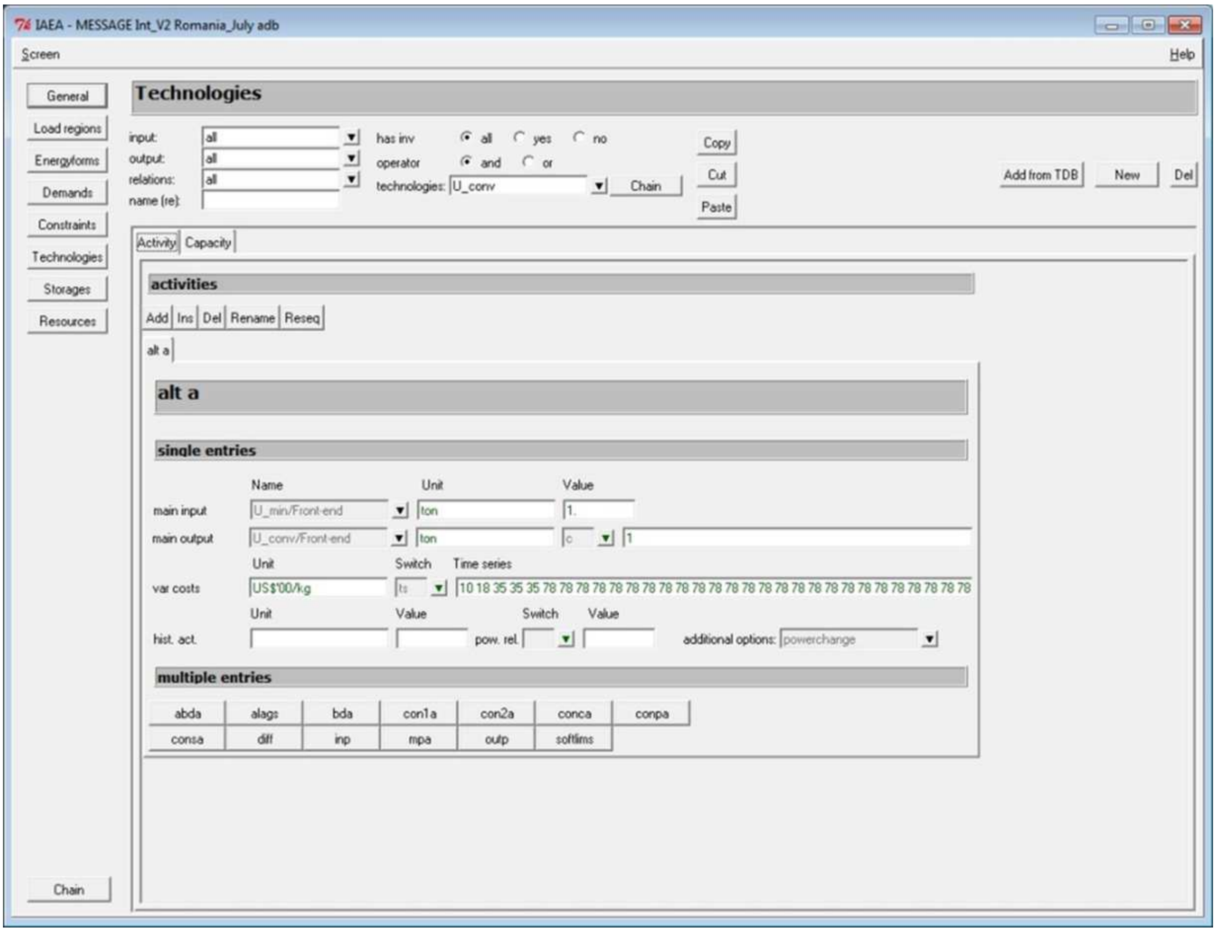


FIG. 40. Case study: energy system modelling in MESSAGE.

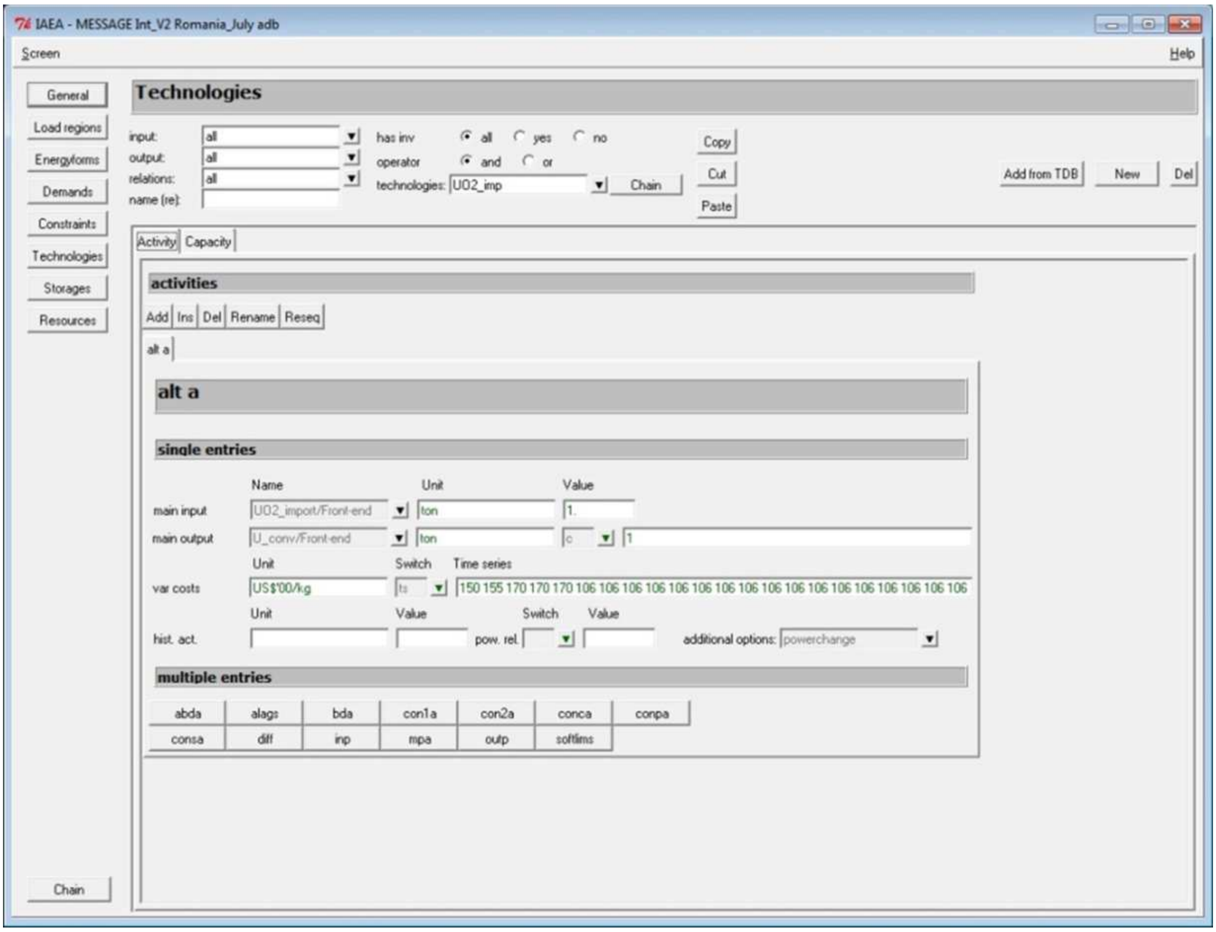
The domestic uranium resources considered in the current study were according to the Ref. [8] as follows: US $130/kg U for 6700 t U of identified resources (RAR+IR); US $260/kg U for 12 700 t U of identified and undiscovered (PR+SR) resources.

Detailed information regarding uranium conversion and fuel fabrication is not publicly available and, therefore, these fuel cycle steps, even those involving domestic facilities, were considered in the model as services that can be bought at a specific cost. However, public reports from Nuclearelectrica S.A. and Cernavoda NPP have been used for estimation of costs.

Both obtaining UO_2 powder from domestic resources in UO_2 Powder Plant Feldioara, and the option of importing it were considered in the model, to follow the latest changes in UO_2 powder supply status. The price was introduced in the corresponding MESSAGE page (see Figs 41(a) and (b)) using the option time series (ts), to take into account the changes registered in the last period and the information available on the Nuclearelectrica S.A. web site, as related to the UO_2 costs' evolution [24, 26]. Both UO_2 powder obtained from domestic uranium and the imported UO_2 powder are representing the U_conv energy form used for CANDU fuel fabrication.



(a)



(b)

FIG. 41. MESSAGE pages for modelling domestic uranium conversion in UO_2 powder (a) and UO_2 powder import (b).

The nuclear fuel for existing CANDU reactors is fabricated by the Nuclear Fuel Plant Pitesti with a production capacity of 110 t U/year [20]. The technology for CANDU fuel fabrication was modelled as a service at the cost of US $100/kg U (see Fig. 42). The same path was used for the fuel corresponding to CANDU 3&4 units operation. Regarding the proposed advanced PWR (advPWR) or advanced HWR (advHWR) reactors to be built after 2035, the fuel (UOX fuel) is assured by imports of already fabricated fuel assemblies. In the model, fuel import for advPWR or advHWR was modelled as a service at costs in line with the international studies and databases [27–29], namely: US $520/kg HM (advPWR, see Fig. 43) and US $190/kg HM (advHWR).

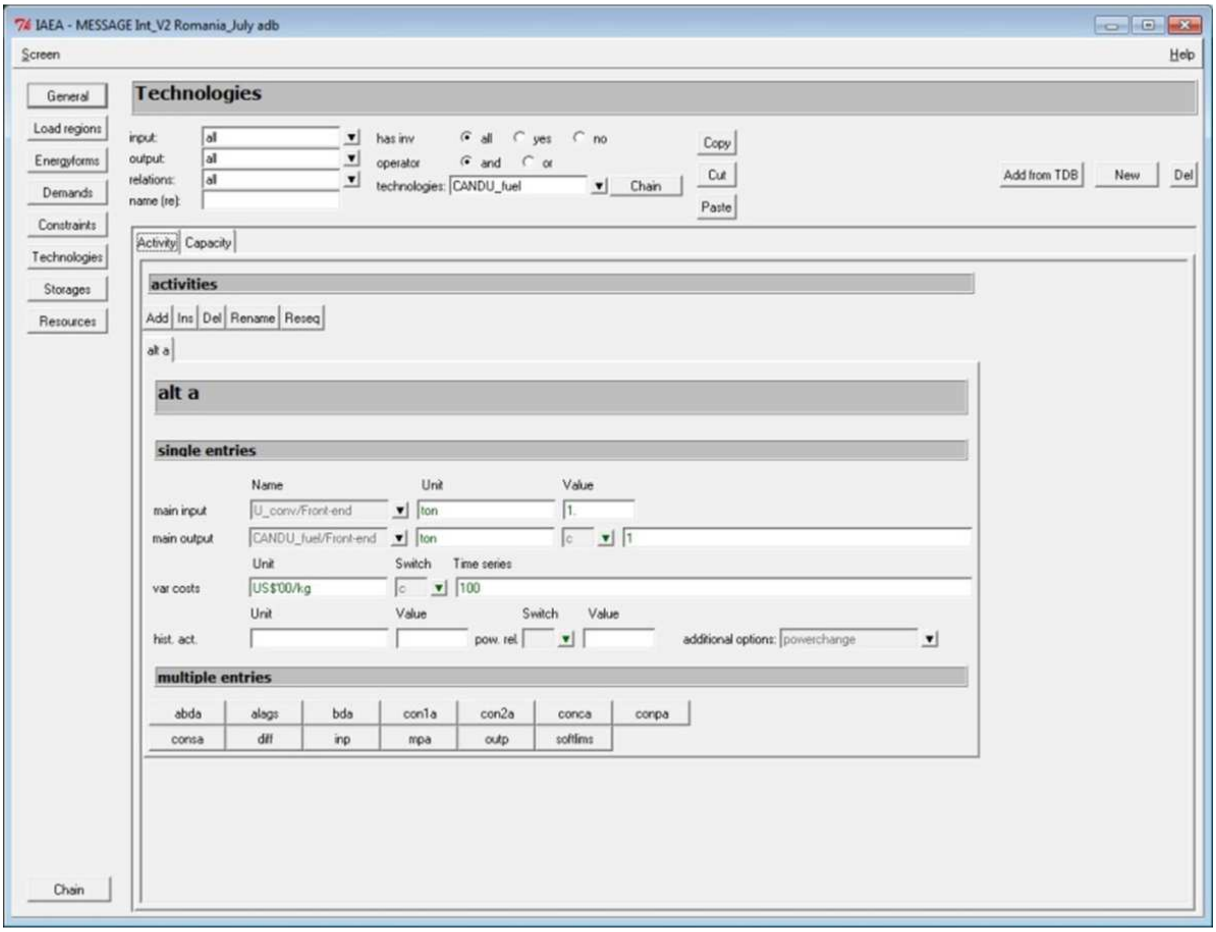


FIG. 42. MESSAGE page for modelling CANDU fuel fabrication.

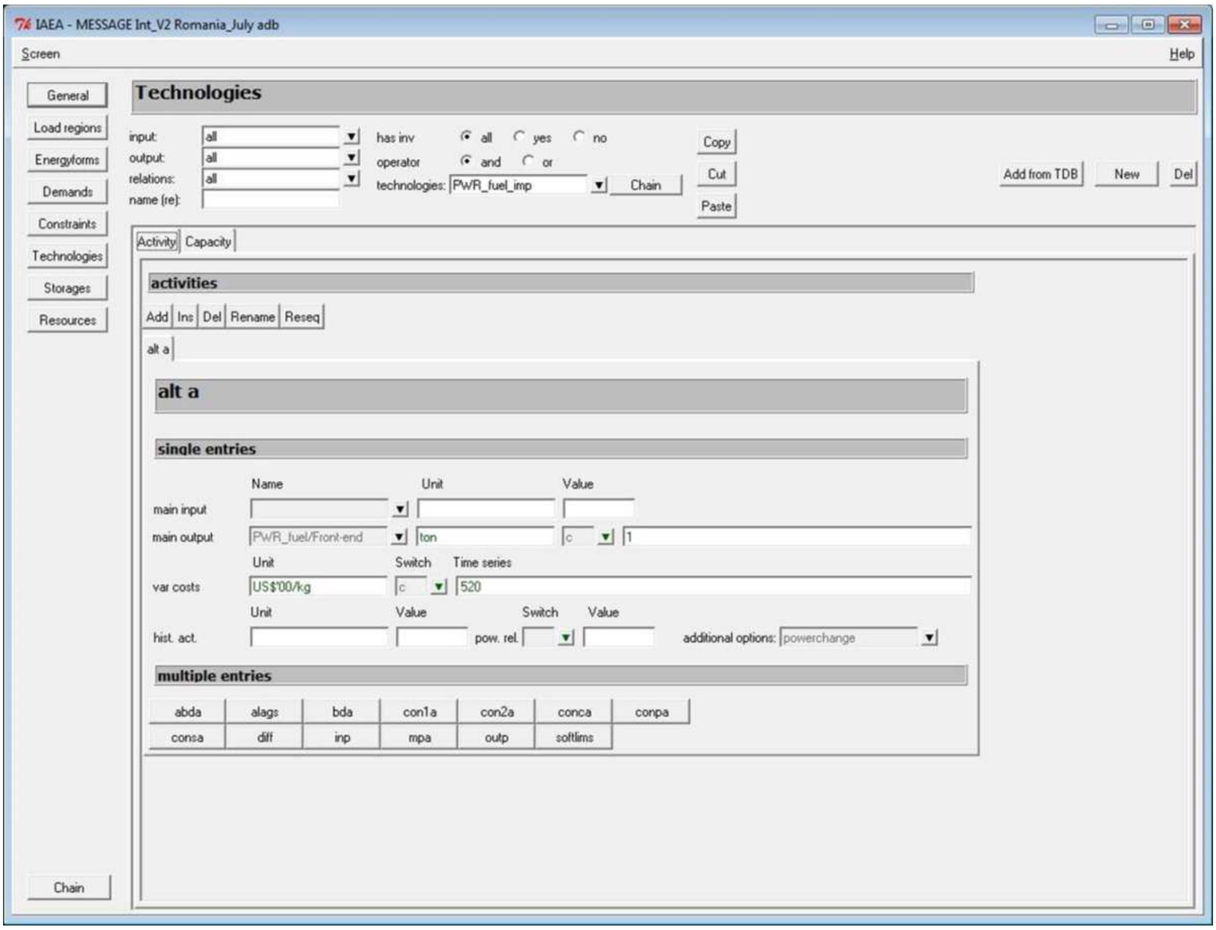


FIG. 43. MESSAGE page for modelling advPWR fuel import.

In order to model the PHWR CANDU nuclear power plants, two technologies have been defined, namely: CANDU12 (for the operating CANDU U1 & U2 reactors) and CANDU34 (for CANDU U3 & U4 reactors, to be built). All technology input data were given using the activity and capacity pages (see Figs 44 and 45 for CANDU12, and Figs 46 and 47 for CANDU34, respectively). The differences between these two technologies comprise the existence of historical capacities (CANDU12), the investment costs (much higher for CANDU34, taking into account multiple delays to reactor construction arising from financing issues), and the bounds on new additional capacities (CANDU12 is equal to 0 and CANDU34 is two units of 720 MW(e) each).

CANDU12 reactors produce 700 × 0.95 = 665 MW(e)·year electricity, consuming 98.071 t HM of fresh fuel. To generate 1 unit of electricity, 0.147 t HM (=98.07/665) of fresh fuel is needed and the same amount is annually discharged from the reactor to the cooling pond. CANDU34 reactors will produce 720 × 0.95 = 684 MW(e)·year electricity, consuming 100.873 t HM of fresh fuel. For each unit of electricity, 0.147 t HM (=100.873/684) of fresh fuel is needed, the same amount being annually discharged from CANDU34 reactors to the cooling pond.

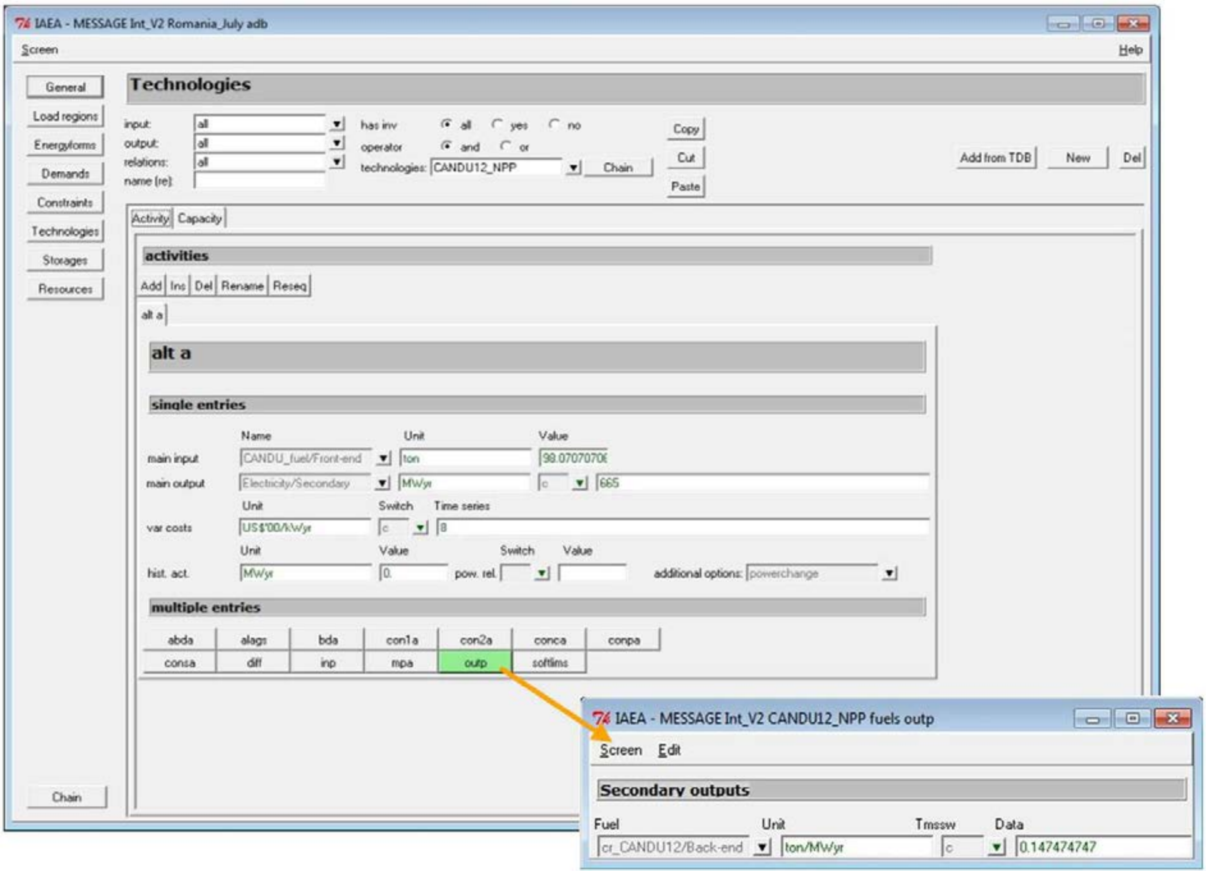


FIG. 44. Modelling of the CANDU12 activity page in MESSAGE.

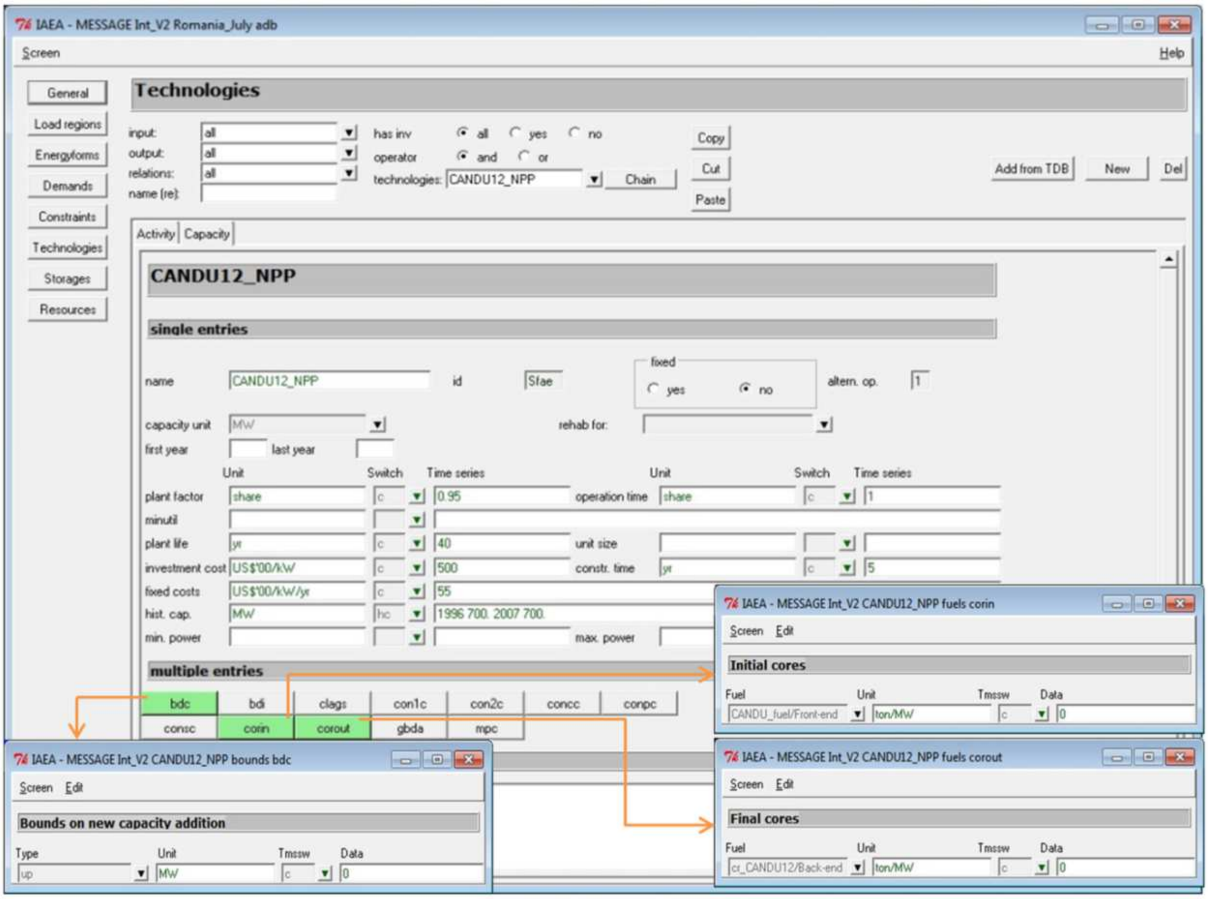


FIG. 45. Modelling of the CANDU12 capacity page in MESSAGE.

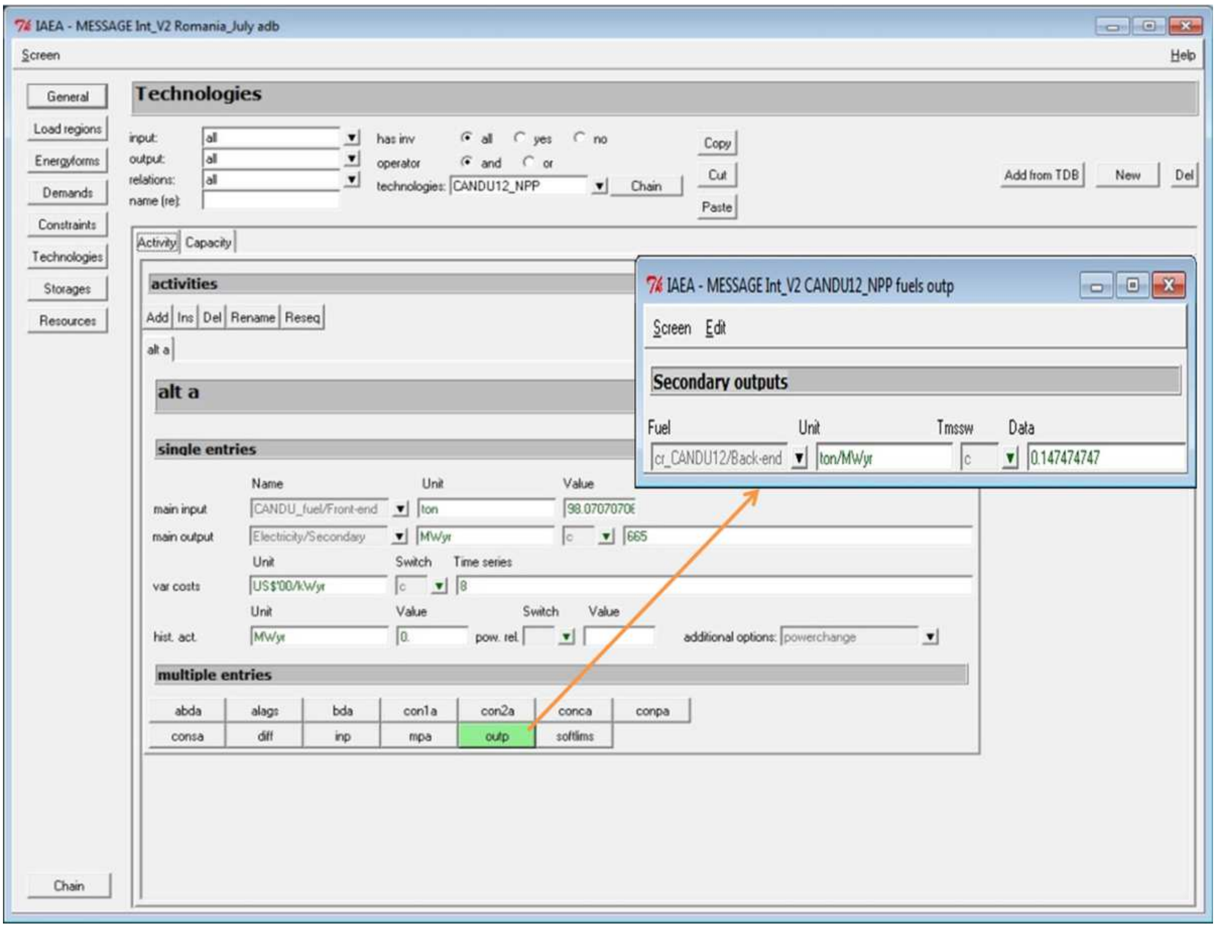


FIG. 46. Modelling of the CANDU34 activity page in MESSAGE.

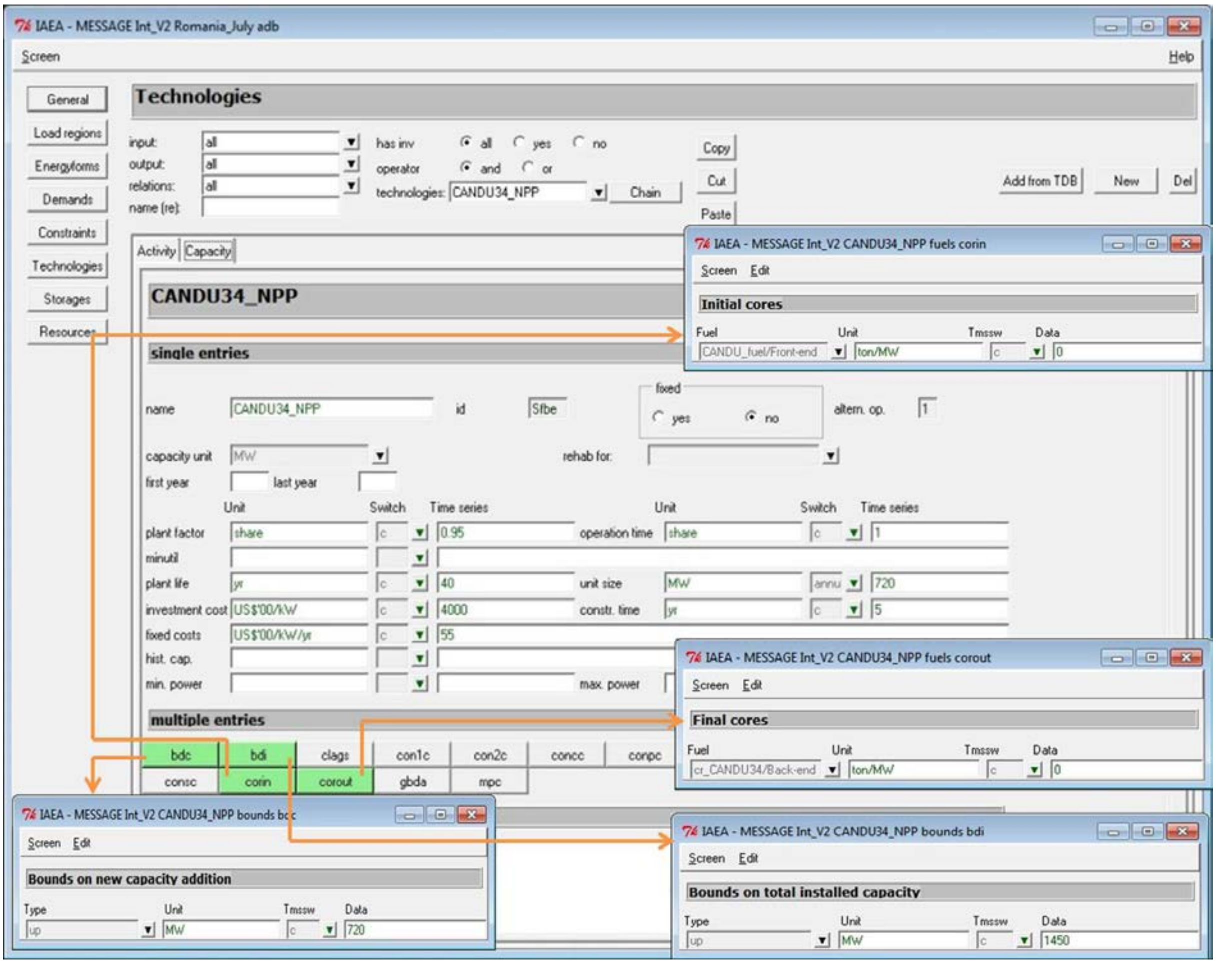


FIG. 47. Modelling of the CANDU34 capacity page in MESSAGE.

The modelling of advPWR (see Figs 48 and 49) and advHWR nuclear technologies in MESSAGE was carried out in a way similar to that used for the previously presented CANDU technology. For both advanced nuclear power plants, the projected in-service was considered after 2035, so ‘first year’ was specified in the capacity page. Also, a boundary on the total installed capacity was used according to the strategic documents in force.

The advPWR installed capacity is 1000 MW(e), with 88.485 t HM initial loading and 22.121 t HM annual reload. The corresponding specific values in ‘corin’ are 0.066 364 = (88.485 - 22.121) / 1000 for UOX fuel, equal to the final core unloading (including fission products) ‘corout’. The advPWR produces 1000 × 0.9 = 900 MW(e)·year electricity, consuming 22.121 t HM of fresh fuel. To generate 1 unit of electricity, 0.0246 (=22.121/900) t HM of fresh fuel is needed, the same amount being annually discharged from the reactor to the cooling pond.

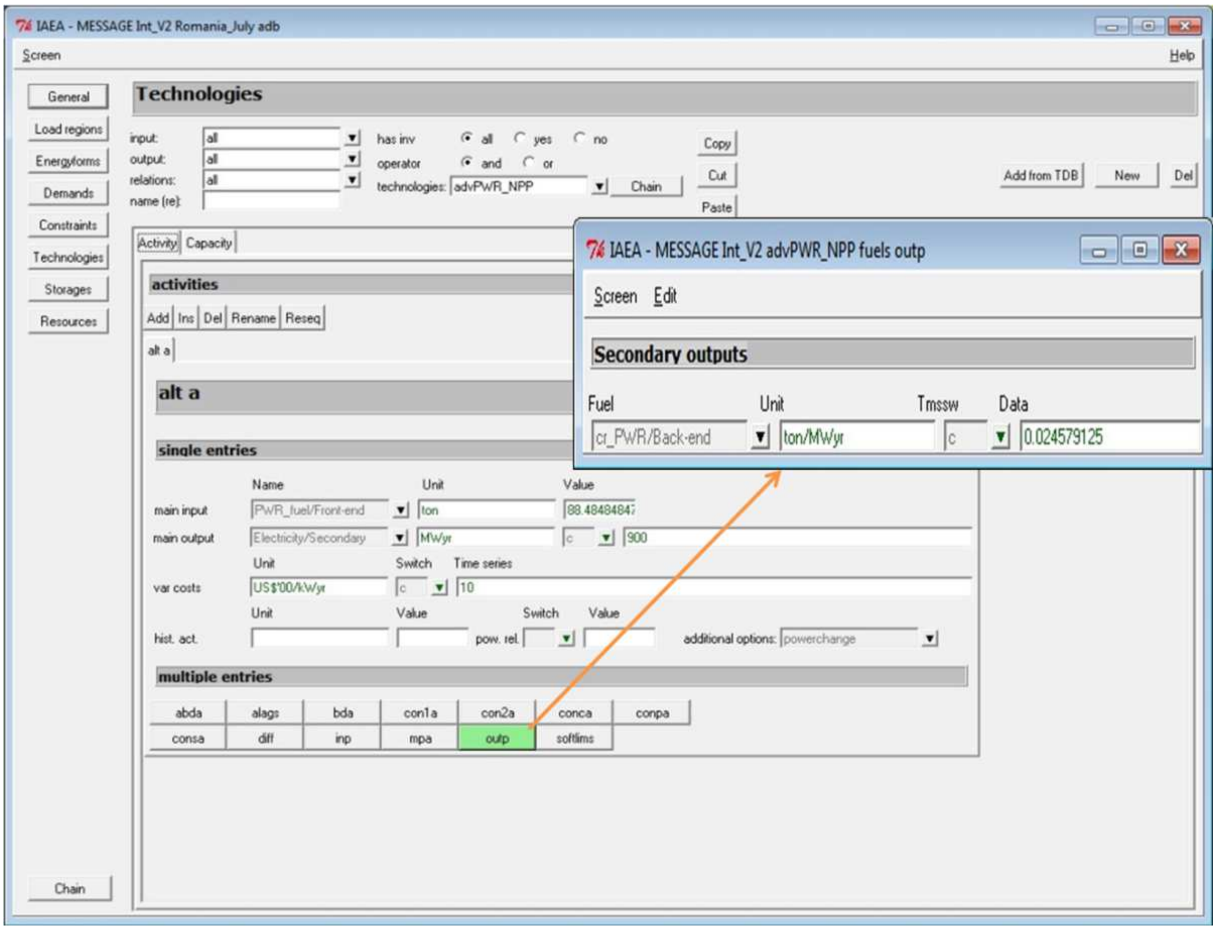


FIG. 48. Modelling of the advPWR activity page in MESSAGE.

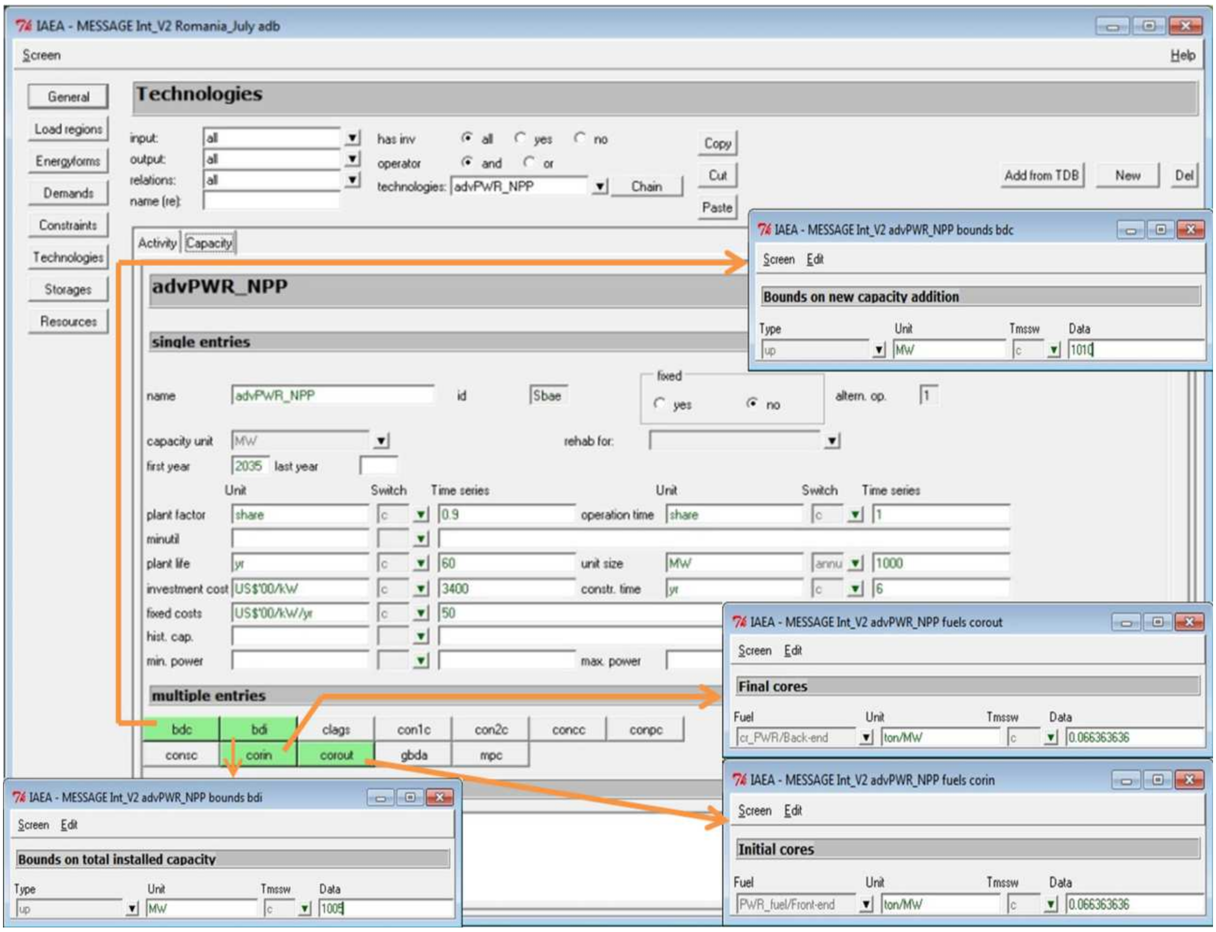


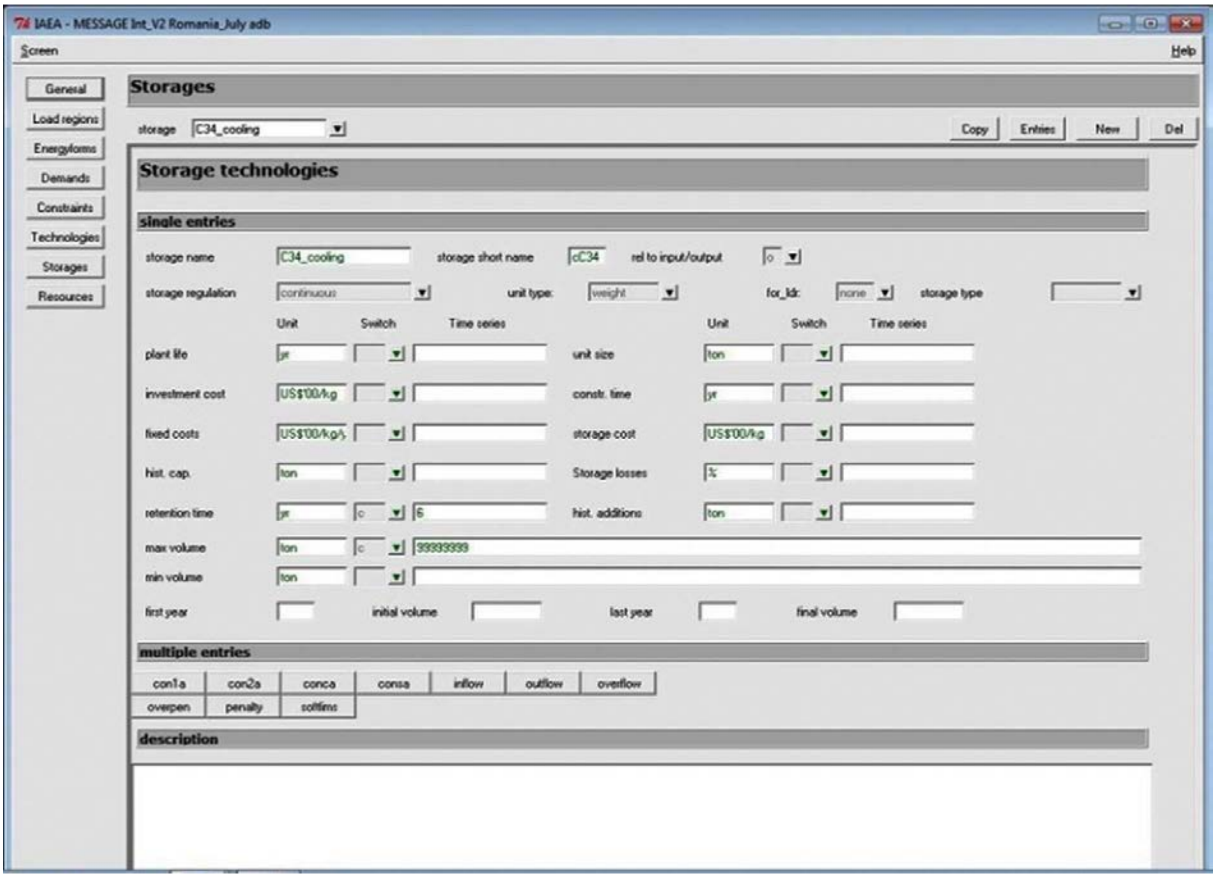
FIG. 49. Modelling of the advPWR capacity page in MESSAGE.

The spent fuel discharged from the reactors is first cooled down in the intermediate wet spent fuel bay inside the nuclear power plants (5 years for the advPWR and 6 years for HWRs), after which the cooling period continues within the intermediate dry storage (50 years for CANDU and advHWR reactors), the related facilities being built on nuclear power plant site. Spent nuclear fuel corresponding to the advPWR will be stored in a regional storage facility, with associated costs, as a service. Both wet and dry intermediate storages were modelled with MESSAGE as separate facilities for each defined type of reactor technology (see Fig. 50 for CANDU34).

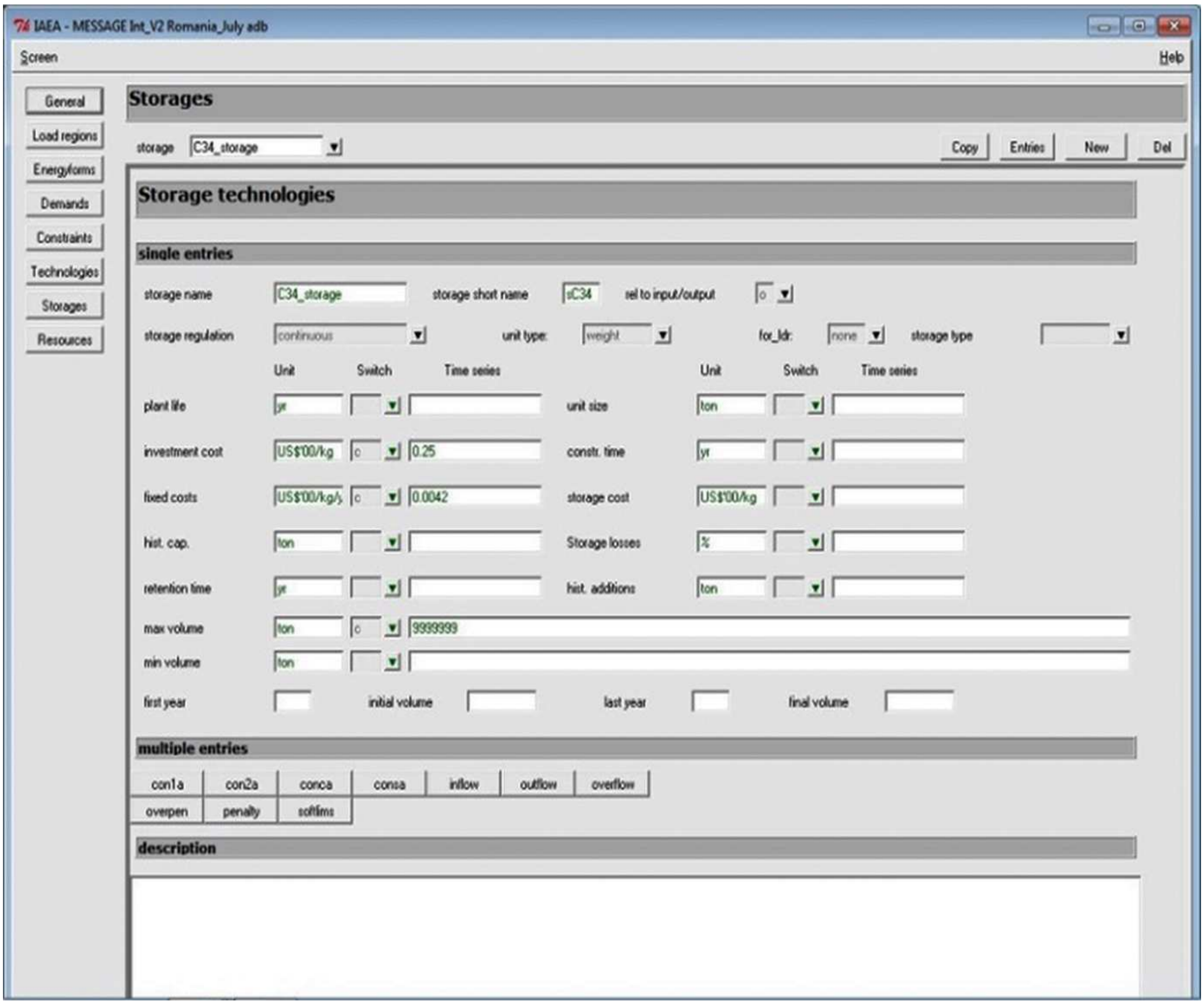
The intermediate wet storage costs are generally assumed to be a small part of the reactor capital and operations costs, and typically they are not added as separate costs. The storage costs are based on commercial cost data associated with the reactor construction and operation. In the current study, waste storage costs (€1.4/MW·h) were included in the variable costs of nuclear power plants; meantime decommissioning costs (€0.6/MW·h) were included in the fixed costs of nuclear power plants (values corresponding to Romanian legislation for CANDU reactors and spent fuel management). However, for intermediate dry storage the investment, O&M and storage costs have been considered according to national and international references [27, 29–31].

In order to allow the discharged spent fuel to move from the reactor core to the intermediate storage, two technologies have been modelled, namely: (i) fc_(reactor type) — take the spent fuel discharged from the reactor core and move it into the spent fuel bay (inside the nuclear power plant building) for cooling (see Fig. 51 for advHWR) and (ii) tr_(reactor type) — take the spent fuel from the spent fuel bay and move it into the spent fuel intermediate dry storage installation (see Fig. 52 for advHWR). Movement of the spent fuel is modelled by using 'consa' (constraint), for these already mentioned technologies being considered a dummy level as output (movement of the discharged SNF).

The technology chain for the case study is presented in Fig. 53.



(a)



(b)

FIG. 50. Modelling of the intermediate wet and dry storages for CANDU34 in MESSAGE.

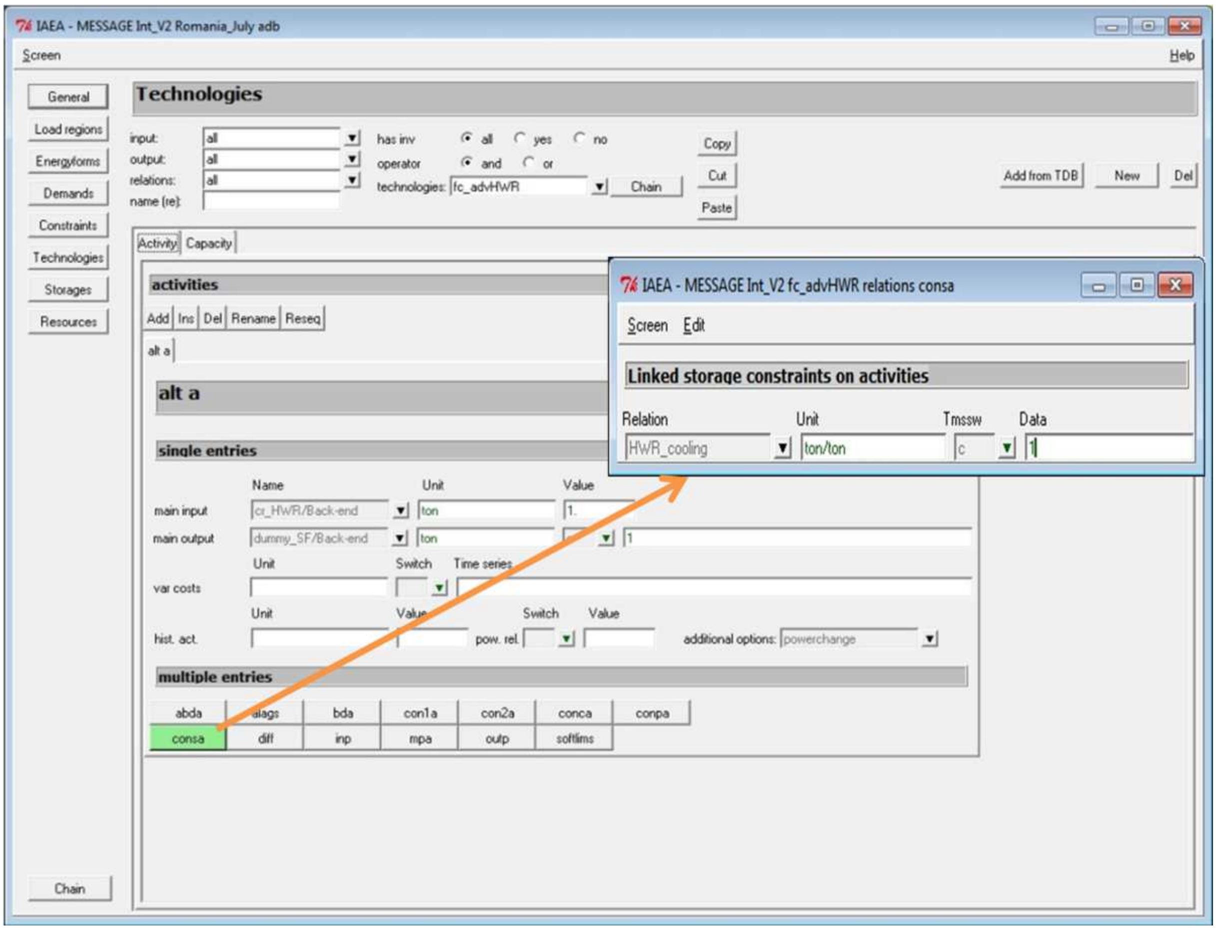


FIG. 51. MESSAGE page for modelling of the fc_advHWR technology.

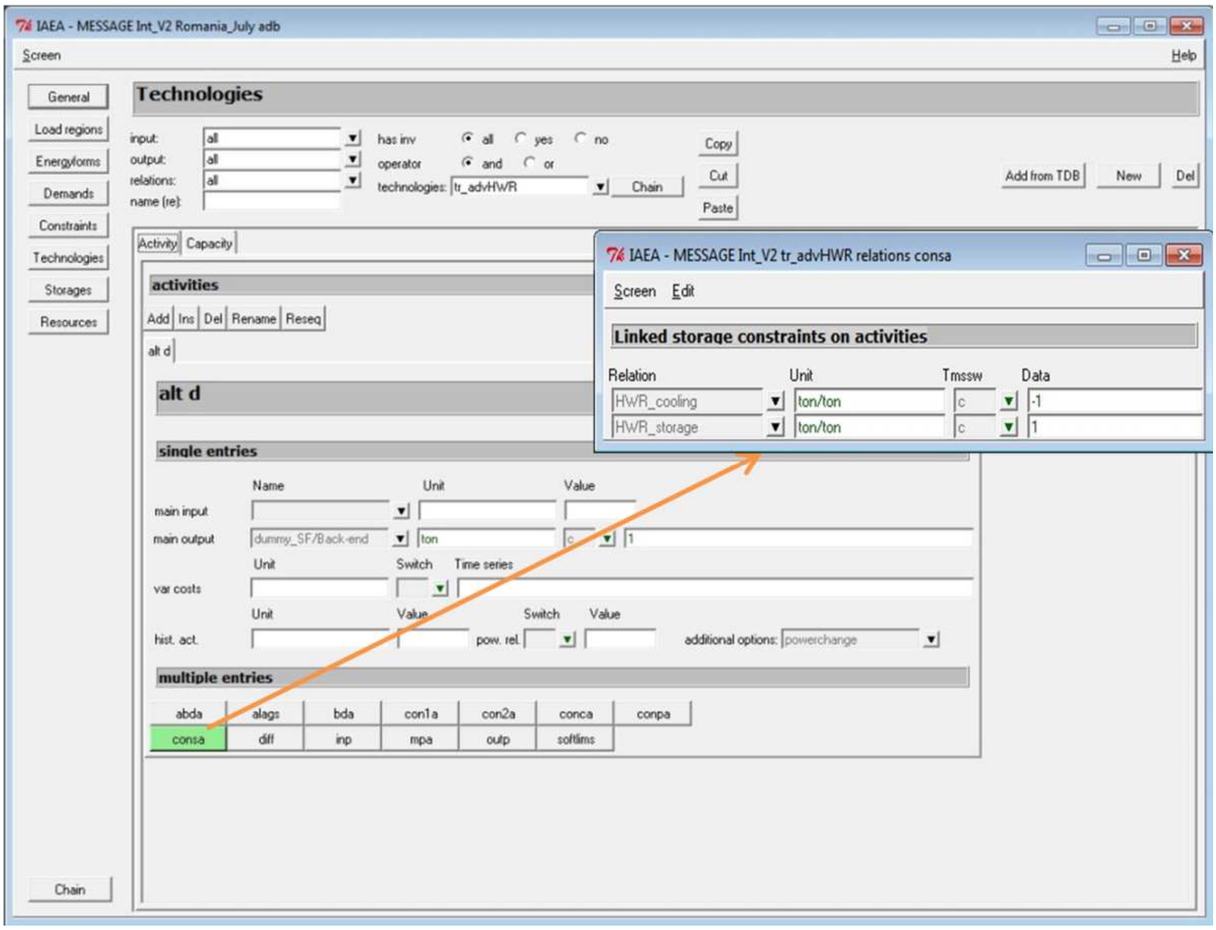


FIG. 52. MESSAGE page for modelling of the tr_advHWR technology.

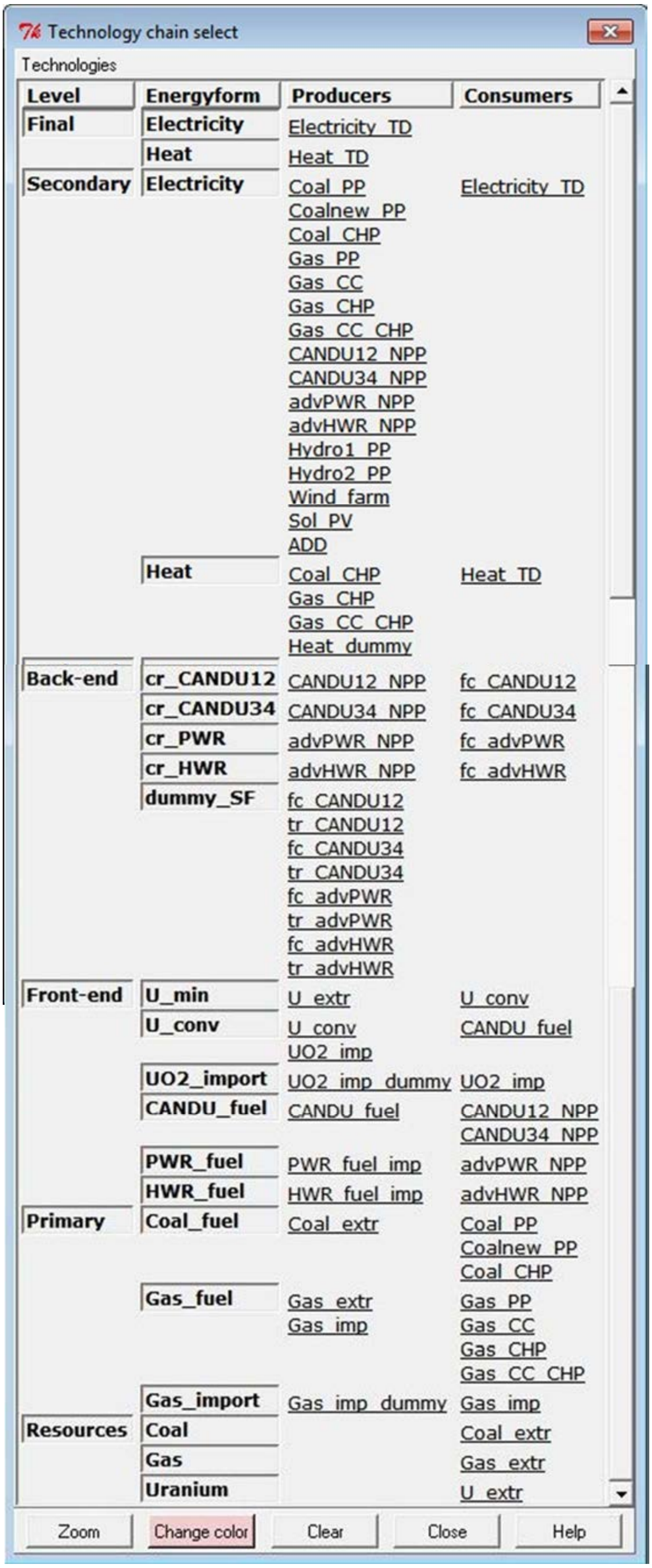


FIG. 53. Case study modelled in MESSAGE: Technology chain.

The economic analysis has been performed for five types of power plants competing in Romania's national energy system for electricity production, namely: nuclear technology (CANDU_new, advPWR and advHWR) and conventional technology on fossil fuels, but using advanced technologies for CO_2 capture (Coal_new and Gas_new).

The calculated costs for electricity generation are plant-level costs at the station, and do not include transmission and distribution costs. In the comparative study for the initial capital investment, uniform investment schedule has been used for all considered technologies. Basic assumptions and data used for the comparative economic analysis have been collected from Refs [8, 20, 26–35], which were used as input values for the NEST calculations. Table 23 contains main input data for power plants specific technical parameters. The data presented in the Table 24 were used for investment limit calculation, according to country specifics.

TABLE 23. POWER PLANT SPECIFIC TECHNICAL INPUT PARAMETERS [8, 20–30]

Parameter	**Unit**	**advPWR**	**advHWR**	**CANDU_new**	**Coal_new**	**Gas_new**
Net electric power	MW(e)	1000	720	720	600	400
Construction time	year	6	6	5	4	3
Life time	year	60	60	40	40	35
Load factor	%	90	90	93	85	85
Thermal efficiency	%	33	33	33	40	52

TABLE 24. COUNTRY SPECIFIC ECONOMIC INPUT PARAMETERS [33–35]

Parameter	**Unit**	**Value**
Discount rate	1/year	0.08
Price of unit electricity sold	mills/kW·h	112
Tax rate	%/100	0.5
Market income[a]	Million US $/year	3800
Market share[a]	%/100	0.5
Profit margin[a]	%/100	0.2
Time of growth[a]	year	6
Adjusting coefficient[a]	%/100	2

[a] Parameters are used only for investment limit calculation, according to country specifics.

Robustness Index (RI) can be defined as ratio of cost associated to alternative source of supply divided by cost of nuclear source of supply; this ratio is usually called the relative competitiveness of 'nuclear/alternative technology' cost ratio. Once a tolerable limit is defined, a larger value of RI indicates better performance. The NES is 'more robust' when indicator values are further from the tolerable limit, and would be 'less robust' when indicator values are closer to the tolerable limit.

In present economic analysis, the ratio for tolerable limit was considered to be 1.0. The nuclear technologies would be cost competitive with the alternative technologies if the ratio of indicator values is greater than 1.0.

2.3.5. Scope of results and findings of the case study

Three scenarios for electricity demand evolution have been taken into account for the considered time horizon. Presented here are only the results obtained for the NESA electricity demand scenario. For the pessimistic electricity demand scenarios, the results were not very different from those obtained for the NESA demand scenario apart from reducing the chances to build CANDU34 units before the advHWR and advPWR units in the high development scenario and even excluding chances to build any CANDU34 unit for a drate of 10%. Various discount rate values (drate = 5%, 8% and 10%) were considered, and taking into account the Romania's conditions and its economic and financial environment, the results obtained for the 8% annual discount rate can be considered as the most appropriate.

Two options were considered relating to raw materials (UO_2 powder) for CANDU fuel fabrication: assuming the use of domestic uranium resources to obtain UO_2 powder (cost is kept at level of 2015, as it was initially negotiated between CNU and SNN), and considering the import of UO_2 powder with more competitive cost (actual situation).

The overall electricity generation mix is shown in Fig. 54 (for 8% annual discount rate and the considered NES development scenarios). The nuclear electric energy annual production for different NES development scenarios is presented in Figs 55–57 assuming the drate = 8% and for the various annual discount rates taking into account the reference and high NES development scenarios.

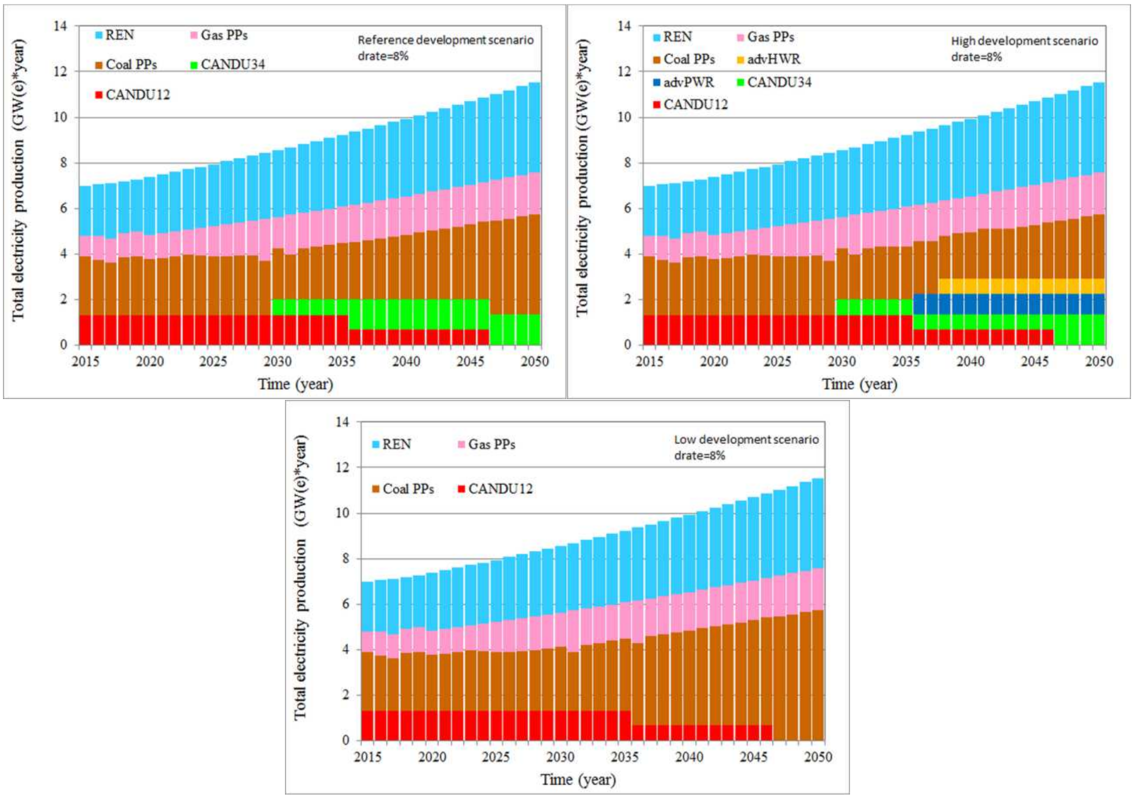


FIG. 54. Annual total electricity production for considered NES development scenarios (NESA energy demand scenario, drate = 8%).

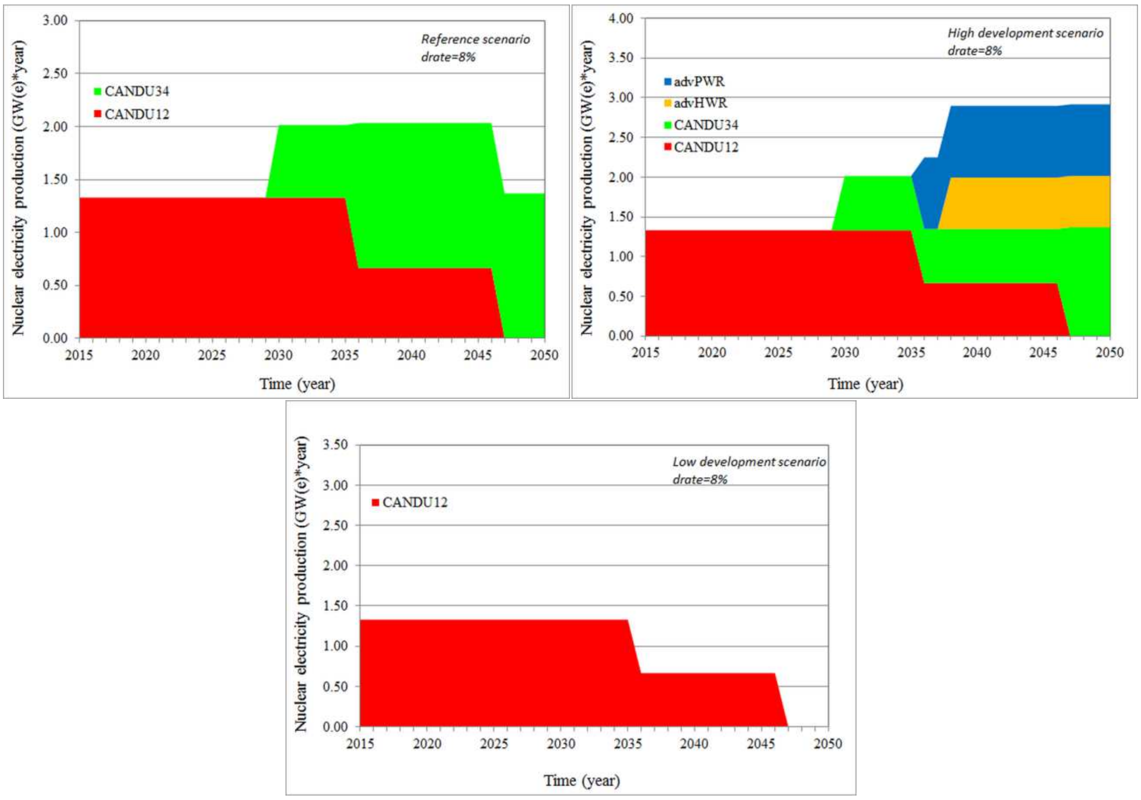


FIG. 55. Annual nuclear electricity production for considered NES development scenarios (NESA energy demand scenario, drate = 8%).

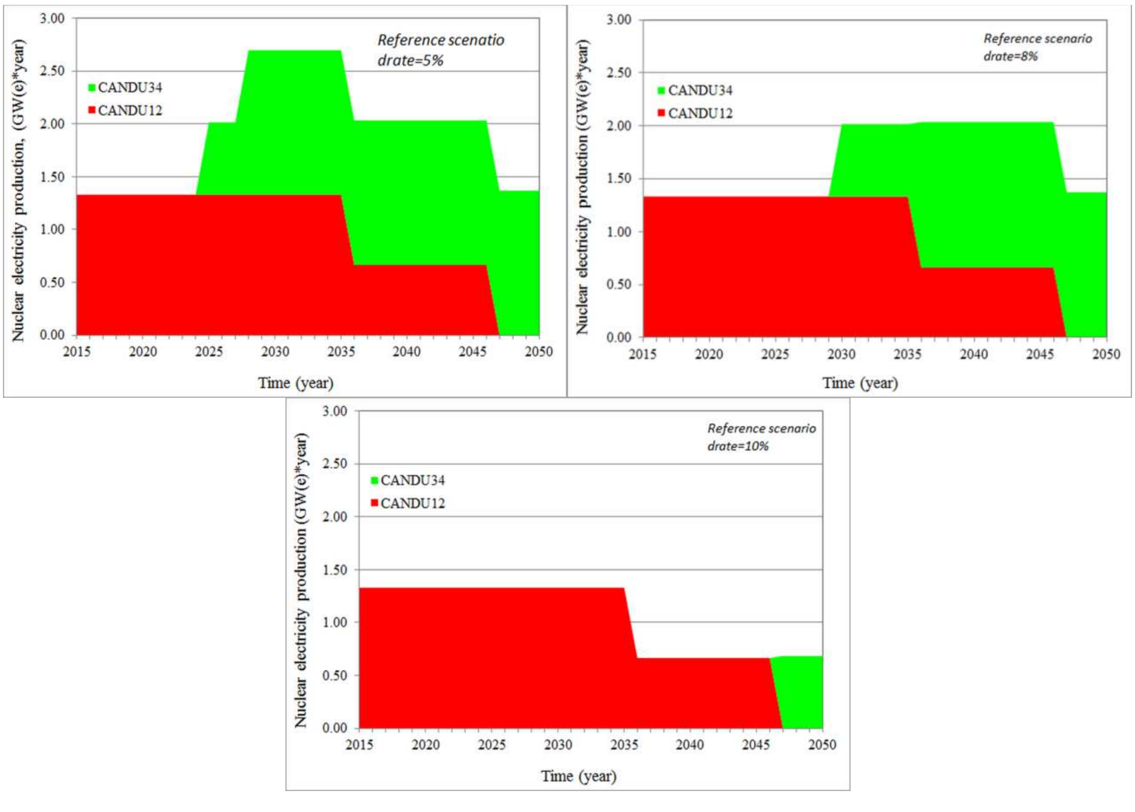


FIG. 56. Annual nuclear electricity production for various annual discount rates (NESA energy demand scenario, reference NES development scenario).

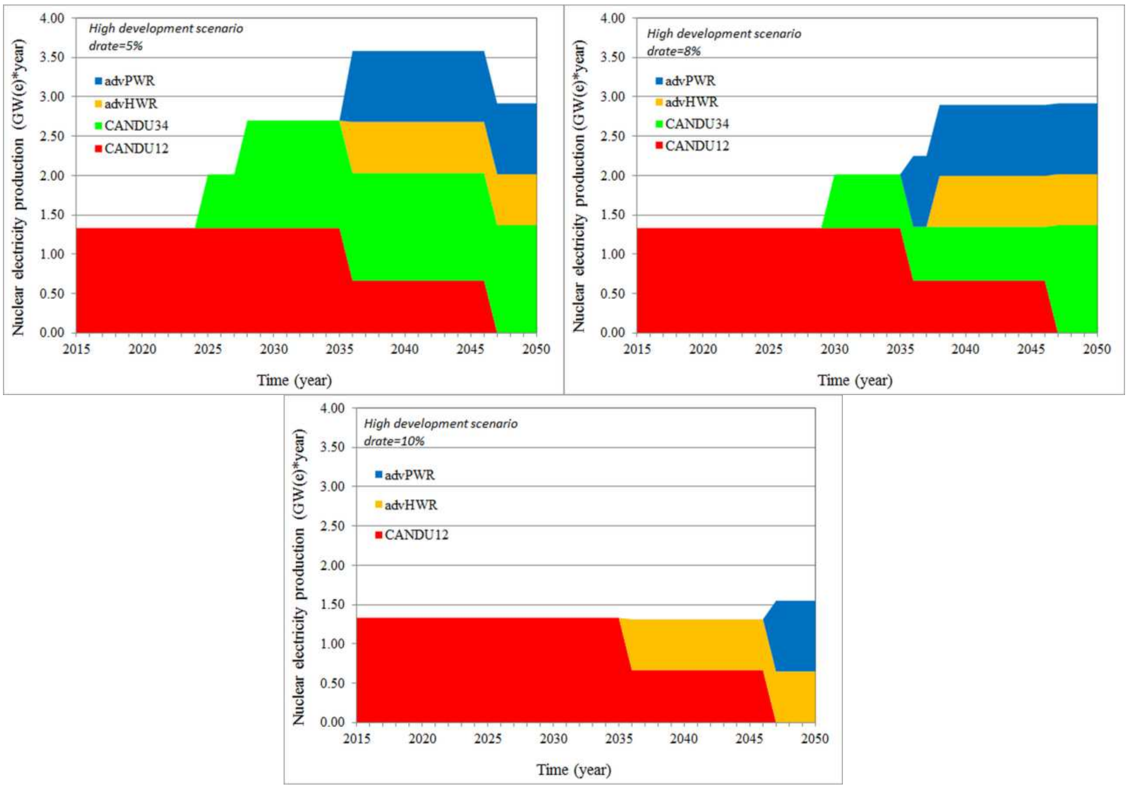


FIG. 57. Annual nuclear electricity production for various annual discount rates (NESA energy demand scenario, high NES development scenario).

By considering the NESA scenario for energy demand evolution, electrical energy generation in the national energy mix reaches 11.53 GW(e) at the end of considered time horizon in the modelling case study.

Total electric energy generation for the considered modelling period is based on increasing both nuclear and renewable electricity shares, both for the reference and high development scenarios. For the reference development scenario, the nuclear energy share in total energy production reaches 32% in 2028–2030 (drate = 5%), 24% in 2030 (drate = 8%) and is maintained at the actual share of 18–20% up to 2022 (drate = 10%). The high development scenario would increase nuclear energy share to 38% in 2036–2037 (drate = 5%) and 30% in 2038–2039 (drate = 8%).

Nuclear share growth in the national electricity production mix is based on newly installed nuclear capacities: reference scenario — 2 new CANDU units for drate = 5% (2024; 2027) and drate = 8% (2029; 2035), and one new CANDU unit for drate = 10% (2046); high development scenario — 2 new CANDU units (2024; 2027), advHWR and advPWR (2035, first year allowed from modelling) for drate = 5%, and 2 new CANDU units (2029; 2046), advPWR (2035) and advPWR (2037) for drate = 8%.

The construction of nuclear capacities will be brought forward at a lower discount rate. As the discount rate value increases, so the investment in nuclear capacities (capital intensive technologies) becomes larger and would be amortized over a longer period of time, thereby delaying nuclear capacity construction.

For the low development scenario, nuclear capacities are limited to the existing ones and the energy demand is met not only on the basis of an increase of the share of renewables, but also through a larger share of coal fired power plants in electricity production. There are significant domestic resources of coal available at a competitive cost (6 times lower than the imported natural gas cost); in this, the reduction of penalties associated with CO_2 emission due to modern solutions for CO_2 capture have also been taken into account. The share of natural gas in energy generation is relatively low as a significant percentage of natural gas consumption is sourced from imports.

Considering two options for CANDU fuel fabrication (using UO_2 from domestic resources or importing UO_2), the cumulative consumption of domestic uranium until the end of the modelling horizon (2050) was as follows: 0.981 kt HM in actual conditions of importing UO_2 powder at a lower cost than the domestic rate, regardless of the NES development scenario or the discount rate considered; 6.7 kt HM (total amount of domestic uranium identified resources (RAR+IR) [8]) for drate = 5% and 8% (reference and high development scenarios), and 5.982 kt HM for drate = 10% (reference and high development scenarios) and also in the low development scenario regardless of the discount rate considered. The total UO_2 powder requirements (domestic and imported) for the considered development scenarios are presented in Table 25, taking into account the above mentioned options for CANDU fuel fabrication. CANDU fuel is used for both CANDU12 and CANDU34 reactors.

The annual fresh fuel requirements are illustrated in Figs 58 and 59 for the considered NES development scenarios at various discount rates. Table 26 presents the spent fuel volume in interim dry storage for considered NES development scenarios and discount rates.

TABLE 25. UO_2 POWDER REQUIREMENTS FOR CANDU FUEL FABRICATION (kt HM)

NES development scenarios	**Discount rate (drate)**	**UO_2 powder amount (kt HM)**	
		Domestic	**Import**
Option1: UO_2 powder imported at a lower cost than the domestic supply from 2016			
Reference development scenario	5%	0.981	9.944
	8%	0.981	8.633
	10%	0.981	5.405
High development scenario	5%	0.981	9.944
	8%	0.981	7.523
	10%	0.981	5.002
Low development scenario	any drate	0.981	5.002
Option2: Use of domestic uranium for producing UO_2 powder (cost maintained at 2015 level)			
Reference development scenario	5%	6.700	4.225
	8%	6.700	2.914
	10%	5.982	0
High development scenario	5%	6.700	4.225
	8%	6.700	1.804
	10%	5.982	0
Low development scenario	any drate	5.982	0

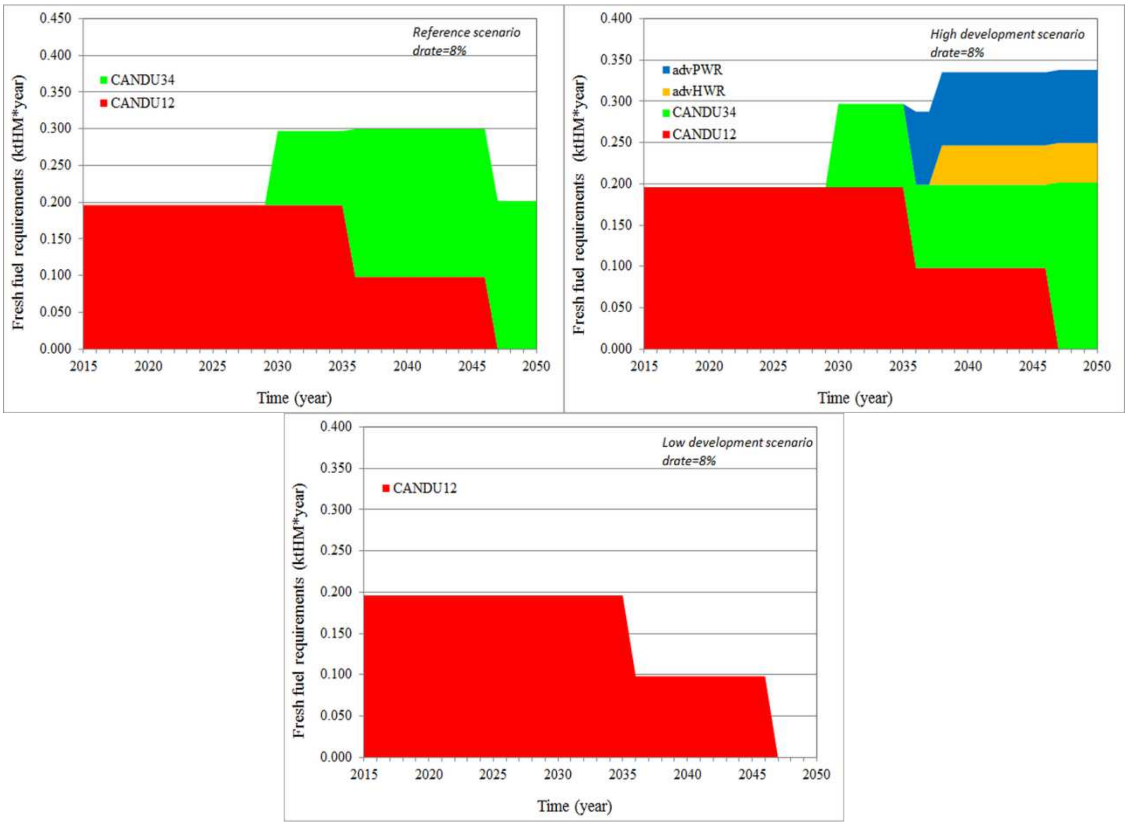


FIG. 58. Annual fresh fuel requirements for considered NES development scenarios (NESA energy demand scenario, drate = 8%).

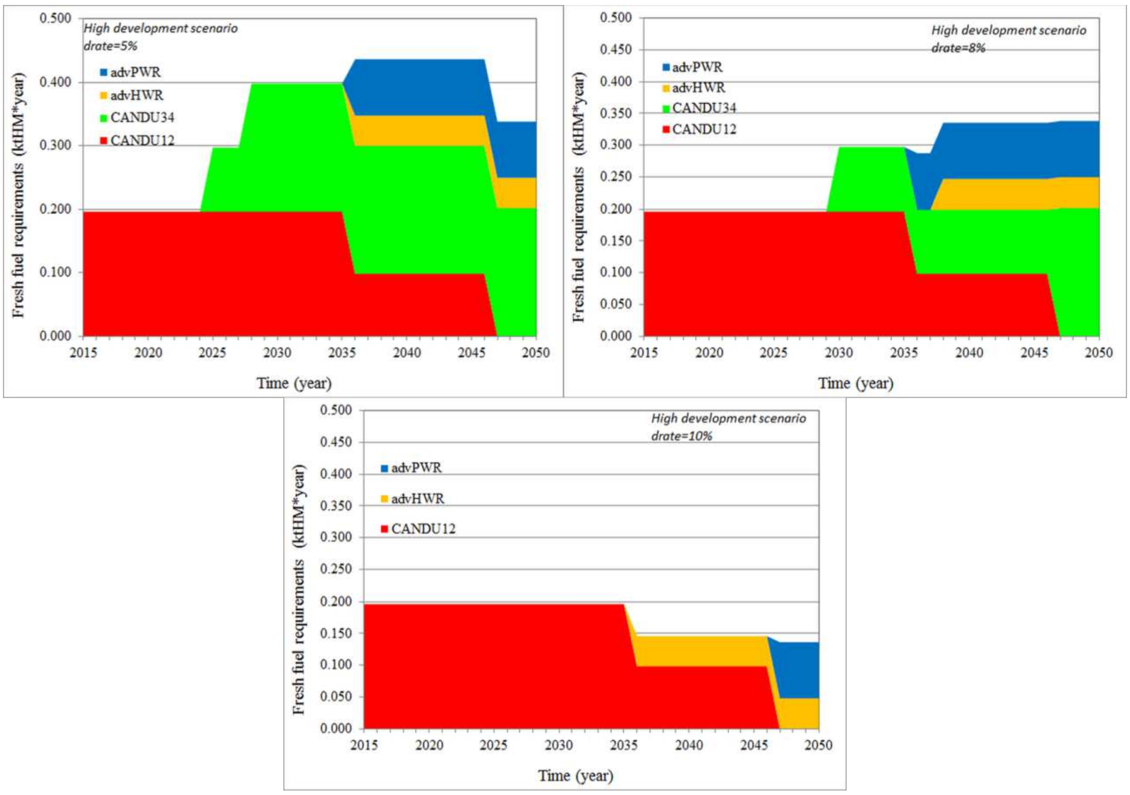


FIG. 59. Annual fresh fuel requirements for considered discount rates (NESA energy demand scenario, high development scenario).

TABLE 26. SNF VOLUME IN INTERIM DRY STORAGES (KT HM+FP)

NES development scenarios	Discount rate (drate)	SNF volume in interim dry storages (kt HM+FP)				
		Total	CANDU12	CANDU34	advHWR	advPWR
Reference development scenario	5%	10.904	7.970	2.934	0	0
	8%	10.167	7.970	2.197	0	0
	10%	7.970	7.970	0	0	0
High development scenario	5%	11.749	7.970	2.934	0.606	0.239
	8%	10.864	7.970	2.197	0.459	0.239
	10%	8.576	7.970	0	0.606	0
Low development scenario	any drate	7.970	7.970	0	0	0

The following competing technologies for electric energy generation in Romania have been considered in the economic analysis: nuclear technology (represented by CANDU Units 3 and 4 — CANDU_new, advanced HWR — advHWR, and advanced PWR — advPWR) and conventional technology (represented by coal fired power plants using lignite fossil fuel, with carbon capture — coal_new, and gas fired power plants operating on a combined cycle, with carbon capture — gas_new).

Specific economic parameters have been calculated for the reference scenario, (see Section 2.3.4 for technical and economic input data of reference scenario), as follows: LUEC, IRR, ROI, NPV and total investment costs (see Table 27).

TABLE 27. CALCULATED VALUES FOR ECONOMIC PARAMETERS OF INTEREST

Technology	Net Capacity (GW(e))	Overnight Costs[a] (US $/ kW(e))	Investment Costs[b] (US $/ kW(e))	Total Investment[c] (× 10^9 US $)	LUEC (× 10^{-3} US $/ kW·h)	IRR	ROI	NPV (US $/ kW(e))
CANDU_new	0.720	5820	7375	5310	65.08	0.128	0.284	4923
advPWR	1.000	3400	4503	4503	49.05	0.162	0.455	6634
advHWR	0.720	3000	3973	2861	40.02	0.183	0.535	7585
Coal_new	0.600	1520	1849	1109	79.03	0.215	0.356	3162
Gas_new	0.400	1099	1285	514	98.30	0.203	0.160	1284

[a] Includes pre-construction/owner's, construction and contingency costs.
[b] Includes overnight costs and interest during construction.
[c] Is given by investment costs multiplied by power plant net capacity.

LUEC values are lower for selected nuclear technologies compared to the ones calculated for classic technologies considered in the analysis. The lowest LUEC value was obtained for the adv.HWR of US $40.02 × 10^{-3}/kW·h, while the highest LUEC value of US $98.30 × 10^{-3}/kW·h is associated with Gas_new technology. Among selected nuclear technologies, CANDU_new has the highest LUEC value (35% and 60% higher than adv.PWR and adv.HWR, respectively).

CANDU_new also has a significantly higher capital investment than other selected nuclear technologies, an aspect that can be explained by the multiple delays and financing challenges registered in the CANDU Units 3 and 4 project, including the investors' withdrawal from the consortium in 2011–2013.

The nuclear technologies fared better than the fossil fuel power plants only with respect to ROI and NPV parameters. On the basis of IRR comparison, nuclear technologies appear less attractive than conventional technologies. However, the rates of IRR = 0.162 (advPWR) and IRR = 0.183 (advHWR) are high enough to suggest that nuclear technology can become attractive for long term development of Romania's national energy system. Notwithstanding the above said, the IRR value for selected nuclear technologies is high enough to justify the Government interest in nuclear projects, taking into account strategic considerations such as increased security of supply by diversification of energy sources.

The needed total investment in selected nuclear technologies was lower than the investment limit calculated, taking into account the Romania's specific national financial environment (except for CANDU new). It should be noted that the capital investment needed for the considered conventional power plants is much lower than that required for the nuclear projects. However, the Government's long term commitment to nuclear energy and strategic considerations such as the increased security of supply by diversification of energy sources, the reduction of greenhouse gas emissions, and the link to the EU Energy Policy and actions for minimizing the impact of global climate change must be taken into account.

Sensitivity analyses have been performed to highlight the effect of various perturbations on LUEC (e.g. discount rate, fixed O&M costs, overnight costs). According to the INPRO Methodology in Economics area [25], robustness index for each NES was calculated by using LUEC values obtained for the considered nuclear and alternative technologies competing in the energy generation. For the reference scenario, Table 28 presents the RI values associated with nuclear technologies of interest.

TABLE 28. ROBUSTNESS INDICES OF NUCLEAR TECHNOLOGIES FOR THE REFERENCE SCENARIO

Power Plant	**LUEC** ($\times 10^{-3}$ **US $/ kW·h**)	**Robustness Index (RI_{ref})**	
		$\frac{LUEC_{Coal}}{LUEC_{Nuclear}}$	$\frac{LUEC_{Gas}}{LUEC_{Nuclear}}$
advPWR	49.05	1.61	2.00
advHWR	40.02	1.97	2.45
CANDU_new	65.08	1.21	1.51
Coal_new	79.03	-	-
Gas_new	98.30	-	-

Eight critical input parameters were selected to estimate RI for deviation from the data used in the reference scenario, namely: discount rate, construction time, fossil fuel price, nuclear fuel cost (natural uranium purchase cost), overnight costs, lifetime, average load factor and thermal efficiency. Each input parameter was perturbed separately, keeping the other parameters at their values considered in the reference scenario. LUEC corresponding to nuclear and alternative technologies were calculated, the ratios $\frac{LUEC_{Alternative}}{LUEC_{Nuclear}}$ being obtained accordingly (see Table 29). Table 29 also includes the variation (in %) of calculated ratios from the ones corresponding to the reference scenario.

TABLE 29. ROBUSTNESS INDICES OF NUCLEAR TECHNOLOGIES FOR CONSIDERED DATA PERTURBATIONS

Perturbed parameter/ power plant	Parameter variation[a]	LUEC ($\times 10^{-3}$ US $/ kW·h)	Robustness index (RI_{pert})			
			$\frac{LUEC_{Coal}}{LUEC_{Nuclear}}$	Variation of RI_{pert} from RI_{ref}	$\frac{LUEC_{Gas}}{LUEC_{Nuclear}}$	Variation of RI_{pert} from RI_{ref}
Discount rate	+3%					
advPWR		61.73	1.33	21%	1.60	25%
advHWR		50.97	1.61	23%	1.94	26%
CANDU_new		83.00	0.99	23%	1.19	27%
Coal_new		81.83				
Gas_new		99.07				
Construction time	+50%					
advPWR		55.89	1.44	11%	1.78	12%
advHWR		46.06	1.75	12%	2.16	13%
CANDU_new		71.85	1.12	8%	1.38	9%
Coal_new		80.73				
Gas_new		99.45				
Fossil fuel price	-30%					
advPWR		49.05	1.25	29%	1.48	35%
advHWR		40.02	1.53	29%	1.81	35%
CANDU_new		65.08	0.94	29%	1.11	35%
Coal_new		61.13				
Gas_new		72.53				
Nat U purchase cost	+10%					
advPWR		49.30	1.60	0.4%	1.99	0.3%
advHWR		40.11	1.97	0.1%	2.45	0.1%
CANDU_new		65.22	1.21	0.1%	1.51	0.2%
Coal_new		79.03				
Gas_new		98.30				
Overnight costs	+10%					
advPWR		52.38	1.54	5%	1.92	4%
advHWR		42.97	1.87	5%	2.34	5%
CANDU_new		70.50	1.14	6%	1.42	6%
Coal_new		80.56				
Gas_new		100.46				
Lifetime	-10%					
advPWR		49.25	1.60	1%	1.98	1%
advHWR		40.20	1.96	1%	2.43	1%
CANDU_new		66.05	1.19	2%	1.48	2%
Coal_new		78.62				
Gas_new		97.65				

Load factor	-10%					
advPWR		53.59	1.51	6%	1.86	7%
advHWR		44.10	1.84	7%	2.26	8%
CANDU_new		73.30	1.11	9%	1.36	11%
Coal_new		81.17				
Gas_new		99.85				
Thermal efficiency	-10%					
advPWR		49.84	1.73	6.7%	2.15	7.0%
advHWR		40.29	2.14	7.8%	2.66	8.0%
CANDU_new		65.40	1.32	8.0%	1.64	8.0%
Coal_new		86.05				
Gas_new		107.22				

[a] '+' is used for increasing parameter value and '-' is used for decreasing parameter value.

In Table 29, differences in RI corresponding to selected reactor types can be noticed. The dramatic change in RI for CANDU_new as compared to other nuclear power plants is mainly due to its higher capital investment and multiple delays in construction. The differences in RI between advPWR and advHWR could be associated with the advPWR higher nuclear fuel fabrication and backend costs, leading to LUEC values 20% greater compared to the corresponding ones for the advHWR.

The robustness index for each NES is given by the lowest RI calculated for considered critical economic parameters' deviations in accordance with the INPRO Methodology in Economics area [25]. For the considered nuclear technologies, the following RI values were obtained (according to RI values shown in Table 28): 1.25 (for advPWR), 1.53 (for advHWR) and 0.94 (for CANDU_new). It is pertinent to consider that the NES is 'more robust' as the associated RI value is further from the tolerable limit (in present case, this limit was established to be 1.0); advHWR is 'more robust' than advPWR and CANDU_new, respectively.

Based on variation of the ratio $\frac{LUEC_{Alternative}}{LUEC_{Nuclear}}$ for considered data perturbations from the ratio values obtained in the reference scenario, it can be noticed that the most critical parameters for NES robustness are (in descending order): fossil fuel price (29% variation for comparison against coal power plant and 35% variation for comparison against gas power plant), discount rate (21–23% variation for comparison against coal power plant and 25–27% variation for comparison against gas power plant) and construction time (8–13% variation for comparison against alternative power plants). The considered perturbations in power plant lifetime and natural uranium purchase cost led to very small variations from the reference scenario, these parameters being the less critical parameters for NES robustness.

The highest impact on LUEC, due to the perturbations, has been observed in capital intensive technologies (nuclear technologies) compared with conventional power plants, especially for annual discount rate changes. The variation of the power plant lifetime registered the lowest impact on calculated LUEC values of the considered competing technologies for electricity generation in Romania's national energy system. The fuel cost changes had a low impact on LUEC for the nuclear technologies, but for classic technologies the impact of fuel costs' variation on the corresponding LUEC was rather high.

As it follows from the results of the case study, nuclear energy is an important candidate for domestic production of electricity in terms of cost competitiveness and safety and security of supply. In order to secure the projected national electricity demand, the nuclear energy share in the national energy mix can be increased from the present value (about 20% of the total production of electric energy) according to the strategic documents in force.

On the basis of the MESSAGE model, assessments of the domestic uranium consumption, the raw material and fresh fuel requirements and the accumulation of spent nuclear fuel discharged from the reactor core were performed for the considered NES development scenarios.

Using the 'cost' objective function/economic competitiveness, the best alternative was chosen irrespective of considering either the UO_2 powder (raw material needed to fabricate the CANDU fuel) or the type of nuclear power plant to be built and included in the national energy mix as a power supply source for competing the conventional (coal and natural gas fired power plants) and renewable (hydro, wind and solar) energy sources.

The MESSAGE model allowed representing nuclear power plant cooling pool and intermediate dry storage as separate storage technologies, a very useful feature for quantifying the amount of spent nuclear fuel discharged from the core and sent to cooling storage and also for monitoring the accumulation of spent nuclear fuel in the interim dry storage.

Based on the results of the case study, the MESSAGE model allowed visualization of characteristic aspects related to the feasibility of the considered NES development scenarios through correlation and consistency of all NES components, taking into account all the constraints and boundary conditions imposed on the system.

2.3.6. Feedback from the case study on NES modelling with the MESSAGE tool

MESSAGE offers flexible modelling and allows the users to decide on the NFC components to be included in the model. Each component of the NFC can be modelled with more technical and economic details if enough information and data are available to the users. Even if minimal technical and economic data are available to the users, MESSAGE allows a simple but quite useful representation of the NFC components.

The MESSAGE model allows representation of the entire nuclear energy system with time dependent parameters for medium and long term planning.

MESSAGE is able to perform energy system optimization and selection of the best alternative for energy generation, considering different kinds of the objective functions (cost, uranium use, waste generated, etc). Consequently, the users have a possibility to assess the different energy chains of reactor and fuel cycle technologies in order to choose an optimal energy chain alternative in terms of the cost competitiveness, lowest consumption of uranium resources, or minimization of waste generation, etc.

Nuclear material flow and waste generated by the reactor operation or fuel cycle activities for a certain energy chain can also be assessed by using the MESSAGE tool.

During extraction/checking of the case study results using the 'interactive results' window, an operational problem was encountered. Annual amount of spent fuel discharged from the reactor core can be extracted from the 'consa' aspect of technology 'fc_NPP' (NPP was CANDU12, CANDU34, advPWR and advHWR in the case study), according to the recommendations given in the User Guide for modelling NES using MESSAGE [2]. The amount of spent fuel transferred from cooling pond to the interim dry storage can be extracted using the 'consa' aspect of technology 'tr_NPP', in order to check its correctness. The extraction of both these results was not possible due to an error being encountered in the background function. This operational problem has already been corrected in newer version of the MESSAGE model.

2.4. RUSSIAN CASE STUDY ON MODELLING OF REGIONAL COLLABORATIVE DEPLOYMENT SCENARIOS AIMED AT SOLVING THE PROBLEM OF ACCUMULATION OF SPENT NUCLEAR FUEL INVENTORY

2.4.1. Scope of the problem and background for the case study

Nowadays, the role of nuclear power in the energy sector of many countries is widely discussed to facilitate decisions ranging from fast development of this energy option down to its total phase out. These complicated and contradictory macroeconomic and social aspects of the current situation with respect to nuclear power add value to the comprehensive and responsible energy planning that has to take into account new challenges and realities. A growing willingness of Member States to strengthen multinational and multilateral cooperation in the nuclear energy sphere is one of the important trends. Several international projects aimed at enhancing sustainability features of nuclear power have been initiated since the beginning of the century, including the two major projects: the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Generation-IV International Forum (GIF).

Consideration of the benefits of, and impediments to, international cooperation necessitates expanding the national boundaries of nuclear energy planning in order to address, on a regular basis, the potential of global and regional energy markets. In these circumstances, the need to use unified planning tools by analysts from different countries increases. Over the past decades the IAEA has developed and disseminated several tools that provide the wherewithal to model national, interregional and global energy systems.

This section presents the case study from the Russian Federation on modelling of multilateral NES using the IAEA's model MESSAGE. The configuration of regional NES simulated in the study was jointly designed in the INPRO collaborative project SYNERGIES [4] by participants from Armenia, the Russian Federation and Ukraine. Belarus did not directly participate in the SYNERGIES project, although experts from Belarus, being active participants of the INPRO project, have provided the data necessary for the case study. To simulate regional configuration and incorporate a complete spectrum of NFC elements, the extended capabilities of the MESSAGE code presented in Ref. [2] were used.

Regarding regional NES cooperation scenarios, the national partners involved in modelling the case study for regional NES represent different options of nuclear power development and deployment. In accordance with the terminology introduced in the INPRO collaborative project GAINS [3], they could be assigned to different nuclear energy strategy groups. The Russian Federation belongs to the nuclear energy strategy group, which pursues a general strategy of spent nuclear fuel recycling. This group plans to build, operate and manage used fuel recycling facilities and permanent geological disposal facilities for highly radioactive waste. Armenia and Ukraine belong to a nuclear energy group, which either follows a strategy of direct disposal of the SNF or that of its reprocessing abroad. This group plans to build, operate and manage permanent geological disposal facilities for highly radioactive waste (in the form of used fuel and/or reprocessed waste) and/or to work in collaboration with another group of countries to have its fuel recycled. Belarus belongs to a group, which has a general strategy of sending spent fuel abroad for recycling or disposal, although the ultimate back-end strategy is still undecided.

The scenarios developed in the SYNERGIES project can serve as a hypothetical example of a potentially 'win–win' cooperation in the NFC front and back ends. The NFC services can be provided by technology holder countries or NFC centres in order to ease the burden of full scale infrastructure development for a NES. A mature market already exists in the front end of the NFC, which enables a country to start or expand a national nuclear power programme without the development and construction of the front-end elements of the nuclear energy infrastructure. Examples of the multilateral approach in the NFC back end have already been demonstrated by several technology holder countries, although there are certain obstacles to be overcome in striving to reach the industrial, public and political consensus in this area. Simulation tools are an important part of the IAEA's methodological framework for analyzing the NES scenarios which assist Member States to foster international cooperation in the nuclear energy sphere.

2.4.2. Objectives of the study and problem formulation

2.4.2.1. The tasks of energy planning solved with the use of the IAEA tools and new issues addressed in the case study

The IAEA tools [36] have been adopted and used in the Russian Federation for solving different tasks since the 1990ies. In spite of the fact that the Russian Federation, as many other countries, has national tools for energy sector modelling, adaptation of the IAEA tools was, and remains, an important part of the national position. The reasons for using the tools disseminated by the IAEA are to:

- Expand opportunities and remove gaps in some areas of energy sector modelling;
- Compare results of modelling with national and international instruments;
- Present national results in a form understandable by the international community;
- Create a basis for joint studies in the scenario studies area.

At the first phase of IAEA tool application in the Russian Federation, the WASP-III Plus code was used for modelling electrical pools in some regions of the country. The module BALANCE of the Energy and Power Evaluation Program (ENPEP) code was applied for projecting energy consumption and greenhouse gas emissions in the Russian Federation. The results of these studies were taken into account during development of the nuclear energy strategies in the regions and at the national level. For example, a report on the role of nuclear power in greenhouse gas emissions reduction prepared with the use of the ENPEP code was presented to the State Duma of the Russian Federation and was discussed at a hearing on the State's policy on the prevention of climate change and global warming.

While some tasks of nuclear energy planning were successfully solved with the use of the IAEA tools noted above, it became clear that these tools are hardly applicable to modelling of a transition from existing NES to the prospective ones with innovative components. Within the models, candidates based on innovative technologies appeared in the optimal plan 15–30 years from the start of the simulation, when their economic characteristics were expected to gain some advantages over other alternatives. The period of transition to maturity which is critical for nuclear energy planning of innovations in NES was not presented in these codes with the necessary detail. Initiation of the INPRO and GIF projects made modelling of the innovative NES especially acute.

INPRO has developed a framework for the analysis and assessment of transition scenarios to sustainable nuclear energy systems. Since the early 2000s, the IAEA PESS and INPRO have commenced joint activities on enhancing capabilities of the IAEA energy planning tools used to model an NES with the inclusion of components based on innovative nuclear energy technologies. During this period, MESSAGE has become the most versatile and the most sophisticated planning tool available at the IAEA. In principle, it could fulfil most of the objectives of the rest of the IAEA planning code family. The capabilities of the code have been further extended in order to model NES with inclusion of innovative components. Some features of the MESSAGE tool with extended capabilities on an NFC simulation have provided opportunities for solving the tasks of the case study aimed at modelling of a multilateral cooperation in the NFC front and back ends.

2.4.2.2. Selection of MESSAGE tool with extended capabilities in NFC simulation for modelling purposes of the current case study

The issues that arise in a transition period to the NES with enhanced sustainability are largely associated with the building of new components for the industrial infrastructure. The MESSAGE tool was selected to address technical and economic issues associated with the building of such infrastructure by means of dynamic modelling of:

— The architecture of an NES including innovative components from 'first of a kind' installations up to serial ones;

— The fuel mass flows between the NES elements;

— Changes in fissile fuel material at each stage of the NFC;

— Balance of the materials.

Extended capabilities of the MESSAGE tool in NFC simulation [2] are very important for description, with necessary completeness, of the time dependent parameters of the entire NES for a long term planning and for assessing the key indicators of the study. Among other things, the model can help to:

— Confirm the feasibility of an NES through the correlation and consistency of all NES components, constraints and boundary conditions;

— Balance fissile material in a closed fuel cycle and determine related requirements on the fuel cycle components;

— Take into account cost of RD&D, construction cost, cost of generated electricity, and cost of spent fuel management and storage;

— Assist the user in the optimization of a NES by comparing alternatives with different options regarding the need for fuel, the volume and the toxicity of the waste, etc.

In this case study, new opportunities provided by MESSAGE's mathematical model were checked on the example of a large multilateral NES. The 'once-through' NFC with thermal reactors is a part of the NES based on established technologies, while the closed nuclear fuel cycle with fast reactors is a part based on innovative technologies. At this phase of tool approbation, the analysis was focused on modelling simplified industrial infrastructure with a schematic diagram of material flows in the NES. The potential of the MESSAGE tool for modelling of a more realistic system with a detailed specification of the economic parameters of all NES components is considered to be addressed in future studies.

2.4.3. Model description and input data

2.4.3.1. Prospects on nuclear energy demand for Russian Federation and country partners on collaboration

The Russian Federation is known for being an advanced country in the nuclear energy field, whether on the industrial or the R&D side. Recently, electricity production in the Russian Federation has practically stabilized. It was 0.2% more in 2015 than in 2014, while consumption in the whole Russian Federation was 0.4% less than in 2014. The balance of production and consumption resulted from the growth in electricity exports.

The NES of the Russian Federation consists of 10 NPPs in commercial operation with 35 reactor units totalling about 27 GW(e) of installed capacity. Eighteen power units utilize the WWER reactors, 11 units use the RBMK, 4 units use the graphite-steam power reactors (EGP) and 2 units have the BN reactors. Nuclear power plants were the only power plants, which increased electricity generation in 2015. They produced 195 billion kW·h, which is 8.2% more than was produced in the previous year. Nowadays, more than 18% of electricity in the country comes from the nuclear power.

In accordance with the energy strategy of the Russian Federation [37], the installed nuclear capacities have to be increased by 1.7 times by 2035 and reach the share of 21% in electricity generation. Two main options of the reactor fleet deployment are under consideration in the roadmap of commissioning/decommissioning of reactor units up to 2035 [38]. The reference scenario is based on the WWER reactor fleet operating in a once-through NFC, while another scenario is based on a two-component system of WWER and BN reactors operating in a partly closed NFC.

Intensive RD&D on innovative nuclear energy platforms based on the closed nuclear fuel cycle with fast reactors and construction of some installations of the closed cycle is under way in the country. However, these efforts and related investments can be economically viable only in the case of high demand for nuclear energy and with commissioning of significant new nuclear capacities. In these circumstances, extension of the scale of the nuclear energy business by multilateral and multinational cooperation becomes a crucial point for the Russian Federation as a nuclear energy technology advocate with a moderate programme of domestic reactor capacity growth.

The Russian Federation is an active participant in international cooperation and has plans for expansion of its activities. The State Atomic Energy Corporation "Rosatom" (ROSATOM) works on a global scale to provide comprehensive nuclear services that range from uranium enrichment to nuclear waste treatment [39]. In 2015, ROSATOM continued to expand its portfolio of overseas orders. At year end, the 10-year order portfolio amounted to US $110.3 billion, while the project portfolio comprised 34 power units for NPPs worldwide.

ROSATOM provides 8% of uranium mined worldwide, 17% of fresh nuclear fuel production, 22% of uranium conversion services and 36% of enrichment services. In 2007, after an initiative of the Russian Federation, the International Uranium Enrichment Center was founded in Angarsk, Siberia, under the guidance of the IAEA. The Russian Federation also has experience in the fuel ‘take back’ option implementation where the leased fuel, once removed from the reactor and cooled down, is returned to the country of origin. Thus, international cooperation has become an integral and important part of the activities in the nuclear energy complex of the Russian Federation. All preconditions exist in the country for further expanding the NFC services provided by the Russian Federation, especially those services in the back end of the NFC.

International cooperation in the back end of the NFC raises many issues and requires essential enhancement of capabilities in the modelling tools used by the partners. The countries which do not plan to recycle SNF within the domestic nuclear power infrastructure need to model and compare the alternative long term strategies of SNF management, taking into account internal possibilities and external services. The countries implementing the strategies of used fuel recycling need to model and assess any additional load on their NFC infrastructure associated with taking back SNF from abroad. Countries need to analyze the problems of transboundary transfer of nuclear fuel, including related liabilities, and estimate economic implications of different scenario realization.

In the current case study, a few simple exemplary scenarios of the multinational collaboration on fresh and spent fuel management are analyzed. These scenarios were developed in the INPRO collaborative project SYNERGIES [4] by participants from Armenia, the Russian Federation and Ukraine, for methodological purposes. Therefore, the scenarios should not be considered as modelling of historical or current factual examples of cooperation. In order to avoid ambiguities in this regard, the countries in the case study are referred to as ‘Holder’, ‘User1’, ‘User2’ and ‘Newcomer’ (Fig. 60). At the same time, some typical features of the prototype countries are taken into account in the proposed scenarios with the aim of reflecting a plausible configuration of the multilateral NES.

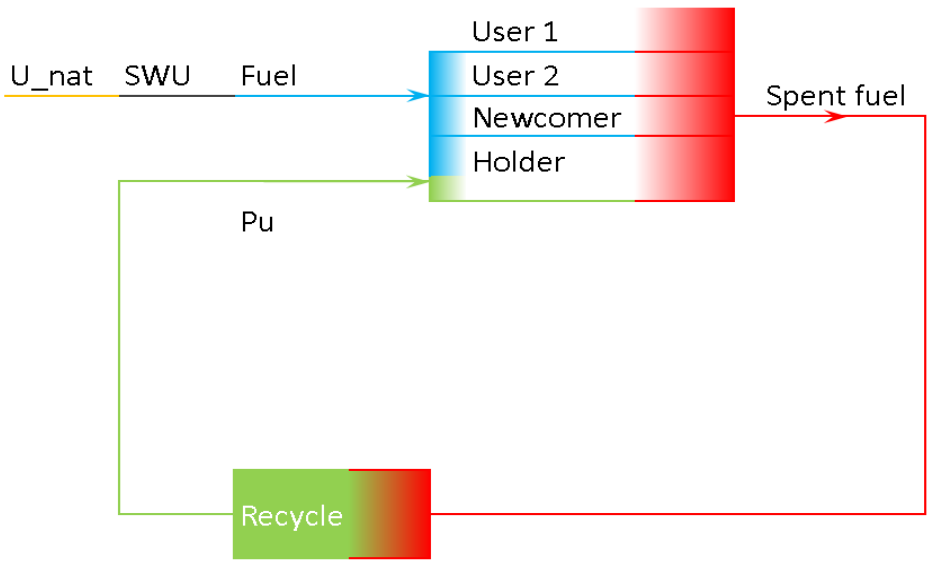


FIG. 60. Simplified scheme of fuel flows in a regional synergistic model.

Some key elements of the Russian Federation's nuclear power development strategy were used in the model building of a 'Holder'. Inclusion of fast reactors in the NES, which is a critical point for the Russian nuclear energy programme, has also to be an essential component of each NES of a 'Holder' implementing the 'take back' option. Indeed, in the case of having an opportunity to multi-recycle nuclear fuel in fast reactors, the 'Holder' can take back used fuel from foreign thermal reactors as a resource indefinitely in a 'take back and forget' option. In the case of non-availability of multi-recycling technologies, SNF from abroad must be classified as high-level waste to be allowed only for reprocessing and returning of all related waste to the country of origin. Thus, the fleet of sodium cooled fast reactors is included in the case study as part of the two component nuclear power of the 'Holder' for providing a multi-recycling scheme.

To define a specific model in the case study, it was assumed that an experienced nuclear power user ('User1') addressed the 'Holder' to reprocess a part of its used fuel while 'User2' and a 'Newcomer' receive a full range of services on the NFC from the 'Holder'. Thus, potential users of a different kind are present in the model of a multinational NES.

2.4.3.2. Reactor and fuel input data

The following types of reactors were considered in the case study:

— RBMK: thermal reactor of uranium–graphite type;

— WWER-440 and WWER-1000: thermal reactors of PWR type;

— AWWER: advanced WWER;

— BN: SFR with a breeding ratio (BR) of 1.14.

All thermal reactors (RBMK, WWER-440, WWER, AWWER) consume UOX fuel, and the fast BN reactor consumes MOX fuel. The U-235 content in natural uranium is 0.007114. The plutonium extracted from the used fuel of the WWER-440, WWER, AWWER and BN reactors is assumed to be reused. RBMK spent fuel is assumed not to be reprocessed but to be kept in temporary storage.

The input data on reactors and associated fuel cycles were prepared in the MESSAGE format using physical and technical calculations carried out by the designers of relevant projects. Technical characteristics necessary for simulation of the cases are shown in Table 31.

Economic data of the reactor and fuel cycle service facilities were based on the data from Refs [2, 38] and are given in Table 30. The discount rate for the case study was 5%.

TABLE 30. REACTOR AND FUEL CYCLE COSTS

Item	Unit	RBMK	WWER440	WWER	AWWER	BN
Investment cost	US $/kW(e)	-	-	-	3500	3500
Fixed O&M cost	US $/kW·year	50	50	50	50	50
Variable O&M cost	US $/kW·year	4	4	4	4	4
Conversion	US $/kg U	17	17	17	17	-
Enrichment	US $/kg SWU	100	100	100	100	-
Fuel fabrication	US $/kg HM	510	510	510	510	1790[a]
Reprocessing cost	US $/kg HM	-	400	400	400	770
SF storage	US $/kg HM·year	10	10	10	10	10
Pu storage	US $/kg HM·year	-	-	-	-	2000

[a] Includes core and blankets fuel costs with the corresponding proportions.

TABLE 31. TECHNICAL REACTOR AND FUEL CYCLE DATA FOR RBMK, WWER-440, WWER, AWWER, BN

Item	Unit	RBMK	WWER-440	WWER	AWWER	BN
Nuclear capacity	MW(e)	1000	440	1000	1000	1200
Annual fresh fuel loading	t HM	30.9	12.0	18.7	24.0	16.3[a]
First loading	t HM	155.9	41.0	65.4	65.4	106.2[a]
Natural uranium (first loading)	t HM/t HM	4.69	3.70	4.38	3.92	-
Enriched uranium (annual)	t HM/t HM	4.69	6.60	7.92	7.92	-
SWU (first loading)	t SWU/t HM	3.43	2.41	3.16	2.65	-
SWU (annual)	t SWU/t HM	3.43	5.6	7.13	7.13	-
Depleted uranium (first loading)	t HM/t HM	3.06	3.06	3.06	3.06	-0.93
Depleted uranium (annual)	t HM/t HM	6.81	6.81	6.81	6.81	-0.91
Plutonium in spent fuel	share	0.01	0.01	0.01	0.01	0.11
Cooling time	year	3	3	3	3	4
Construction time	year	-	-	-	5	5
Lifetime	year	45	45	45	60	60

[a] Includes core, axial blanket, radial blanket.

2.4.3.3. *Assumptions, scenarios and boundary conditions*

The following assumptions were adopted in order to calculate the material flows in the model:

(a) Base year is 2010.

(b) For simplicity, all process losses in the chain are assumed to be zero.

(c) Reported period is 2011–2080. However, the modelling horizon was extended to 2011–2130 to take into account edge effects with linear interpolation on the total installed capacity.

(d) The mathematical model takes into account historical capacities for RBMK, WWER-440, WWER up to 2011 and the initial volumes for the associated thermal reactor storages (see Fig. 61 and Table 32).

(e) RBMK spent fuel is not reprocessed.

(f) New RBMK, WWER-440, WWER units will not be commissioned as of 2011 owing to their outdated designs. Consequently, there are two candidates to cover 'Holder' demand after 2030: AWWER and BN.

TABLE 32. INITIAL VOLUME OF REACTOR SPENT FUEL STORAGE

Reactor type	**RBMK**	**WWER-440**	**WWER**	**AWWER**	**BN**
Spent fuel storage, initial volume (t HM)	9379.77	235	3293.34	0	0

Specific features of the international partners are:

- The 'Holder' country operates RBMK, WWER-440, WWER, AWWER, BN plants.
- The 'Holder' country has a wide range of the front end and back end fuel cycle facilities (including UOX and MOX fuel reprocessing).
- The 'Holder' provides front end and back end fuel cycle services to 'User2' and to 'Newcomer'.
- The 'User1' may deliver SNF from WWER units to the 'Holder' for reprocessing.
- 'User2' and 'Newcomer' operate the AWWER reactor design of the 'Holder'. They deliver the spent fuel of the AWWER to the 'Holder' country for reprocessing. The AWWER reactor of 'User2' is scheduled to be commissioned in 2020 (1000 MW(e) capacity). The first reactor unit of 'Newcomer' is to be commissioned in 2018 (1200 MW(e) capacity), the second is to be commissioned in 2020 (1200 MW(e) capacity).

There are two parts in the demand data (Table 33). The first part, up to 2030, is based on the Russian Federation's strategy in energy sector development [37]. The second part, 2031–2100, refers to experts' evaluation [40]. The annual demand increases by nearly 2 GW(e) from 2011 to 2050, by 2.5 GW(e) for 2051–2070 and, on average, by 1 GW(e) for 2071–2090.

TABLE 33. NUCLEAR ELECTRICITY DEMAND FOR 'HOLDER' UP TO 2100

Year	2011	2030	2050	2070	2090	2100
Nuclear capacity (GW(e))	24	58	100	152	173	192

There is obligatory commissioning of reactor units according to the schedule up to 2030. For example, a fast reactor is to be introduced in 2018 with the capacity 1200 MW(e). There is a 600 MW(e) annual fast reactor capacity increase in the years between 2020 and 2030.

After 2030, the model has more flexibility to commission the most economically attractive technology and fast reactors are introduced according to plutonium availability. Figure 61 shows the general assumptions made with respect to time frames.

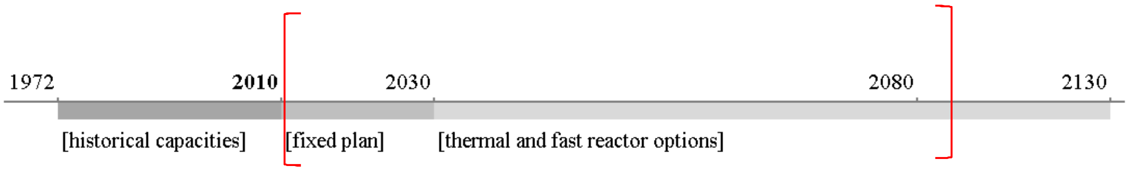


FIG. 61. Case study report period for a mathematical model.

The current study considers two scenarios:

(1) The scenario in which 'Holder' does not take the SNF from 'User1' for reprocessing. Hereafter this scenario will be referred to as the 'W/O Export_U1' scenario.

This scenario contains two variants. The main variant assumes that fast reactors are introduced according to plutonium availability. The complementary NES variant of 'W/O Export_U1' scenario contains a low SFR share. This variant is to demonstrate front-end and back-end characteristics of the NES in the case where SFR commissioning would be much less than in the main variant with high share of SFRs. It includes the SFRs' share of 15% by 2050, rising to 50% by 2100 (to be referred to as low share of SFR).

(2) The scenario of collaboration of the 'Holder' with 'User1' consisting of reprocessing of 'User1' SNF at the holder's facilities. Hereafter, this scenario will be referred to as the 'W Export_U1' scenario.

Both of these scenarios assume collaboration of the 'Holder' with 'User2' and 'Newcomer'. The collaboration means delivery of 'User1', 'User2' and 'Newcomer' spent fuel for recycling on 'Holder' facilities. The 'Holder' also provides front end fuel cycle service to 'User2' and 'Newcomer'.

The strategy referred to in Table 33 was developed in the period of the country's economic recovery. Nowadays, the strategy is being revised. With economic development and growth of electricity demand having slowed down, the planned rate of energy capacities' commissioning will probably be reduced. It also relates to SFR introduction into the Russian Federation's nuclear energy system. In the drafts of the roadmap for the nuclear capacities commissioning/decommissioning currently under consideration [38], the time of fast BN-1200 reactor commissioning is to be postponed until 2025 and the number of BN-1200 units to be commissioned by 2035 is reduced to five units. Nevertheless, it was decided not to change, in the given case study, the key scenario assumptions made for the SYNERGIES study.

It should be noted that in consideration of the slowing down of domestic nuclear energy demand, mutually beneficial 'win–win' collaborations with other countries which need energy become an even more important driver of the national nuclear industry.

Uranium deposits [41] have been classified into different categories and volumes as shown in the Table 34.

TABLE 34. NATURAL URANIUM GRADES AND RESOURCES IN THE RUSSIAN FEDERATION

	Unit	Grade a	Grade b	Grade c	Grade d
Cost	US $/kg	80	130	260	300
Resource	tU	172 900	314 300	191 800	772 000

Grade 'a' represents reasonably assured conventional resources at the price of US $80/kg. Grade 'b' is inferred to conventional resources. As of 1 January 2011, the prognosticated resources (grade 'c') amounted to 191 800 t U and the speculative resources (grade 'd') totalled about 772 000 t U.

Plutonium is considered in the study as a fuel resource. The initial quantity of the stored Pu that may be used for MOX fuel production is assumed to be 13 t.

Figure 62 shows the UOX fuel reprocessing capacities of the 'Holder'. The model assumptions on UOX fuel reprocessing capacities were made by using an example of the programme for SNF management infrastructure creation up to 2030, which was approved in the Russian Federation in 2011 [38]. The capacities shown in Fig. 62 relate to three reprocessing plants of which the first one has been operational since 1970. The capacities' inputs are shown in Fig. 62. The operational life for reprocessing facilities is 60 years.

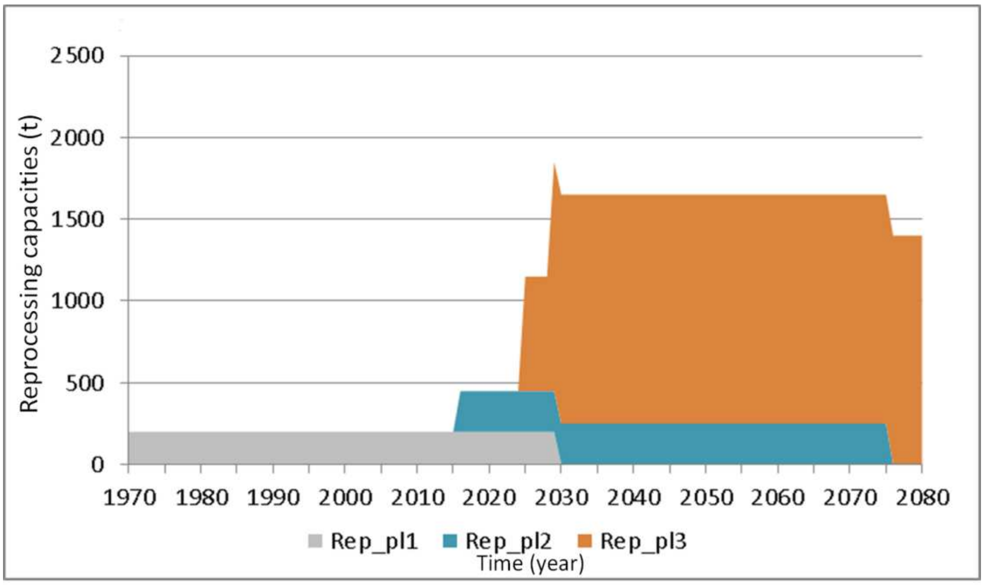


FIG. 62. UOX fuel reprocessing capacities of the 'Holder'.

Reprocessing capacity for the fast reactor nuclear fuel cycle in the model is not limited. All BN spent fuel is assumed to be reprocessed. Considerations for the introduction of reprocessing for the SNF of SFRs, along with other issues which have been raised by the study, need further investigation.

Figure 63 shows 'User1' annual spent fuel delivery to the 'Holder' reprocessing plants developed in the SYNERGIES project. The form of the graph and peaks correspond to the reload and final discharge of SNF from reactors in the user country.

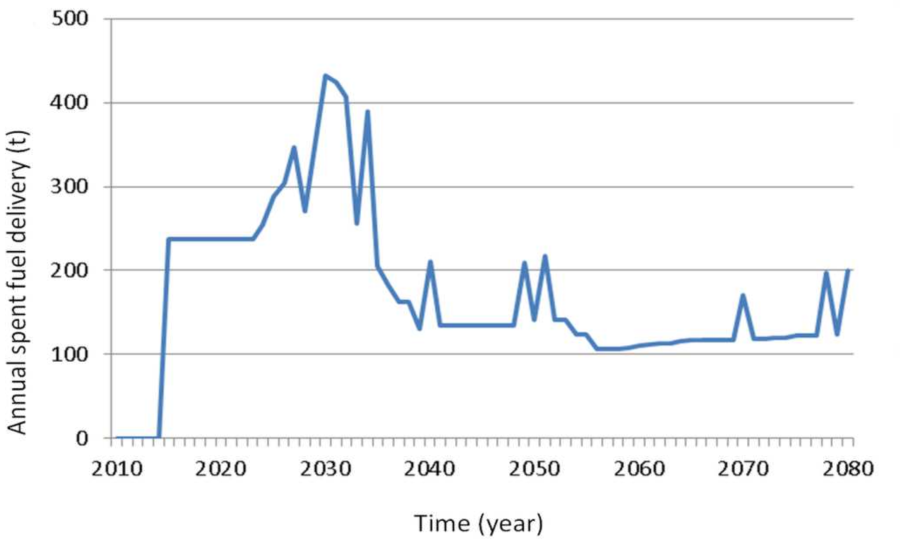


FIG. 63. 'User 1' annual spent fuel delivering to the 'Holder' reprocessing plants for reprocessing.

2.4.3.4. Fuel cycle options and schemes

A fuel cycle scheme for the NES arrangement used in the case study is presented in Fig. 64. The scheme has four main parts: (i) resources (includes natural uranium resources available in the mathematical model), (ii) front end (includes all main industrial elements from uranium conversion to fresh fuel fabrication), (iii) reactor has thermal reactors on the top and SFRs at the bottom of the scheme, and (iv) cooling interim storage and reprocessing facilities.

2.4.3.5. Metrics (indicators) for scenario analysis

The following indicators from the list of key indicators proposed in Ref. [3] were calculated for 'Holder' scenario, 'W/O Export_U1' and 'W Export_U1':

(a) Nuclear capacity according to reactor type;

(b) Cumulative demand for natural uranium;

(c) Separative work units;

(d) Fresh fuel requirements;

(e) Accumulation of spent fuel;

(f) Fuel reprocessing capacity;

(g) Accumulation of plutonium.

The results of the calculation and analysis performed for some of these indicators are discussed below.

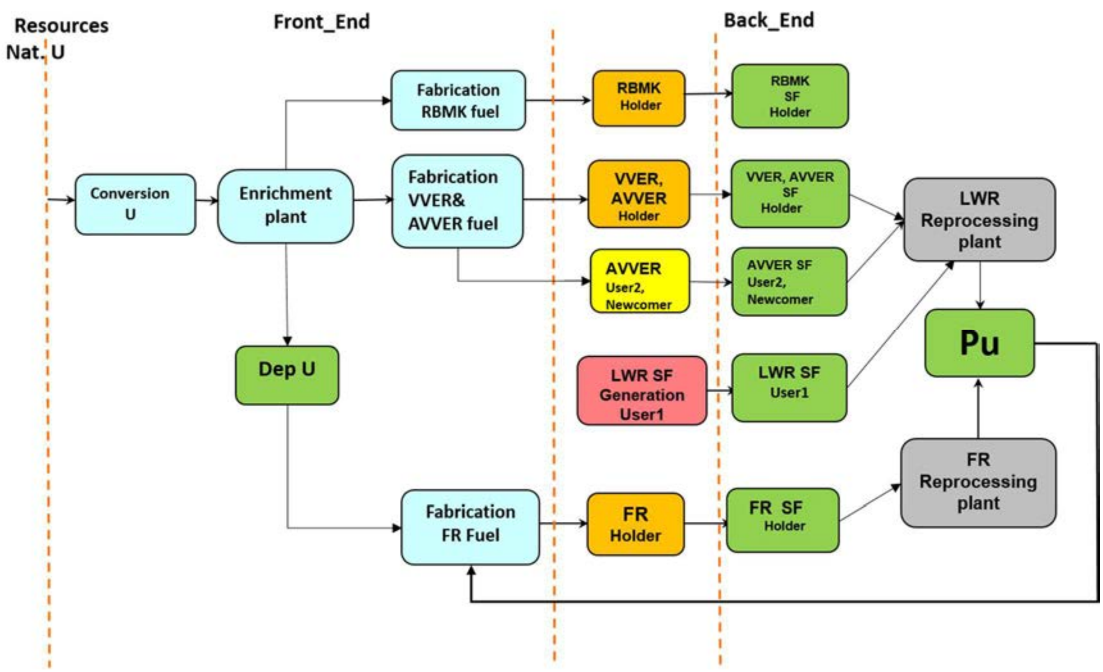


FIG. 64. Fuel cycle scheme of NES arrangement.

2.4.4. Modelling of selected NES elements with MESSAGE

2.4.4.1. Selected MESSAGE pages illustrating modelling of WWER, AWWER, RBMK, SFR and closed fuel cycle

Usually, simulation of material flows between countries using the MESSAGE tool involves the creation of a multiregional case. However, in the given case, as Section 3.2 of this report describes, nuclear power systems of ‘User1’ country, ‘User2’ country and the ‘Newcomer’ country have been modelled before the overall system simulation and information on the possible services from an external market for their national NES requirements was ready for use. This made it possible to present the main aspects of the initial stage of multilateral cooperation within a single region MESSAGE case, which has taken into account all essential aspects of the task.

A simplified scheme of the fuel flows in the case study is shown in Fig. 64. The scheme represents the nuclear energy system of the multinational NES: natural uranium resources; installations for conversion and enrichment; plants for fuel production for all types of reactor in the system; plants with RBMK, PWR/APWR, SFR reactor units; storage of nuclear fuel; and plants for reprocessing LWR and SFR spent nuclear fuel.

As it is shown in the scheme, plutonium is recycled and used for the production of the MOX FR fuel. The use of other products of reprocessing was not considered in this study. According to the assumptions accepted above, fuel for the LWRs of the ‘Holder’, ‘User2’ and ‘Newcomer’ is produced by fabrication plants of the ‘Holder’ country. To take into account the total consumption of natural uranium and SWU, reactors of the ‘Holder’, ‘User2’ and ‘Newcomer’ countries were included in the scheme. Individual energy forms at the ‘Demands’ level were specified for each country.

Supply of spent nuclear fuel from the ‘User1’ country to the ‘Holder’ country was modelled by the chain consisting of components producing and storing spent nuclear fuel. SNF of ‘Holder’, ‘User1’, ‘User2’ and ‘Newcomer’ is reprocessed at the radiochemical plants of the ‘Holder’ country.

Some features for modelling individual elements of the calculation scheme are described below and illustrated by screenshots of the MESSAGE interface.

Data on commissioning reactors in the ‘Holder’ country are prepared on the basis planned targets of energy sector development in the Russian Federation and also on the latest publication of the scenarios for deployment of nuclear power in the country [38]. To avoid inaccuracies associated with the use of the average value of plant factor for power units in the translation unit of energy, all energy forms at the ‘Demands’ level were set in MW, i.e. expressed in terms of the required capacity, rather than the required energy, as is usually done in MESSAGE modelling (Fig. 65). The plant factor for MESSAGE capacity data for all reactor technologies is equal to one, and the plant factor typical for each type of reactor was taken into account in the calculation of the first load and annual reloads.

The simplified scheme of material flows (Fig. 64) shows the aggregated chain of nuclear material flows for RBMK and PWR/APWR reactor types prior to the nuclear fuel production step. In the MESSAGE case, an individual mass flow chain is used for each of these reactor types to describe all the main steps of nuclear fuel preparation (conversion, enrichment, production) (Fig. 66).

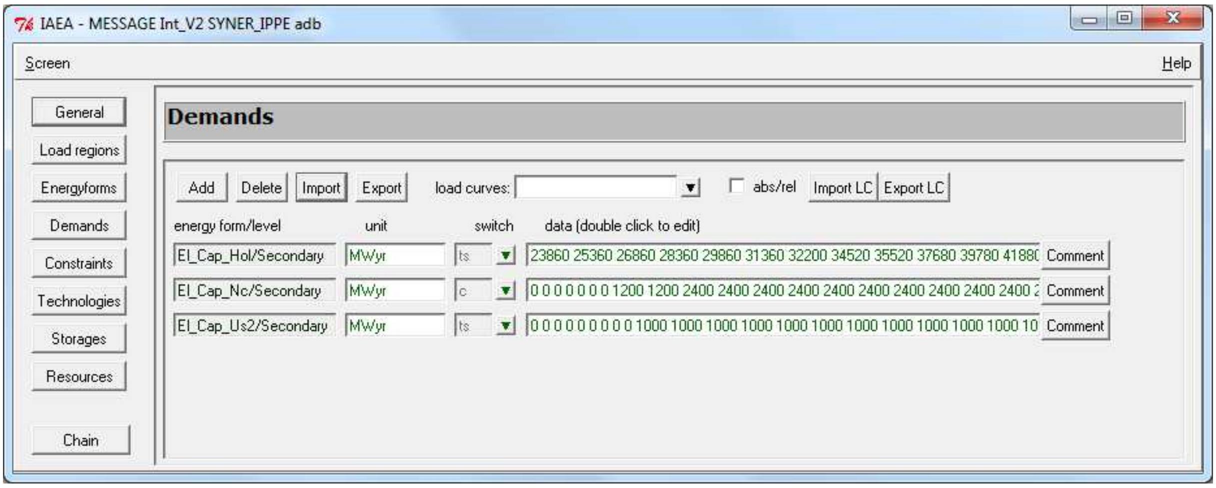


FIG. 65. Country demand modelling.

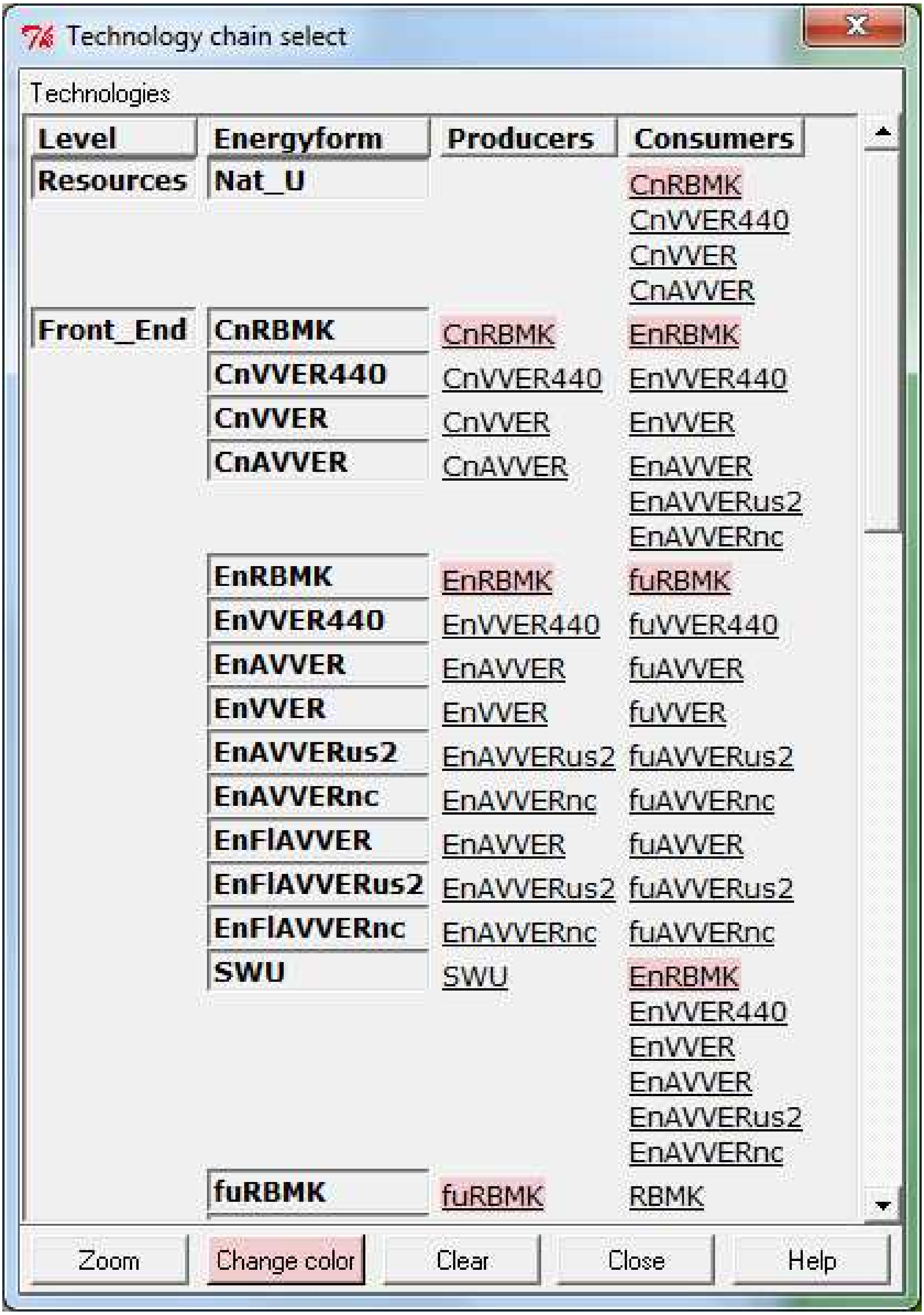


FIG. 66. Front end part, technology chain.

Availability of natural uranium for the fabrication of fuel for NES reactors was assumed in this case study to be limited by the 'Holder' uranium resources. Disparity in enrichment level of the first core and annual reload fuels was taken into consideration for more precise calculation of natural uranium consumption. Two alternatives were used in enrichment technology and fuel fabrication technology when modelling the AWWER reactor front end chain to represent the disparity. Figures 67 and 68 show input data for MESSAGE technology which models two alternative uranium enrichment processes for annual load ('alt h') and first core ('alt l') fuel fabrication. As discussed, fuel cycle mass flow parameters, including SWU and natural uranium annual requirements and annual depleted uranium production in uranium enrichment processes, were prepared in MESSAGE format and based on data received with the use of reactor codes (see Table 31).

As discussed, a closed NFC is under consideration; therefore, the accuracy of the plutonium balance calculation is essential for the case study. The plutonium content in SFR core fuel and SFR annual load fuel is different. This was the reason to model SFR first core fuel fabrication and annual load fuel fabrication with individual technologies. At the same time, averaged SFR nuclear fuel data were used to simplify the MESSAGE case (see Table 31). MESSAGE data for 'activity' of SFR technology are presented in Fig. 69. Fresh fuel is delivered by secondary input. According to the case assumption discussed above, the plant factor of the SFR is equal to one and therefore the annual electricity generation is 1200 MW(e). Annual fresh fuel consumption by the SFR reactor is 16.3 t HM (see Table 31). This gives an annual fresh fuel consumption per unit of electricity output equal to 0.01358 t HM (≈16.3/1200). The same amount of SNF is discharged annually from the reactor.

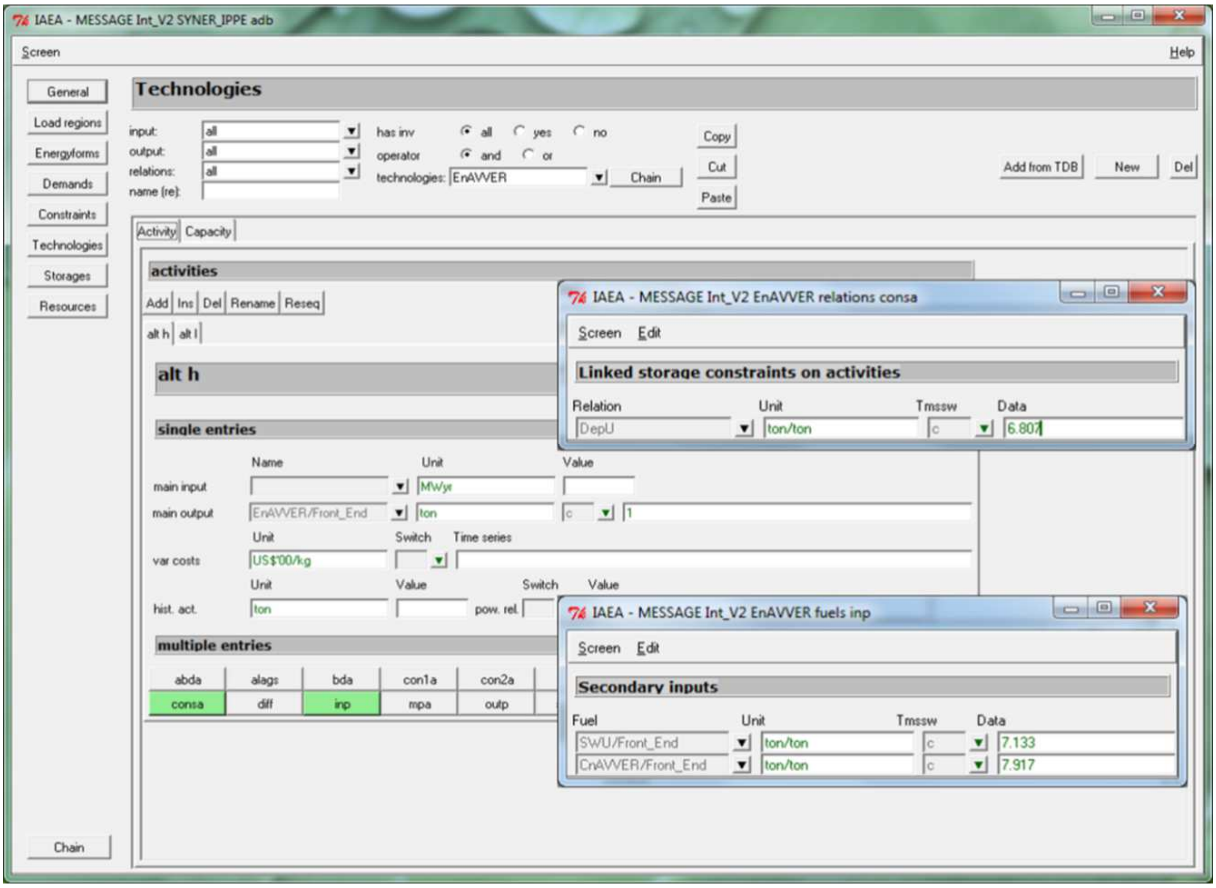


FIG. 67. Modelling of AWWER fuel enrichment ('alt h').

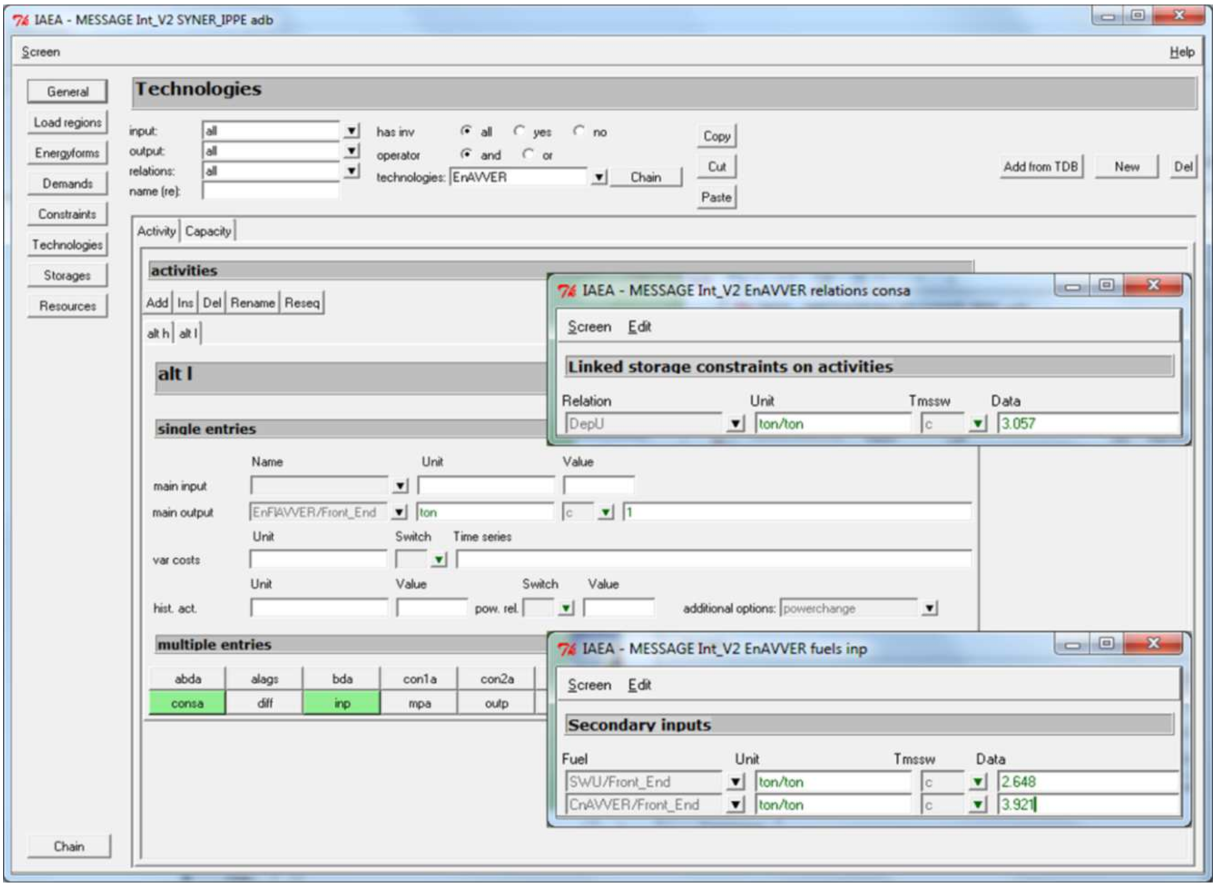


FIG. 68. Modelling AWWER fuel enrichment ('alt l').

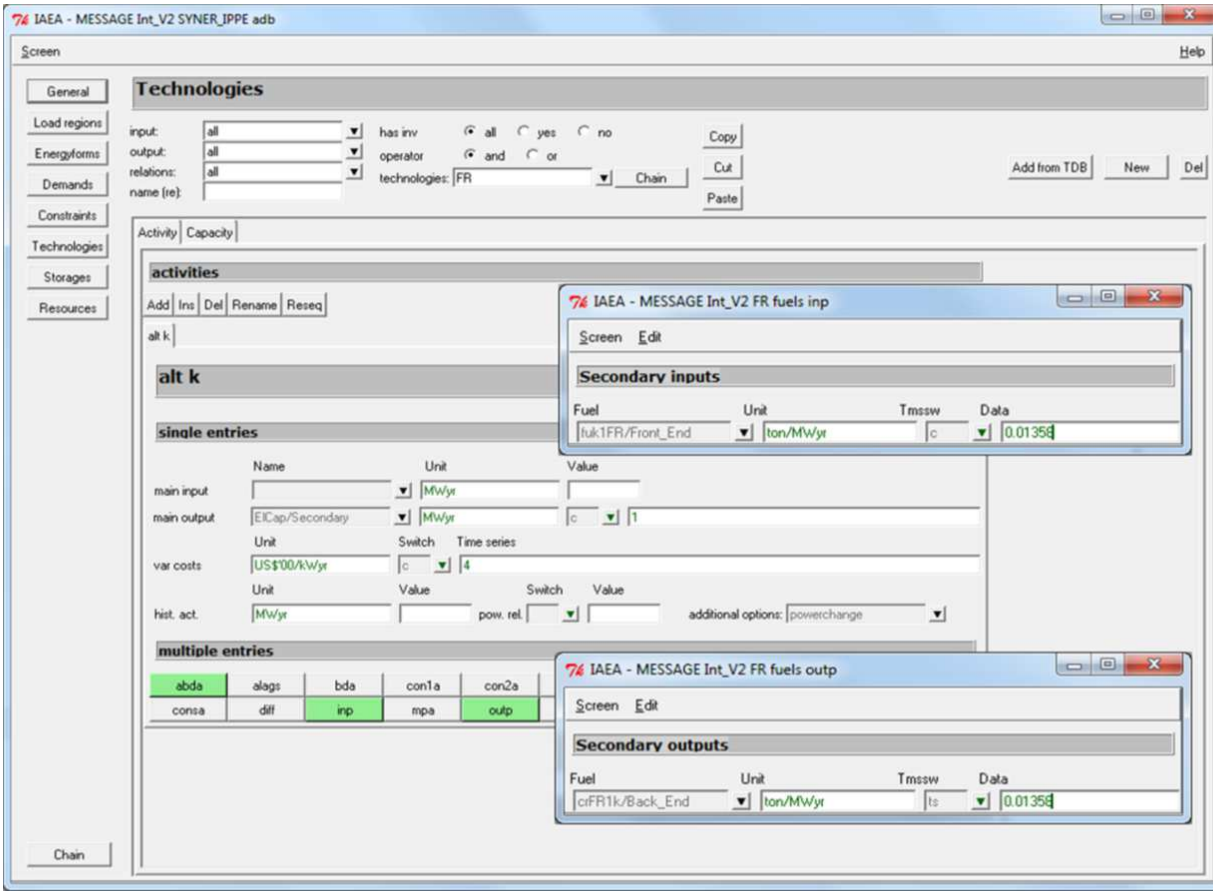


FIG. 69. SFR modelling, 'activity' window.

Figure 70 shows SFR technology 'capacity' data. The initial core loading is 106.2 t HM (see Table 31). Specific value of final core discharge in 'corout' is 0.0885 (= 106.2/1200). Specific value of initial core loading in 'corin' value is one annual reload less, and equal to 0.07492 (= 0.0885 – 0.01358).

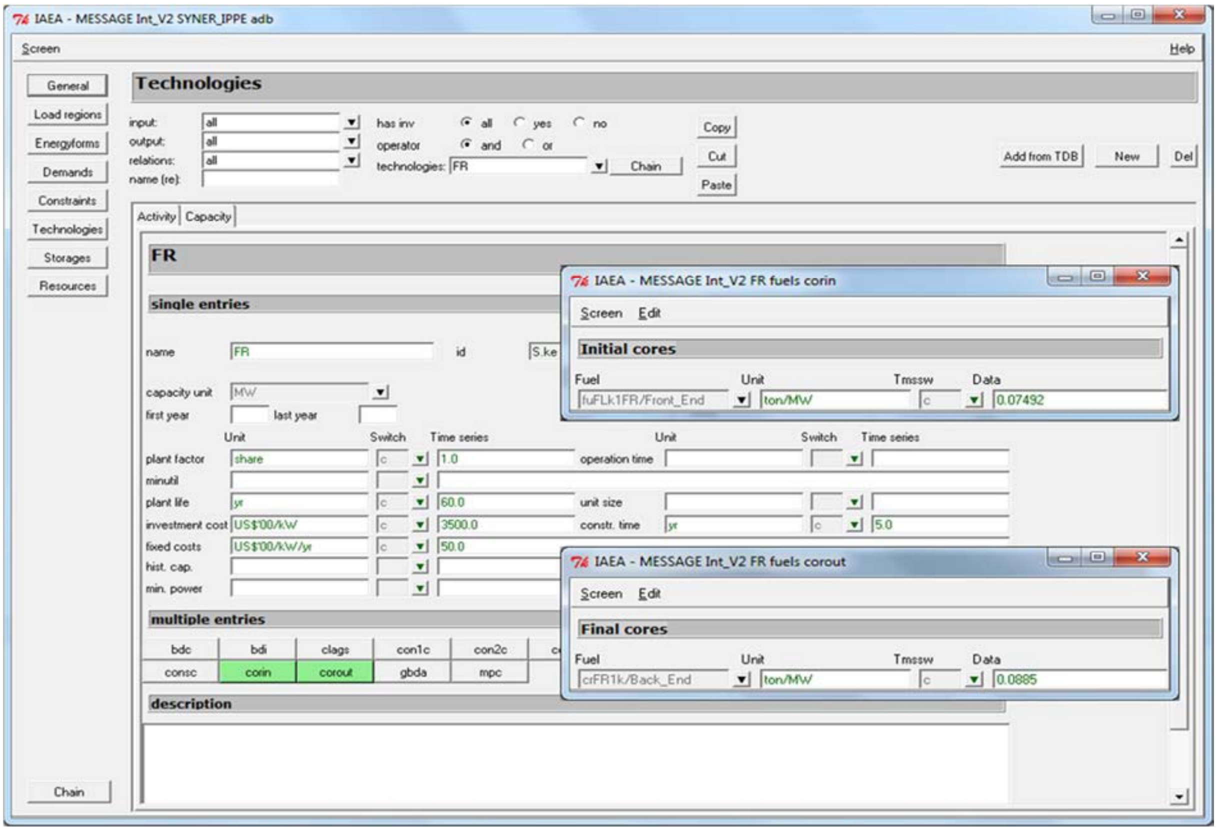


FIG. 70. SFR modelling, 'capacity' window.

SNF delivery from the 'User1' country is modelled with technology fcUs_1 which has no input, and 'generates' planned SNF flow. The input data for fcUs_1 technology are shown in Fig. 71. Graph in 'adba' window presents SNF delivery schedule. As discussed, these are input data provided by 'User1' country in the frame of the SYNERGIES project (see Fig. 63). fcUs_1 technology is connected with a proper storage. SNF accumulated in storage can be reprocessed at the 'Holder' country's UOX reprocessing facility.

SNF fuel accumulated in all the storage facilities of PWR/APWR reactors is available for reprocessing. UOX fuel reprocessing is modelled with ReUOX technology. An alternative is used to model reprocessing of SNF accumulated in each of the six SNF storage facilities: WWER-440_SF, WWER_SF, AWWER_SF (AWWER belongs to the 'Holder's' NES), AWWERus2_SF (AWWER belongs to the 'User2's' NES), AWWERnc_SF (AWWER belongs to the 'Newcomer's' NES) and User_1_SF. Plutonium is the only useful product derived from ReUOX technology which is taken into consideration (Fig. 72). According to the technical characteristics of discharged light water reactor fuel, 0.01 t HM of plutonium is extracted when 1 t HM of SNF is reprocessed (see Table 31).

Another available source of plutonium for FR fuel production is that derived from reprocessing of SNF produced by FR, which is accumulated in FR_SF storage and can be reprocessed at a MOX reprocessing facility of the 'Holder' country. ReFR technology is used to model FR SNF reprocessing. ReFR technology data inputs are presented in Fig. 73. Discharged fuel of FR contains a level of plutonium an order of magnitude greater than the SNF of light water reactors (see Table 31). It was assumed that the FR SNF reprocessing is available on demand.

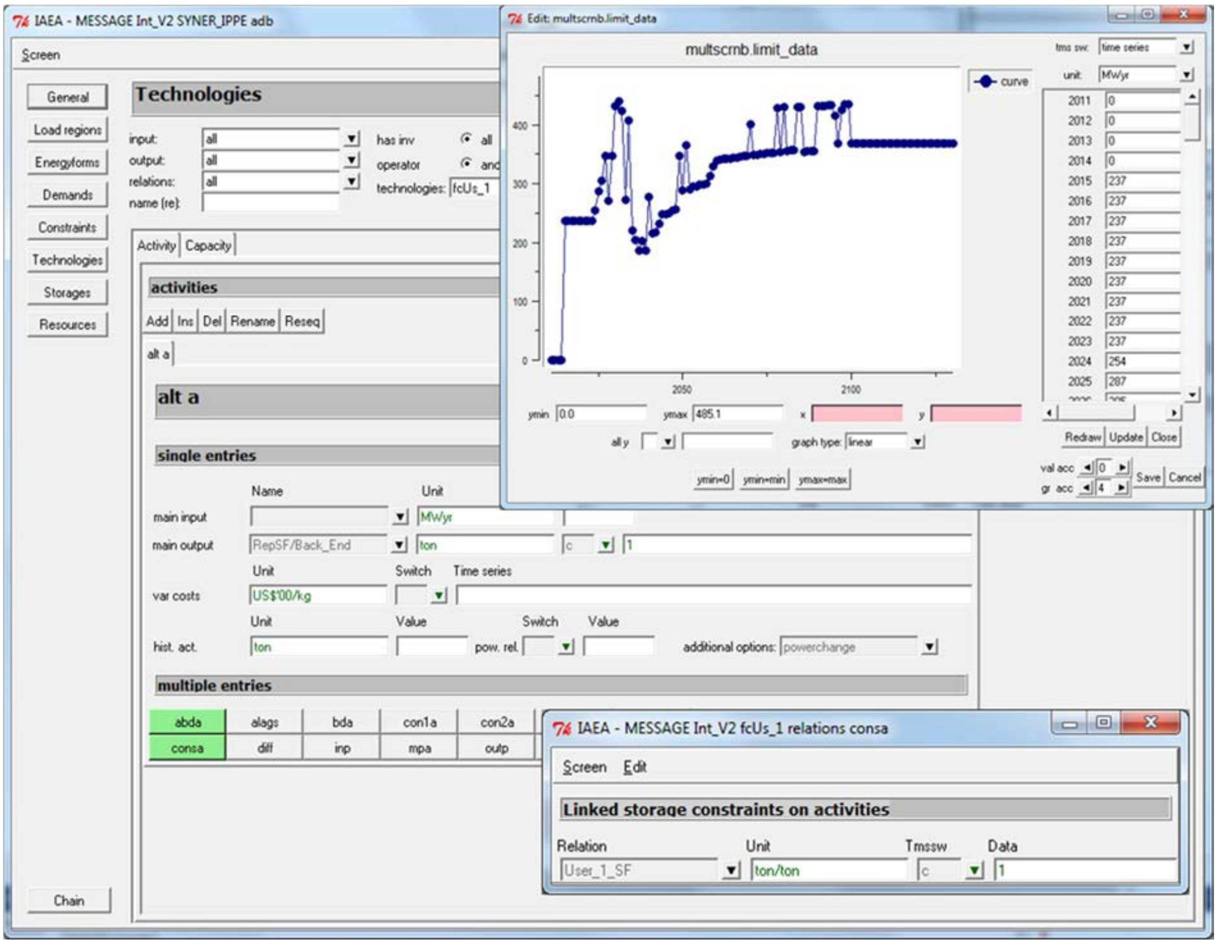


FIG. 71. fcUs_1 technology input data.

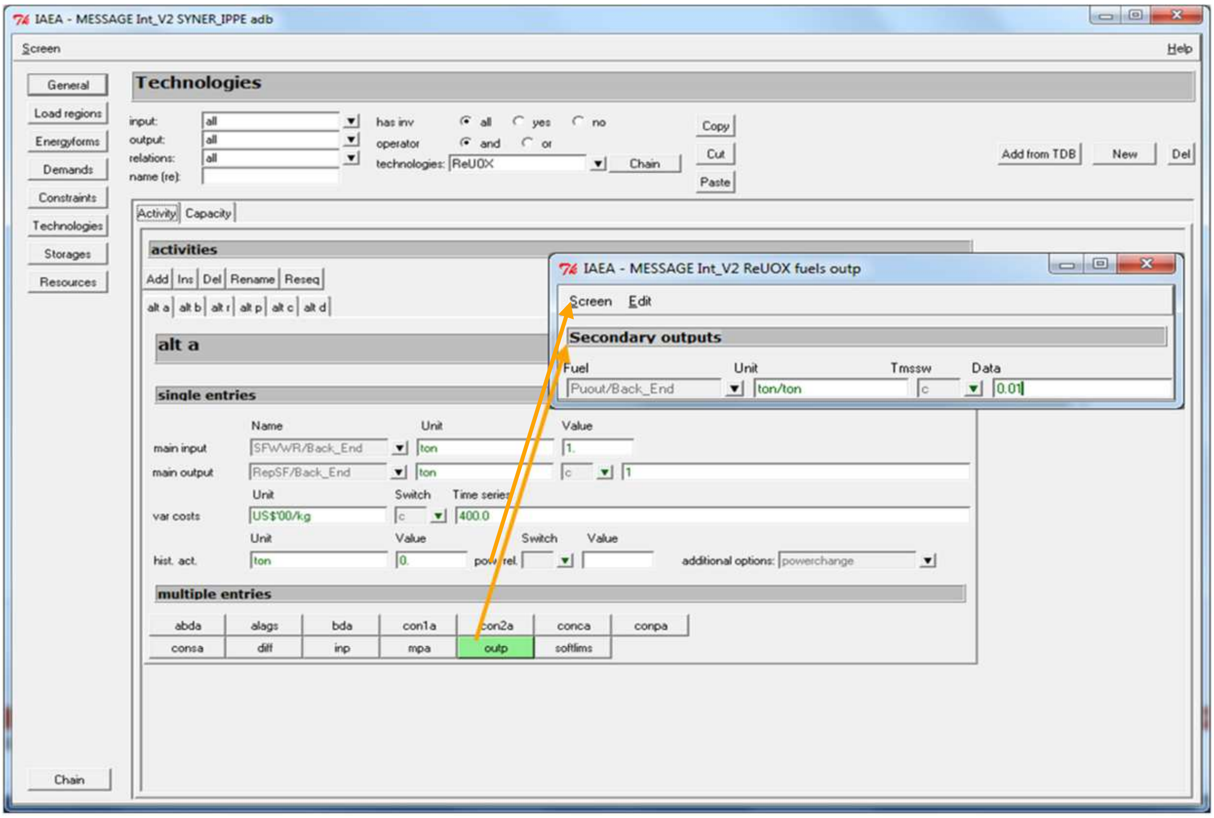


FIG. 72. Modelling UOX spent fuel reprocessing.

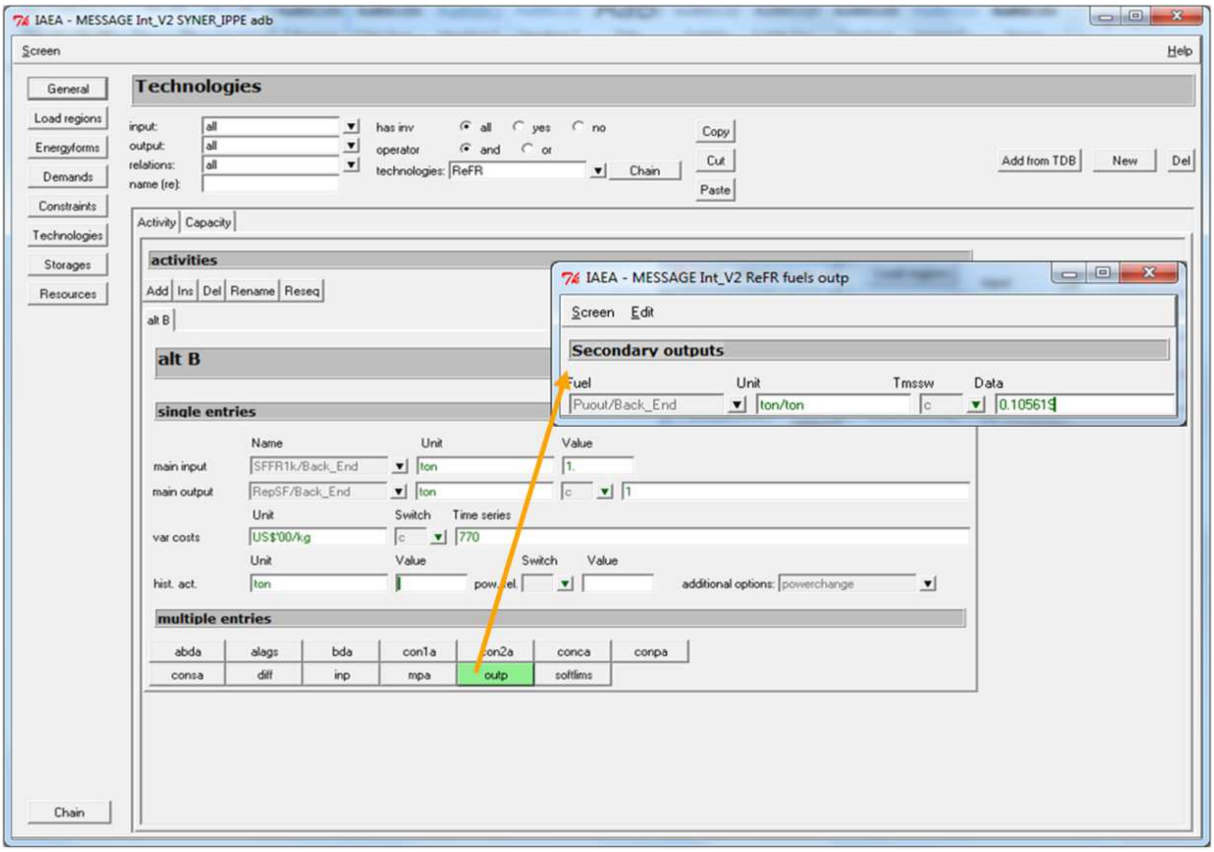


FIG. 73. Modelling MOX spent fuel reprocessing.

2.4.5. Scope of results and findings of the case study

2.4.5.1. Main outputs calculated with MESSAGE

Nuclear capacity by reactor type

The structure of the Russian Federation's nuclear power generating capacities calculated for the main variant assuming a high share of SFR after 2030, as defined by plutonium availability, is shown in Fig. 74. Calculations of the indicators were performed for the following two scenarios: without SNF from 'User1' ('W/O Export_U1') and with SNF from 'User1' ('W Export_U1').

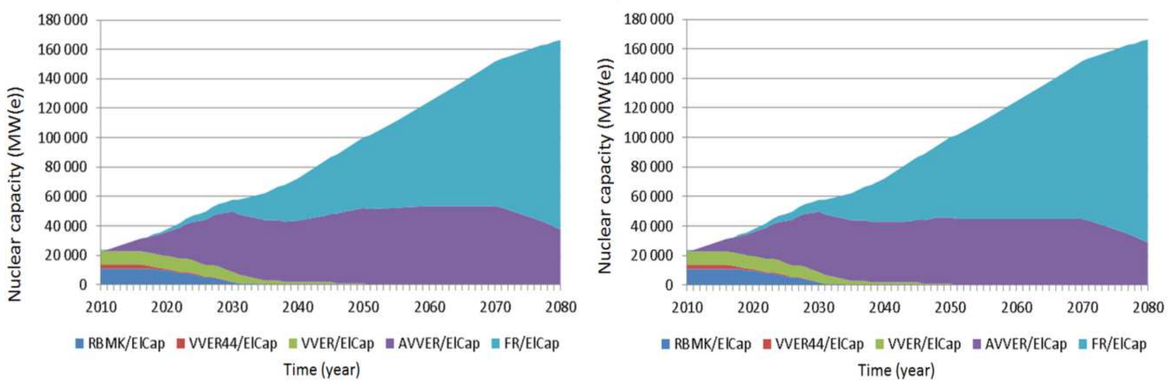


FIG. 74. Structure of 'Holder' nuclear capacity in 'W/O Export_U1' (a) and 'W Export_U1' scenario and (b) high share of FRs.

From Fig. 74 it can be seen that addition of the 'User 1' SNF to the amounts assumed by the 'Holder' does not change significantly the structure of the 'Holder' nuclear power capacity. Nevertheless, the graph in Fig. 75 demonstrates that the share of BN reactors would be increased in this case to about 7%. Thus, within the model assumptions, spent fuel from 'User 1' does not significantly influence the fast reactor capacity growth but should be taken into account by the 'Holder'. Growth of SNF import could make this effect much more considerable.

The structure of the Russian nuclear power generating capacities calculated for the complementary variant with the low share of SFR after 2030 is shown in Fig. 76. It includes SFRs share of 15% by 2050 and 50% by 2100.

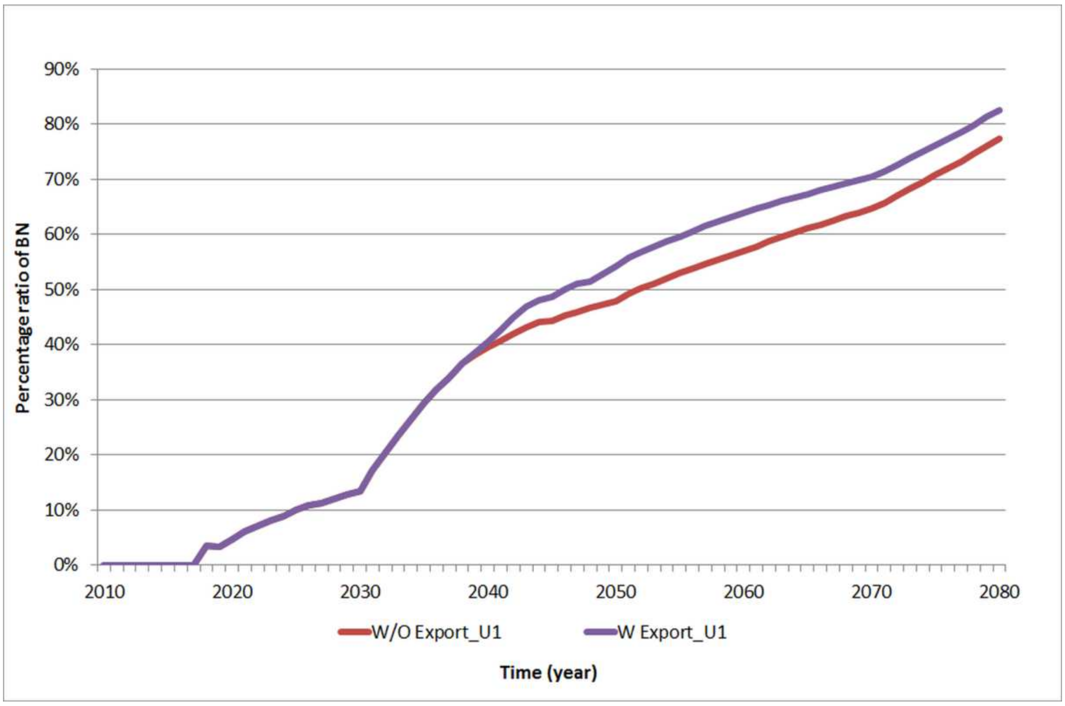


FIG. 75. The percentage ratio of BN in 'W/O Export_U1' and 'W Export_U1' scenario, high share of FRs.

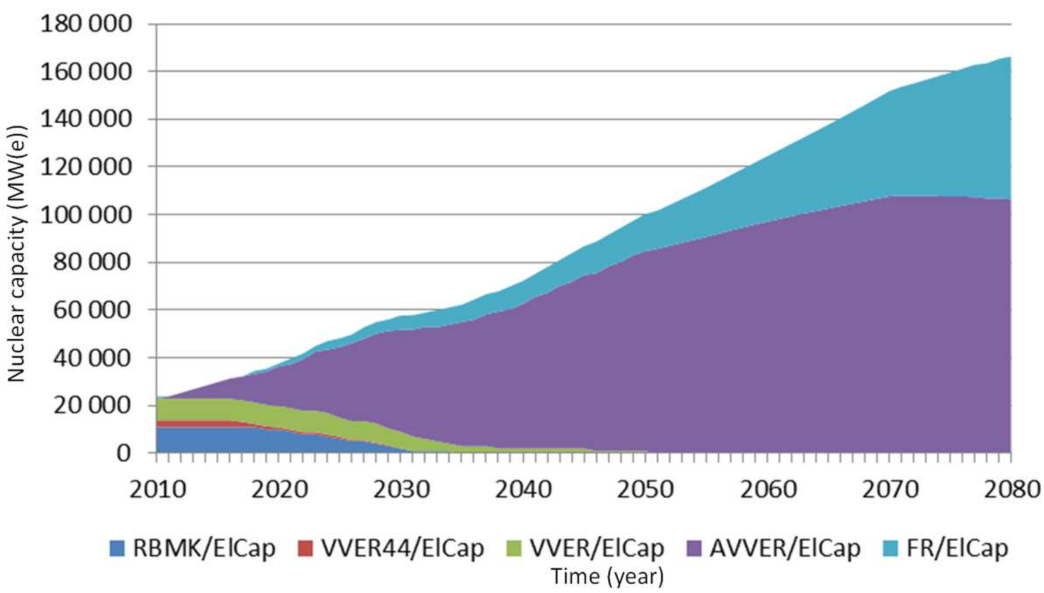


FIG. 76. The percentage ratio of BN in 'W/O Export_U1' scenario, low share of FRs.

Cumulative demand for natural uranium for fast reactors' share

Cumulative natural uranium demand for the scenarios is shown in Fig. 77. Spent nuclear fuel from WWERs and FRs located in the regional group is reprocessed, and plutonium extracted from this SNF is used in the BN fuel. From Fig. 77 it can be seen that the 'W Export_U1' scenario slightly reduces natural U consumption (~60 000 t) as a result of the use of additional plutonium in MOX fuel instead of UOX.

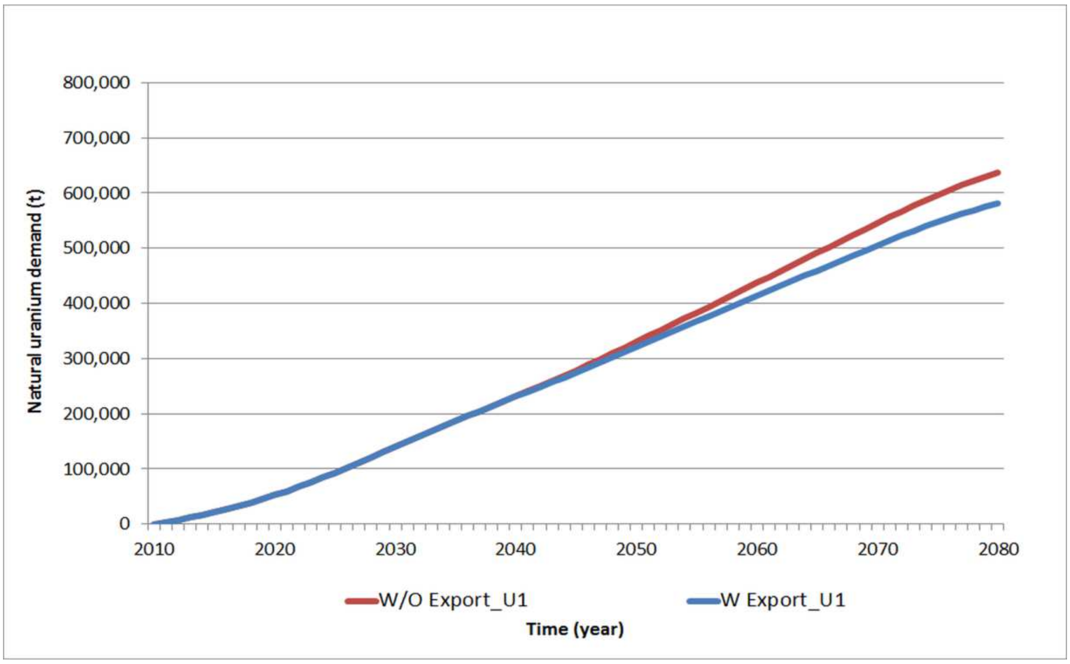


FIG. 77. Natural uranium demand for the 'W/O Export_U1' and 'W Export_U1' scenario, high share of FRs.

No perceptible impact on the natural uranium price in the NES under consideration was identified for these two scenarios. However, it is true only for the scenarios with a high share of fast reactors. In the case of absence or a low share of fast reactors in the nuclear power generating capacities' structure, the growth of natural uranium prices in the recipient country and, hence, the cost of services of fresh fuel fabrication for thermal reactors in the NES can increase quite significantly. Natural uranium demand for the variant of the 'W/O Export_U1' scenario with low share of fast reactors is shown in Fig. 78(a). Natural uranium demand in the variant is about 1 million tons, which is much higher than the ~600 thousand tons demand in the case of a high fast reactor share in the scenario (see Fig. 78(b)).

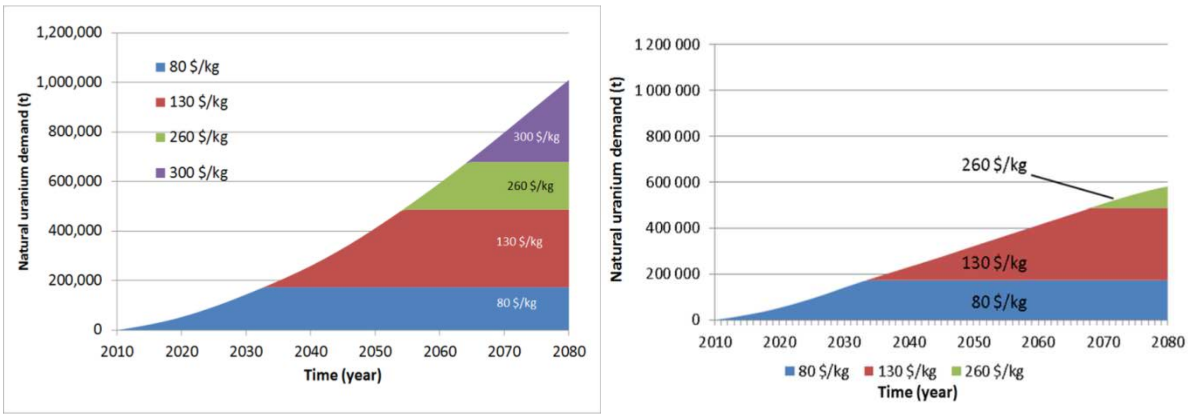


FIG. 78. Cumulative demand for natural uranium and relevant cost for (a) the variant of 'W/O Export_U1' scenario with a low share of fast reactors and (b) for the 'W Export_U1' scenario with a high share of fast reactors.

The increase in natural uranium consumption in the case of low fast reactor share results in exhaustion of low cost uranium deposits and reporting to categories of the more expensive uranium (US $200–300/kg) (Fig. 78(a)). As shown in Fig. 78(b), in the case of high fast reactor share in the recipient country the partners of regional cooperation can benefit from the use of cheap natural uranium (US $80–130/kg) because of the utilization of more plutonium in fuels instead of uranium in the system with a high share of fast reactors.

In the case under consideration, the level of cooperation in the back end of the NFC is rather low. Therefore, the spent fuel export from abroad (‘W Export_U1’ scenario) does not unduly influence the cost of natural uranium compared with the scenario without spent fuel export (‘W/O Export_U1’). The effect of a high share of fast reactors versus a low share is much more significant in itself. However, growth of SNF exports to the technology ‘Holder’ from different users may be significant motivation for increasing the share of fast reactors and will eventually result in a perceptible impact on the uranium cost.

Separative work units (SWU)

Figures 79(a) and (b) below illustrate the demand for enrichment services for cases examined in the study. These figures represent demand for enrichment services for the variants of the ‘Holder’ nuclear power structure with low and high share of fast reactors. The expected effect of demand reduction for enrichment services during transition to a higher share of fast reactors is observed. As it can be seen from Fig. 79(b), regional cooperation would enhance the reduction effect in enrichment services.

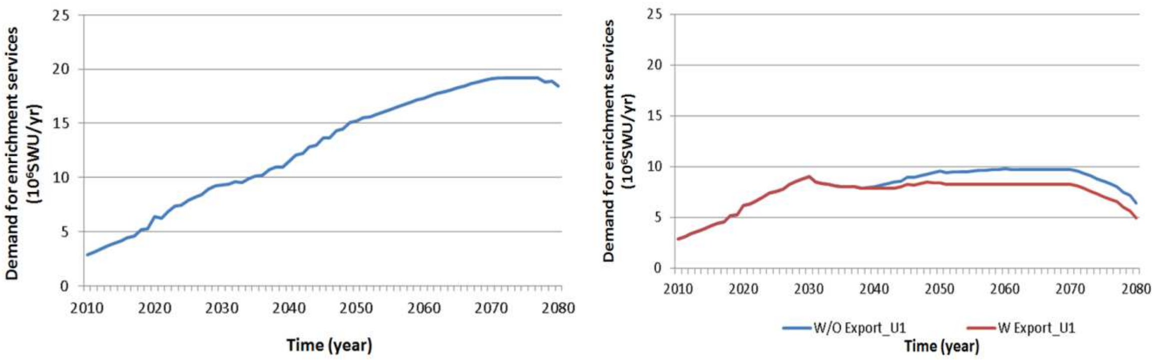


FIG. 79. Demand for enrichment services for the variants of ‘Holder’ nuclear power structure with low (a) and high (b) share of fast reactors for scenarios without and with SNF from ‘User1’ respectively.

Management of SNF and plutonium

Figures 80(a) and (b) demonstrate that accumulation of SNF in a country, which receives this fuel from abroad, is very sensitive to the ratio of thermal and fast reactors in its NES. There is a trend to significant growth of accumulation of SNF in the storage facilities of ‘Holder’ in the variant with a low share of fast reactors (see Fig. 80(a)). The contribution of SNF supply from abroad in this variant is quite perceptible.

In the variant with a high share of fast reactors, plutonium from the WWER SNF of ‘Holder’ and ‘User1’ could be used by 2050 (see Fig. 80(b)). As mentioned above, at present there are no plans in the 'Holder' country to reprocess SNF from RBMK reactors (green area in the figures).

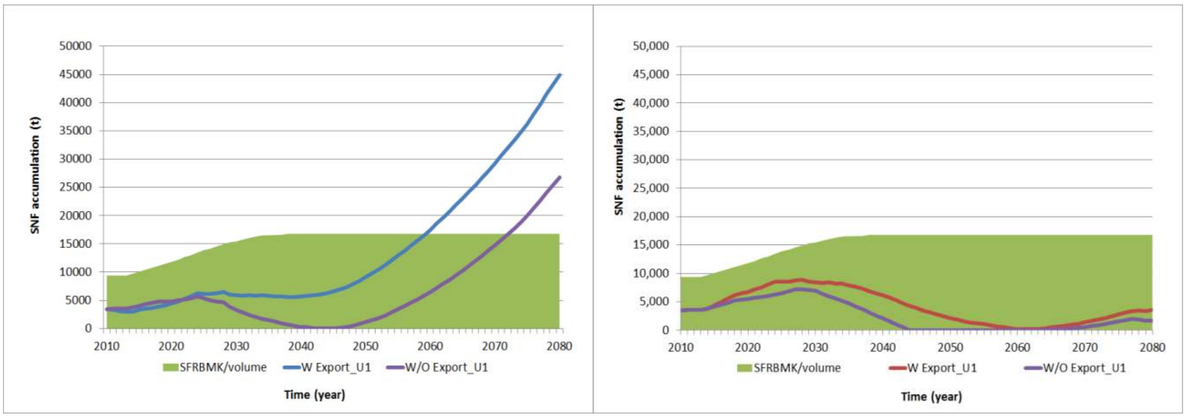


FIG. 80. SNF accumulation in 'Holder' storage facilities for low (a) and high (b) share of fast reactors for scenarios without and with SNF from 'User 1' respectively.

As shown in Fig. 81, in the main variant with a high share of fast reactors, plutonium from the storage can be used before all SNF is reprocessed. This means that after separation, plutonium has to be directed to the fuel fabrication unit without any delay.

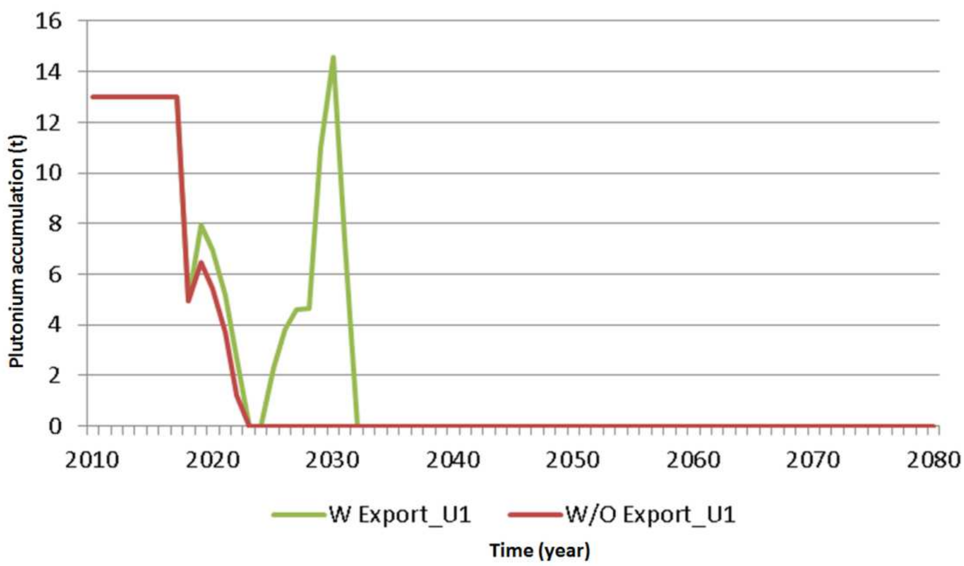


FIG. 81. Plutonium accumulation in the high share of fast reactors variant.

There is a peak of plutonium accumulation under 'W Export_U1' scenario between 2020 and 2030 owing to the high cost of accumulated spent fuel storage.

While demonstrating the potential for avoiding excessive accumulation of SNF and plutonium through regional collaboration, the study noted economic impediments to implementation of this option in the near term. At present, technical and institutional procedures are not developed in detail and the price formation in the area is not transparent. Long term intermediate level waste storage looks more attractive from an economic point of view, although it faces certain challenges over the long term.

WWER fuel reprocessing requirements

Figure 82 illustrates that regional cooperation of 'User1' and 'Holder' in the back end of the nuclear fuel cycle would not result in a significant impact on the capacities of the 'Holder''s WWER fuel reprocessing plants planned for commissioning in the national programme of a closed nuclear fuel cycle.

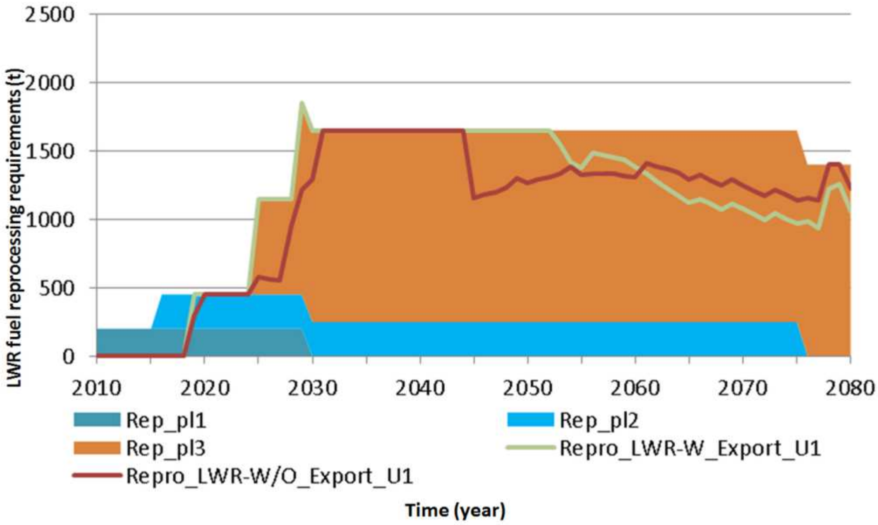


FIG. 82. LWR fuel reprocessing requirements for the high share of fast reactors variant.

However, Fig. 82 also demonstrates that reprocessing capacities do not have sufficient capacity reserves to allow significant growth in the amount of SNF for reprocessing in the case of enhancement in regional/interregional collaboration. The estimated capacities for BN spent fuel reprocessing for the scenarios with a high share of fast reactors ('W/O Export_U1' and 'W Export_U1' scenario) are presented in Fig. 83.

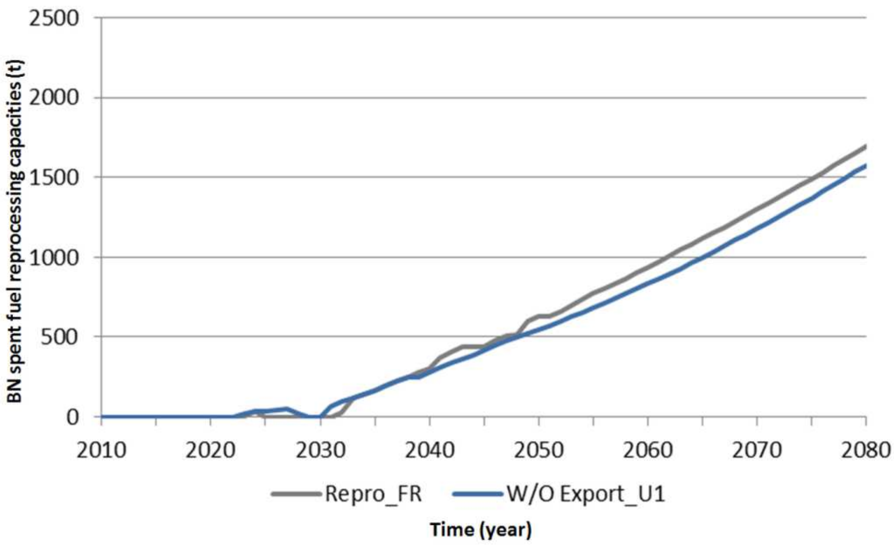


FIG. 83. BN spent fuel reprocessing capacities for those scenarios with a high share of fast reactors (‘W/O Export_U1’ and ‘W Export_U1’ scenario).

2.4.5.2. Main conclusions and findings of the case study

To date, only preliminary steps have been taken in modelling of regional and global collaboration in the back end of the NFC. Within the scope of the SYNERGIES collaborative project, it was agreed to consider a model scenario of regional cooperation of a technology holder and several users. Representatives from Armenia, the Russian Federation and Ukraine have developed an example scenario of the initial stage of regional collaboration in order to understand the benefits and limitations of a cooperative approach.

It was decided that this scenario does not represent the realities of cooperation between these countries in the nuclear energy sphere, but demonstrates some opportunities and impediments on the way to cooperation. To emphasize a conventional and generalized character of the model, it was assumed that a certain experienced nuclear power ‘User1’ sends a part of its used fuel to the technology ‘Holder’ for reprocessing. With that, a ‘User2’ country and a ‘Newcomer’ country receive a full range of services in the nuclear fuel cycle from the ‘Holder’. A supply scenario of spent fuel to the technology ‘Holder’ was prepared by the SYNERGIES participants from Ukraine. The scope of services from a ‘User2’ country was defined by the SYNERGIES participants from Armenia. The scope of the services from a ‘Newcomer’ country was agreed upon with representatives of Belarus.

This conventional scenario of regional cooperation is based on the reference reactor and fuel cycle technologies of the partners and was modelled in the case study by using the MESSAGE code with enhanced capabilities for a NES simulation. Some drivers and impediments to multilateral cooperation were identified on the basis of the direct results of the modelling and through a discussion on the related issues. Among drivers identified by the participants of the case study are:

— Substantial savings of natural uranium for collaborating partners accruing from the substitution of ^{235}U in the UOX nuclear fuel of the WWER by plutonium extracted from UOX SNF of WWER and used in MOX fuel for fast reactors;

— Opportunity to avoid excessive accumulation of SNF and plutonium therein through plutonium utilization in the multilateral NES;

— Economy of financial and human resources for the users by eliminating creation of expensive nuclear energy infrastructure of the closed NFC while receiving all benefits of the cycle;

— Expansion of nuclear energy business for the technology holders and cost reduction of NFC services;

— Possibility to utilize cheaper categories of uranium for both users and technology holders.

Along with the drivers, some impediments to regional collaboration were also identified:

— Technical and institutional procedures are not developed in detail;

— Price formulation in this area is not transparent and does not stimulate implementation of reprocessing abroad;

— Political and economic instability may hamper multilateral collaboration.

On the whole, it could be concluded that enhancement of multilateral collaboration in the back end of the NFC represents a meaningful step towards achieving sustainable nuclear power.

2.4.5.1. Suggestions for further elaboration of the model

Several suggestions presented below seem to be essential for improving simulation models of the regional or/and interregional collaboration and they are planned for realization by the participants of the case study.

A high priority task of future activities is further elaboration of logistics of the mass flows in the multilateral NES and roadmapping of the infrastructure development. This work should include modelling of:

— Discreet commissioning/decommissioning of the NPP units and NFC installations of the potential partners;

— More large-scale used fuel supply from different user-countries to a holder-country;

— Transportation of spent nuclear fuel and fissile materials, etc.

It is also necessary to enhance the database associated with the MESSAGE tool application for modelling of multilateral collaboration. A weak point of the base is lack of technical and economic data on some elements of the closed NFC chain and large uncertainty of the available data, especially in the economic area.

An actual and ambitious task for future studies in which MESSAGE tool could show its potential is modelling the routes of reprocessed products of the SNF (regenerated uranium, plutonium, MA) and development of an approach for evaluation of the plutonium and MA economics.

Stepwise implementation of the directions for further elaboration of the model and demonstration of the results of the model applications in the national studies and in the joint IAEA projects like SYNERGIES will be an important part of the Member States' activities on the way to a 'win-win' collaboration in area of nuclear energy.

2.4.6. Feedback from case study on NES modelling with MESSAGE tool

2.4.6.1. Aspects in which MESSAGE model was useful in this study

Application of the MESSAGE code was useful in this study due to basic capabilities of the model and extended capabilities developed for a more precise simulation of the NFC.

The discount cash flow analysis involved in the tool is very useful for modelling purposes in the short term, but in the long term case studies (more than 50 years) there are some problems related to the discounting of investments of back-end facilities. As a rule, recycle facilities come into operation after the middle of the model time-frame. In such cases, front-end elements have bigger influence than the back-end ones. However, the back-end is also important for the entire NES. As such, it is important that sensitivity analyses are performed for assessing the impact of discount rate on the results. It is generally recommended that a low discount rate should be used for a long term assessment.

The capability of MESSAGE to model not only direct, but also reverse material flows was addressed in the given case to simulate a closed nuclear fuel cycle. Separated plutonium is considered in the model as an additional and technological energy resource. Through the process of optimizing the structure of the nuclear power system MESSAGE solves two problems simultaneously: calculates the availability of additional resources and assesses the economic feasibility of their use. The interconnection of these opportunities allows to use MESSAGE for finding of an optimal plan for building of a very complicated nuclear energy system. The solution of the task by means of simulation models requires multiple runs for an acceptable approximation to a desired 'minimum cost' point, which is never known for certain in these approaches.

A useful option in application of MESSAGE for modelling of NESs is evaluation of 'marginal states' of the systems. By assigning economic benefits to some technologies or technological chains, or vice versa, by imposing certain restrictions, one can estimate 'marginal states' of interest for a given system. It can be, for example, the maximum/minimum rate of construction of fast reactors with various breeding ratio or the need for reprocessing capacities that minimize the accumulation of plutonium. The corresponding fuel and material balances, which are very important in this kind of studies, are provided in MESSAGE in a single program run.

An example of a 'marginal state' of the system under consideration is illustrated in Fig. 84 that describes the structure of electricity production under an assumption of SNF reprocessing without reprocessing of the BN spent nuclear fuel.

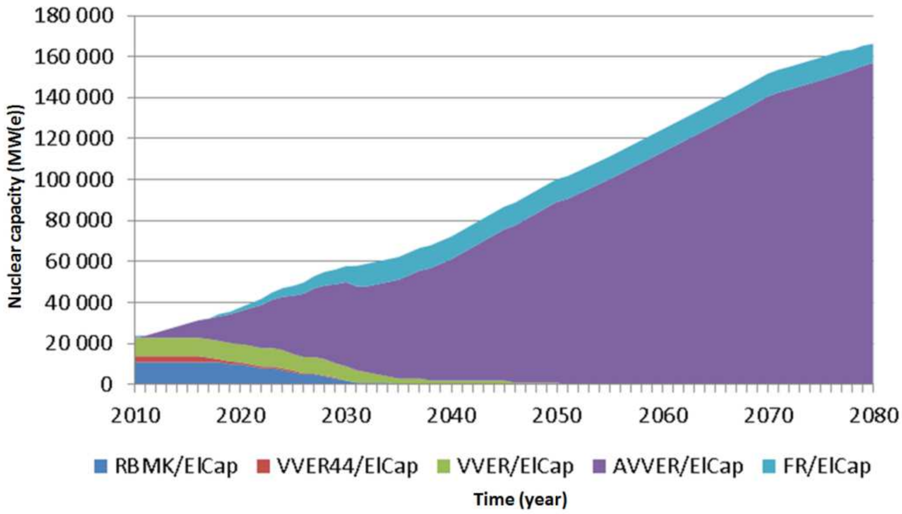


FIG. 84. Structure of the 'Holder' nuclear capacity in case of absence BN reprocessing spent nuclear fuel facility.

It can be seen that in this 'marginal state' only very limited number of fast reactors could be commissioned during the modelling period. As a result, the advantages of the use of fast reactors in terms of uranium savings, reduction of WWER SNF and the plutonium therein, could not be fully realized. At the same time, premature commissioning of a large plant for reprocessing of the used fuel of fast reactors would mean unjustified costs.

Finding an optimal ratio of spent fuel reprocessing from fast and thermal reactors is very important but complicated issue which depends on both economic and strategic circumstances. Although some studies demonstrate economic advantages of reprocessing of the SNF of FRs versus reprocessing of the SNF of thermal reactors, it is no case for economics of a large international fuel cycle centre where the cost of reprocessing should be compared with the cost of SNF repositories' construction in many countries.

The capabilities of the MESSAGE tool for modelling of the stepwise construction of the NFC installations and relevant economics were only preliminary addressed in the case study and were found very useful for further comprehensive studies of the national and multilateral nuclear energy systems.

2.4.6.2. Benefits and areas for improvement related to the use of the MESSAGE tool

As it has been noted in the previous section, the approach proposed by the IAEA to the nuclear power systems simulation within the capabilities of MESSAGE has provided several unique opportunities for modelling of the specific features of the considered case. However, several areas for refinement, related to the use of the tool, were identified by the participants of the study.

The MESSAGE code allows to model discreet capacities of the nuclear power corresponding to the input of individual nuclear power units. This feature is especially important for evaluation of plutonium amount for the first and annual loadings in fast reactors using MOX fuel. However, this feature should be carefully used because it expands the complexity and size of the model, requiring more sophisticated commercial solvers.

The framework provided in the User's Guide does not explain modelling of a detailed isotopic composition evolution for the multi recycled fuel during operation of a NES. It would not be reasonable to require from the framework being focused on economic issues to model a detailed isotopic composition of the multi recycled fuel, which is a prerogative of advanced sophisticated physical codes. Nevertheless, in the case study it was found that an acceptable accuracy of the fissile material balance in a closed NFC can be provided by supporting MESSAGE input data with the additional data received from an advanced physical code. The Russian physical code CYCLE [42] was used for this purpose. Because of very preliminary character of the results of this approach implementation, they were not included in this report.

Some other results provided by the MESSAGE tool during the work on the case study were found to be very significant but will need further comprehensive analysis. For instance, although the first valuable experience in direct modelling of individual plants and installations of the closed NFC has been gained, it was concluded that correct judgement on the tool capabilities in this area would need further elaboration of the input data related to the NES under consideration and cross-verification of the obtained results with the ones obtained using other instruments of the NES simulation.

2.5. UKRAINIAN CASE STUDY ON MODELLING OF NUCLEAR FUEL CYCLES

2.5.1. Introduction

The current study illustrates the Ukrainian experience in using the MESSAGE models for analyzing national energy systems. The study focuses mainly on modelling of different nuclear reactors (LWR with UOX and MOX fuels, HWR with fuel from regenerated uranium, fast reactors, supercritical water reactor (SCWR)) and nuclear fuel cycles (open fuel cycle, partially closed fuel cycle, closed fuel cycle) in the energy system structure.

The MESSAGE tool provides an opportunity to analyze variations in electricity production and electricity consumption. The results of the performed scenario modelling are presented. This section also includes a brief discussion on challenges and future plans for energy systems.

Country profile

Ukraine is located in the eastern part of Europe. Ukraine borders the Russian Federation to the east and north-east, Belarus to the north-west, Poland and Slovakia to the west, Hungary, Romania and Moldova to the south-west, and the Black Sea and Azov Sea to the south and south-east, respectively. The territory of Ukraine covers an area 603 500 km^2 and the country has a population of about 44.5 million. Nominal GDP is US $90.6 billion, as of 2015 [43].

Energy system

Ukraine has a developed energy system. Total installed capacities of power stations for electricity generation are approximately 55 GW, with the allocation of technologies in the energy mix given below and presented in Fig. 85 [44]:

- Thermal: 34 102 MW (coal: 27 845 MW, gas: 6469.4 MW).
- Nuclear: 13 835 MW.
- Hydro 6220.5 MW (conventional: 4711 MW, accumulated: 1509.5 MW).
- Wind: 438.5 MW.
- Solar: 458 MW.

- Biofuel: 64.6 MW.

The structure of electricity production [45] is shown in Fig. 86.

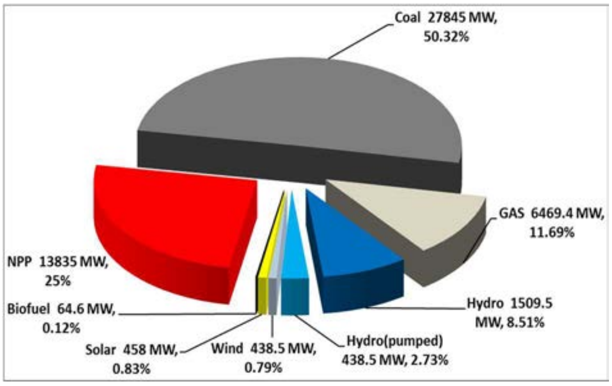


FIG. 85. *Installed capacities of power plants at the end of 2014.*

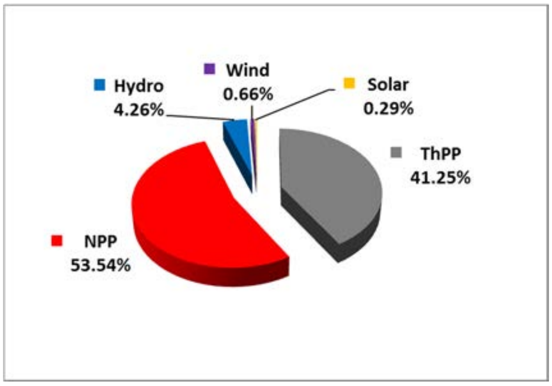


FIG. 86. Average structure of electricity production

The general structure of electricity consumption in Ukraine is shown in Fig. 87. The main consumers are metallurgy (24%) and civil (28%), with municipal consumers (12%) being the third largest consumers of electricity [46].

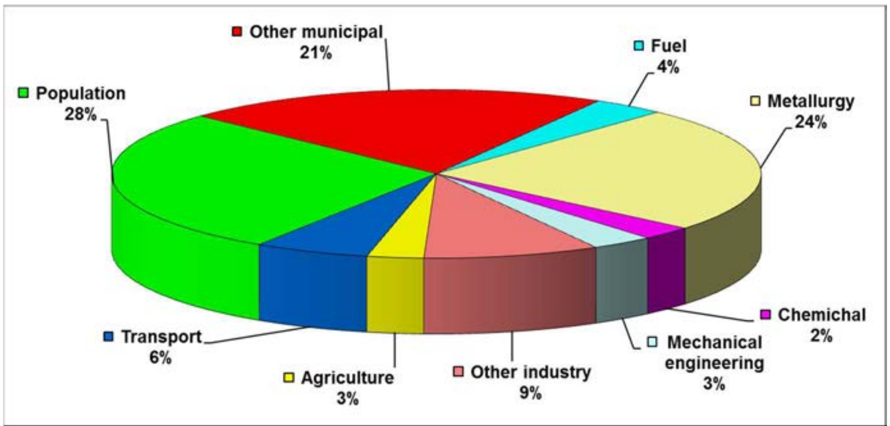


FIG. 87. Structure of electricity consumption.

Nuclear energy in Ukraine

Nuclear energy supplies nearly 50% of the total electricity production in Ukraine. The current total installed capacity of nuclear energy is 13 835 GW, with reactor details provided in Table 35. Four nuclear power stations are operating 13 WWER-1000 and 2 WWER-440 nuclear reactors. The open fuel cycle of the country is based on WWER type reactors, having SNF pool storage and options for shipping spent fuel to other countries for long term storage and reprocessing. One nuclear power station has a dry storage facility for long term storage of SFAs for 50 years.

Fuel management comprises a ‘wait and see’ strategy. For minimizing the financial expense of SNF management, the Centralized Spent Nuclear Fuel Dry Storage Facility, with a capacity of 5560 t HM, is under construction and will be commissioned after 2018. According to the 2013 official energy strategy edition, five LWRs with UOX fuel will be commissioned by 2030.

In the period 2015–2016, the average nuclear power plant's load factor was 75%.

The lifetime of Rivne-1 and Rivne-2 (total 0.835 GW) was extended for 20 years in 2011–2012. In the period 2015–2019, the termination of project operation time is expected for nine units, in 2026 – for one unit, and in 2035 – for two units. There are plans for lifetime extension of nuclear power plants for 20 years. It is envisaged that the share of nuclear energy will be secured and maintained at 50% in the national energy mix until 2035. Plans in the development of nuclear energy generation include:

- Increasing safety of operation of installed reactors;
- Nuclear power plant lifetime extension for 20 years;
- Increasing reliability and efficiency of nuclear power plants;
- Commissioning of new reactors;
- Advances in NFC, fuel management, spent fuel and radioactive waste management.

TABLE 35. NUCLEAR REACTORS IN UKRAINE

Name	Type	Capacity (MW(e))	Operational
Khmelnytsky	WWER	1000	1987
	WWER	1000	2004
Rivne	WWER	420	1980
	WWER	415	1981
	WWER	1000	1986
	WWER	1000	2004
South Ukraine	WWER	1000	1982
	WWER	1000	1985
	WWER	1000	1989
Zaporizhzhia	WWER	1000	1984
	WWER	1000	1985
	WWER	1000	1986
	WWER	1000	1987
	WWER	1000	1989
	WWER	1000	1995
Total	WWER	13 835	

2.5.2. Objectives and problem formulation

The development of nuclear energy system in Ukraine was considered in accordance with the Updated Energy Strategy 2013, which covers the period up to 2030. There is no available officially documented plan for nuclear deployment after 2030.

The main objective of modelling in this case study was assessment of deployment of nuclear energy capacities after 2030 based on different nuclear fuel cycle strategies. The comparison of different NFC strategies was based on criteria of material flow and costs' minimization.

Modelling of energy system development scenario made it possible to:

- Define the share of nuclear electricity generating technology in the structure of the electricity generation system over a prolonged period;
- Analyze possible development scenarios of the electricity generation and, particularly, the nuclear sector;
- Study the necessary construction of new nuclear capacities, with an optimal schedule for new construction and spent fuel accumulation;
- Study possible challenges and necessary measures for development of the nuclear energy system.

Modelling was intended to study the scenarios with:

- Open fuel cycle with LWR;
- Developments of the energy system on the basis of a supercritical water reactor;
- Partially closed fuel cycle with MOX fuel in LWR and fuel from regenerated uranium in HWR;
- Closed fuel cycle with FR;
- Variation of electricity production and consumption (investigation of possible impact on nuclear electricity generation).

2.5.3. Model description and input data

2.5.3.1. Prospects for national nuclear energy and country's partners for collaboration

Ukraine is a user country and has an extensive nuclear energy infrastructure, which includes uranium mining and milling, zirconium production, manufacturing of the top and bottom nozzles of the fuel assembly, manufacturing of main equipment for nuclear power plants, technical and scientific support, and an independent regulatory body. Ukraine does not have uranium enrichment and spent nuclear fuel reprocessing facilities. The nuclear infrastructure is based on an open (once-through) nuclear fuel cycle. Starting from 2018, the Russian Federation will handle the spent fuel reprocessing of WWER-440 reactors and return the fission products to Ukraine.

Currently, international collaboration in the NFC is provided in areas of uranium enrichment and fresh nuclear fuel fabrication, WWER-440 SNF reprocessing, and WWER-1000 SNF long term storage. Deployment of new reactor designs must be considered in Ukraine, along with appropriate elements of the NFC and the strengthening of international collaboration in the following areas:

— Uranium enrichment;

— Fresh fuel fabrication;

— MOX fuel fabrication;

— Technical and scientific support of nuclear power plants' operation;

— Normative documentation development;

— Personnel training.

2.5.3.2. Electricity consumption

The prognosis for electricity consumption up to 2100 obtained in collaboration with the Institute of Economy and Forecasting of National Academy of Science of Ukraine is shown in Fig. 88.

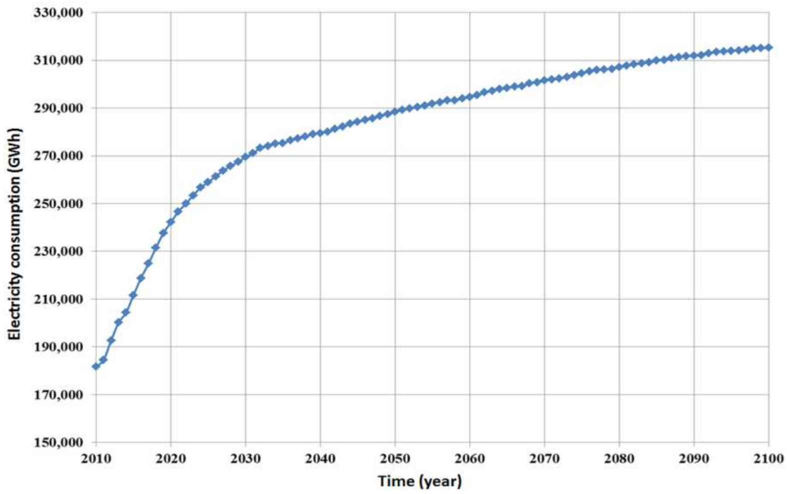


FIG. 88. Forecast of electricity consumption.

2.5.3.3. Options and fuel cycle schemes

The general scheme of the energy system model is presented in Fig. 89.

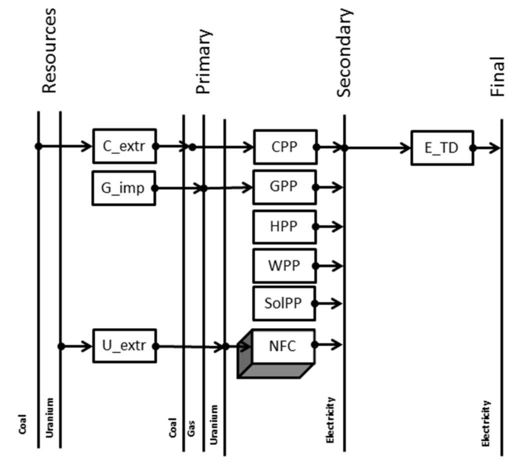


FIG. 89. General scheme of the energy system model.

The model includes:

- Resources of coal and uranium.
- Technologies for extraction of coal (C_extr).
- Technology for gas import (G_imp).
- Technology for uranium extraction (U_extr).
- Technologies for electricity generation: coal power plants, gas power plants, hydro power plants, wind power plants, solar power plants;
- Nuclear power plants are described in blocks, depending on the type of nuclear fuel cycle.
- Electricity transport and distribution system (E_TD).

The description of the NFC block depends on the type of NFC. The following fuel cycle schemes were considered in the model and are shown in Figs 90–93:

- Open fuel cycle with LWRs;
- Partially closed fuel cycle with MOX fuel in LWR and HWR with reprocessed uranium fuel (ReU fuel);
- Closed fuel cycle with FR (MOX fuel);
- Open fuel cycle with supercritical water reactor.

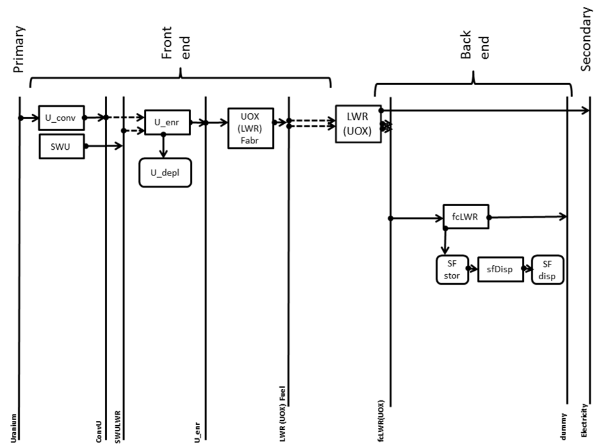


FIG. 90. Open fuel cycle based on LWR with UOX fuel.

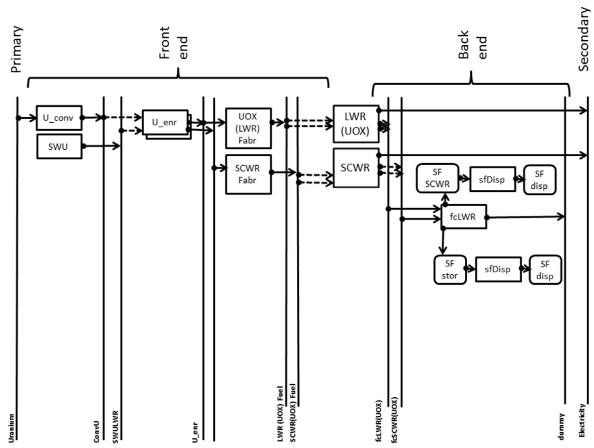


FIG. 91. Open fuel cycle based on SCWR with UOX fuel.

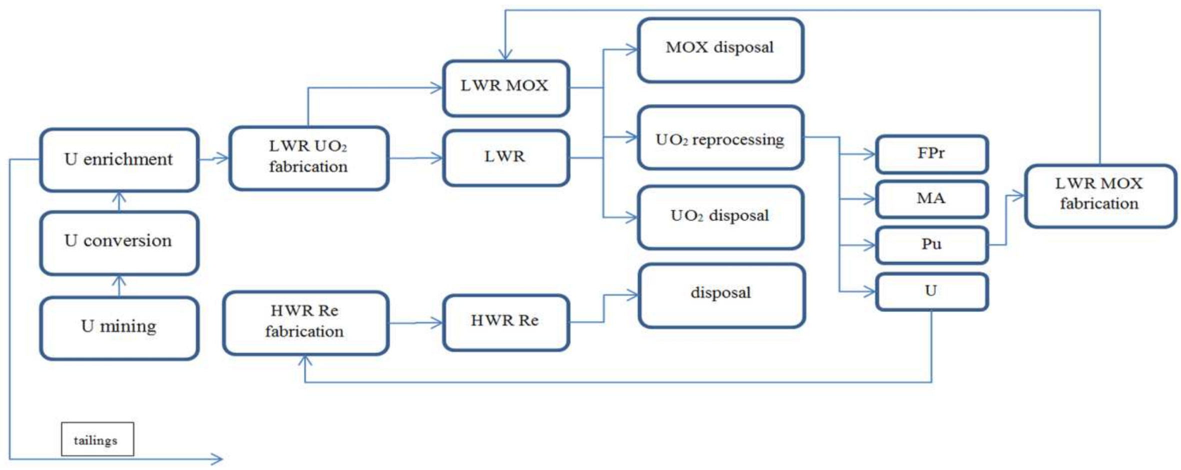


FIG. 92. Partially-closed fuel cycle based on LWR with MOX-fuel and HWR with regenerated uranium.

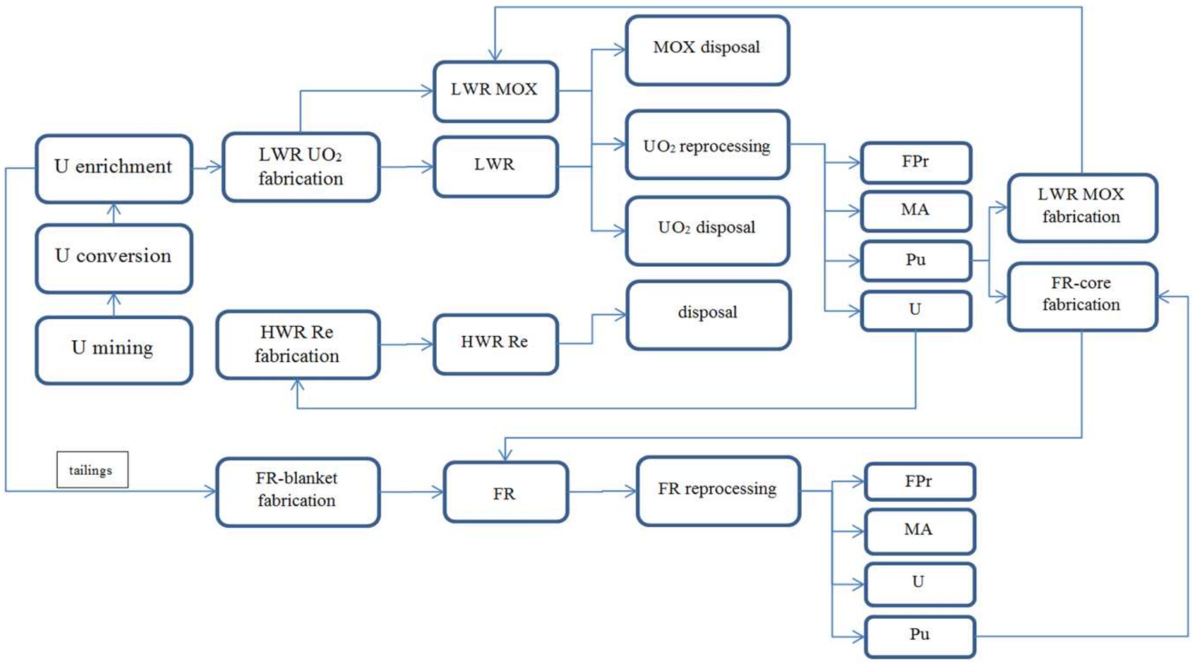


FIG. 93. Closed fuel cycle based on LWR with MOX-fuel and HWR with regenerated uranium and FR.

2.5.3.4. Technical and economic input data for reactors and fuel cycle

<u>Supplies of uranium</u>

Ukraine possesses considerable natural resources of uranium ores. Uranium extraction is conducted mainly by the direct mining method and partly by underground leaching. Most of the Ukraine's uranium resources are low grade ore deposits.

Uranium resources and price categories selected for the study are taken from [47] and are provided in the Table 36.

TABLE 36. PRICE CATEGORIES OF SUPPLIES OF URANIUM

Category	**Price category (US $/kg)**	**Supply (t)**	**Source**
Reasonably assured resources	100	135 000	Ref. [47] Table 3, page 17
Confirmed (inferred)	120	64 500	Ref. [47] Table 4, page 18
Prognosis (prognosticated)	150	22 500	Ref. [47] Table 11, page 25
Implied (speculative)	260	255 000	Ref. [47] Table 11, page 25
Combined		477 000	

<u>Uranium conversion</u>

For the purpose of study in a long term prospect, the cost of uranium conversion was considered as US $10/kg.

<u>Uranium Enrichment</u>

The cost of uranium enrichment was assumed on the basis of open data of the UxC company [48]. For long term prospect in the study, enrichment costs were taken at US $130/kg.

Fuel fabrication

The costs of fresh fuel manufacturing were considered on the basis of open data of Idaho National Laboratory (INL) [49], Organisation for Economic Co-operation and Development (OECD) [50] and IAEA [51].

The cost of UOX fuel fabrication for the current study was considered at US $300/kg HM. The cost of MOX fuel fabrication for light water reactors was taken at US $1500/kg HM and the fuel fabrication cost for heavy-water reactors from regenerated of uranium was assumed to be US $200/kg HM. The fuel fabrication cost for fast reactors was taken at US $2400/kg HM.

Reprocessing of spent nuclear fuel

Ukraine does not have official plans regarding set up of facilities for reprocessing of LWR SNF. For the purpose of the current study, reprocessing of SNF of operating Ukraine NPPs was designed as a service for the whole period of study in the MESSAGE model.

The cost parameters of reprocessing services were based on estimations from INL [49], OECD [50] and IAEA [51].

The SNF reprocessing cost for LWR was estimated as US $2000/kg HM and the SNF reprocessing cost for fast reactors was taken to be US $2200/kg HM.

SNF Storage

According to the renewed strategy of the Ukraine energy system development, the SNF management is foreseen as ‘postponed decision’ up to 2030. The strategy of fuel management is yet not elaborated in the mid and long term periods for the NPPs.

For modelling purpose, it has been assumed that spent UOX fuel of LWR reactors is placed in the Central Spent Nuclear Fuel Storage Facility (CSNFSF) for long term storage with a total volume 5650 t HM.

Storages of other SNF types were not linked to any definite depository.

The cost of SNF storage (UOX LWR, MOX LWR, FR) was considered as US $300/kg HM in the study. This estimation was carried out on the basis of data from Refs [49–52].

Disposal of SNF and high-activity reprocessing products

For the MESSAGE model in the current study, the cost of SNF disposal in geological structures was taken at US $600/kg HM which corresponds to data of the IAEA and OECD (US $400–1000–1600/kg HM for year 2009 and US $600/kg HM for year 2012).

Disposal cost for high-activity reprocessing products (fission products and minor actinides) was approximated as US $10 000/kg FP, where FP designates fission products.

These estimations were carried out on the basis of data from Refs [5, 49–51].

Fixed and variable costs of power units

The fixed and variable costs of power units were considered as US $69.3/kW and US $0.5/MW·h, respectively. These values were estimated on the basis of data provided in Refs [53, 54].

Capital cost for construction

The capital costs for construction were considered for LWR — US $5000/kW [4]; for HWR — US $4000/kW; and for FR — US $6000/kW, accordingly.

Summary table of technical and economical parameters for reactors and NFC

Technical and economical input data for different reactors and fuel cycle stages used in the study are summarized in Table 37.

TABLE 37. PARAMETERS OF TECHNOLOGIES AND STAGES OF NFC USED IN MODEL

Parameter	**Unit**	**WWER-1000**	**WWER-1200**	**LWR (MOX)**	**SCWR [55]**	**ReHWR**	**FR BN-1200 (BR = 1.19)**
Thermal power	MW(th)	3 000	3 200	3 200	3 575	2 064	2 900 [56]
Electric power	MW(e)	1 000	1 120	1 120	1 600	728	1 200 [56]
Heat	Gcal/h	-	-	-	-	-	-
Efficiency	%	33	35	35	44.8	35.3	42.068 [56]
Plant factor	%	78	90	90	90	90	90 [56]
Enrichment	%	4.7	4.7	7% (Pu)	10 (assumed)	0.9[e]	18.2 (Pu) [56]
Burn-up	GW·d/t	60	60	60	70	13 [57, 58]	113 [56]
First loading	t HM	78 174.8[a]	78 174.8[a]	19 543.7[c] 58 631.1[c]	83.8[d]	88	Total / Pu 41.5 / 7.802 [56]
Annual loading	t HM	17 265.6[b]	17 265.6[b]	4 316.4[c] 12 949.2[c]	16.7[d]	52.113[d]	Total / Pu 8.05 / 1.513 [56]
Construction cost	US $/kW	3 400 - Kh3Kh4	5 000	5 000	5 000	4 000	6 000 (Expert estimation, there are no publications)
Fixed cost [52]	US $/kW	69.3	69.3	69.3	69.3	55.0	69.3
Variable cost [52]	US $/MW·h	0.50	0.50	0.50	0.50	0.50	0.50
Period of exploitation	year	50	60	60	50	35	60 [56]
Construction period	year	6	6	6	6	5	6
Uranium conversion cost	US $/kg HM	10 [48]	10 [48]	10 [48]	10 [48]	-	-
Uranium enrichment cost	US $/EPP	130 [48]	130 [48]	-	130 [48]	-	-
Fuel fabrication cost	US $/kg HM	300 [50, 51]	300 [50, 51]	1 500 [49–51]	300	200	2 400 [49, 56]
Cost of SNF disposal	US $/kg HM	600 [5, 49–51]	600 [5, 59–51]	600 [50–53]	600 [5, 49–51]	600 [5, 49–51]	
Reprocessing cost of SNF	US $/kg HM	2 000 [49–51]	2 000 [49–51]	2 000 [49–51]		-	2 200 [49, 50, 56]

Parameter	Unit	WWER-1000	WWER-1200	LWR (MOX)	SCWR [55]	ReHWR	FR BN-1200 (BR = 1.19)
Intermediate storage cost of SNF	US $/kg HM	300 [51]	300 [51]	300 [51]	300 [51]	-	300 [51]
Disposal cost of SNF reprocessing products (MA, FP)	US $/kg HM	10 000 [49–51]	10 000 [49–51]	10 000 [49–51]	-	-	10 000 [49–51]

a Core of nuclear reactor contains 163 fuel assemblies. Each assembly contains 545 kg of UO_2. Molecular mas of UO_2 is 238 + 16 × 2 = 270; Share of U is approximately 0.88 (238 / 270 = 0.881 48). So, the weight of U in core is 163 (Fuel assemblies) × 545 (kg of UO_2) × 0.88 (share of Uranium) = 78 174.8 kg U.

b Under assumption that perspective annual re-fuel contains 36 assemblies;
36 (Fuel assemblies) × 545 (kg of UO_2) × 0.88 (share of Uranium) = 17 265.6 kg HM.

c Calculated; Considering that 25% of core is loaded by MOX-fuel;
Total core load — 78 174.8 kg HM, MOX fuel — 0.25 × 78 174.8 = 19 543.7 kg HM;
Annual reload — 17 265.6 kg HM, MOX fuel — 0.25 × 17 265.6 = 4 316.4 kg HM;
Total core load — 78 174.8 kg HM, UOX fuel — 0.75 × 78 174.8 = 58 631.1 kg HM;
Annual reload — 17 265.6 kg HM, UOX fuel — 0.75 × 17 265.6 = 12 949.2 kg HM.

d Calculated.
Annual reloading is calculated as $G_x = \frac{365 \times W \times \varphi}{\eta \times B}$, where W: Reactor installed capacity, B: Burn-up, φ: Plant factor and η: Thermal efficiency;
$G_x = \frac{365 \times 1600 \times 0.9}{0.448 \times 70} = 16\,760.2$ kg HM;
Total core load is calculated as $G_f = \frac{W \times T_{ef}}{\eta \times B}$, where T_{ef}: mean nuclear fuel residence time in days;
Under assumption of 5 years fuel company T_{ef} is calculated as 365 (days) × 5 (years) × 0.9 (plant factor) = 1642.5; Hence,
$G_f = \frac{1600 \times 1642.5}{0.448 \times 70} = 83\,801.02$ kg HM.

e Under assumption that reprocessed uranium from spent UOX fuel of LWR is used for fabrication of fresh fuel for HWR and remaining uranium in spent UOX fuel contains ^{235}U at the level of 0.9%.

The salient details of the centralized facility for the intermediate storage of spent nuclear fuel are provided in the Table 38.

TABLE 38. INTERMEDIATE CENTRALIZED STORAGE OF SPENT NUCLEAR FUEL [52]

Parameter	Unit	Value
Commissioning year	-	2015
Total capacity	t HM	5650
Term of SNF loading	year	50
Term of exploitation of repository	year	100

2.5.3.5. Non-nuclear generation

Ukraine possesses its own significant coal resources (Table 39), but mining costs are rather high owing to the depth of the deposits. Gas resources are imported because of the insignificant local resources. Typical technical and economic parameters used in the model are provided in the Table 40.

TABLE 39. NON-NUCLEAR POWER RESOURCES

Type	Resource	Cost
Coal	56 billion t	US $100/t
Gas	Unlimited (import)	US $400/1000 m^3

TABLE 40. PARAMETERS OF TECHNOLOGIES FOR NON-NUCLEAR GENERATION USED IN THE MODEL

Parameter	Unit	Coal	Gas	Hydro	Wind	Solar
Capacity	MW(e)	300	300	-	-	-
Efficiency	%	33	47	-	-	-
Plant factor	%	55	32	25	25	16
Construction cost	US $/kW	1600	1300	2200	1900	5000
Fixed cost [53]	US $/kW	57	20.3	14	31	12
Variable cost [53]	US $/MW·h	4.5	15	2.4	-	-
Term of exploitation	year	40	30	80	25	15
Construction period	year	4	2	10	1	1

2.5.3.6. Important assumptions and boundary conditions

The following assumptions were used when modelling the scenario:

(1) Nuclear share in the generation mix may not be more than 50%.

(2) Five LWRs with UOX fuel are to be commissioned by 2030 (in accordance with the basic scenario of the Ukraine's updated energy strategy).

(3) Closed NFC based on FR is possible after 2030 (FR is a developed technology, but nowadays it is not widely used. It is assumed that FR and related technologies will have been approved by 2030).

(4) There is the possibility to commission, annually, no more than one reactor of any type after 2030.

(5) Commissioning of LWR with UOX fuel, LWR with MOX fuel, HWR with regenerated uranium, and FR is defined by the model after optimization.

(6) LWR and FR SNF reprocessing is possible.

(7) MOX fuel application is possible after 2030. One quarter of the core will be loaded with this type of fuel.

(8) The commissioning of HWR with ReU fuel is possible after 2030.

(9) The option for LWR SNF disposal is considered (US $600/kg HM), with no constraints regarding the repository capacity.

(10) The option for spent MOX fuel disposal is considered (US $600/kg HM), with no constraints regarding the repository capacity.

(11) HWR SNF (ReU-fuel) is transported for disposal at the cost of US $600/kg HM; the repository capacity is not limited.

(12) The possibility of SNF reprocessing is allowed at the start of the modelling period.

Additional specific scenarios are described in following paragraphs.

2.5.3.7. Metrics (indicators) for scenario analysis

The following indicators were calculated in scenario analysis of the NFC model:

- Structure of electricity generation;
- Amount of electricity generation by a nuclear power station;
- Share of nuclear generation in total mix;
- Total installed capacities of nuclear generation;
- Schedule of new capacities' construction;
- Spent fuel accumulation;
- Reprocessing products' accumulation.

2.5.4. Modelling of selected NES elements with MESSAGE

2.5.4.1. Selected MESSAGE pages illustrating modelling of reactor technologies and closed fuel cycle

General options for model construction

In this section, some general options are shown to illustrate the construction of a nuclear fuel cycle model in MESSAGE.

Energy forms **Front_end** and **Back_end** are created in 'Energy forms' options (Fig. 94). **Front_end** and **Back_end** groups are corresponding energy levels of the model.

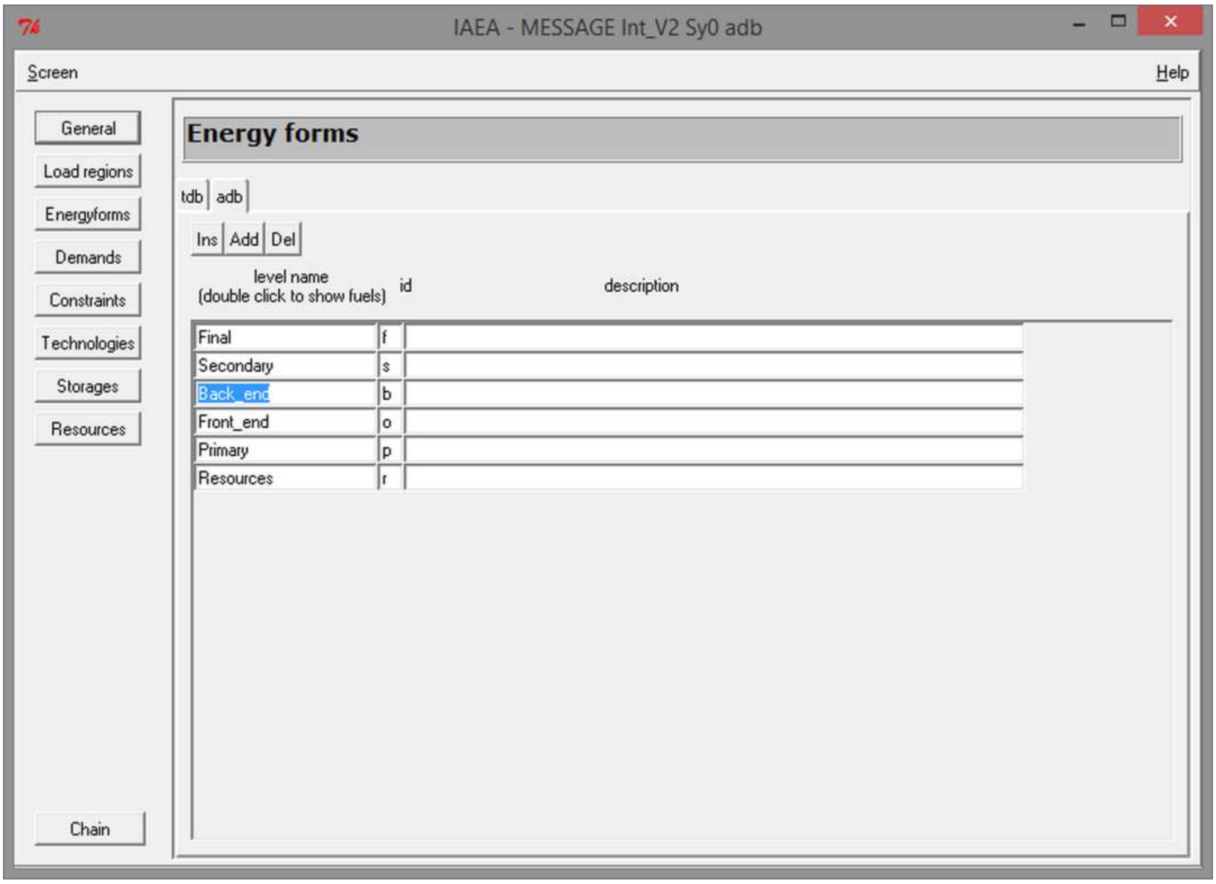


FIG. 94. Energy forms.

Front_end form combines levels for description of uranium conversion, uranium enrichment, and fuel fabrication. **Back_end** form combines levels for description of spent fuel unloading from reactor technologies (Fig. 95).

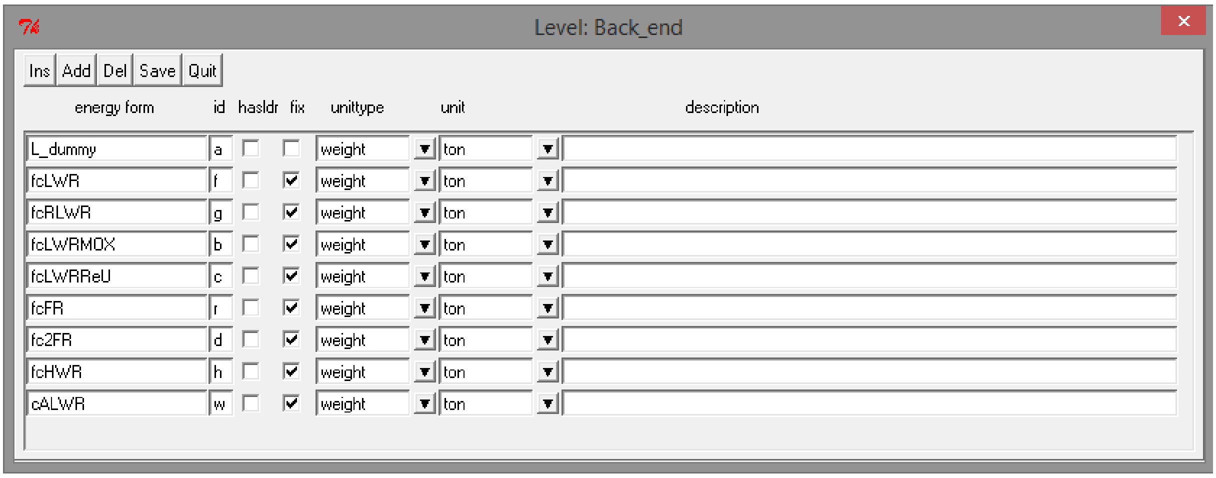


FIG. 95. Back end energy levels.

Constraint ‘nuclear generation produces electricity of not more than 50% of the total mix’ is constructed in **group1** of **constraints** (Fig. 96). In group1 of constraints, it is necessary to create a new relation (named **Nucl**). In **limit type** drop box, select **activity** and in **unit type** drop box select **energy**. In **lower lim** parameter set drop box switch c and put in 0. Then **entries** button shows the window where technologies are selected (Fig. 97).

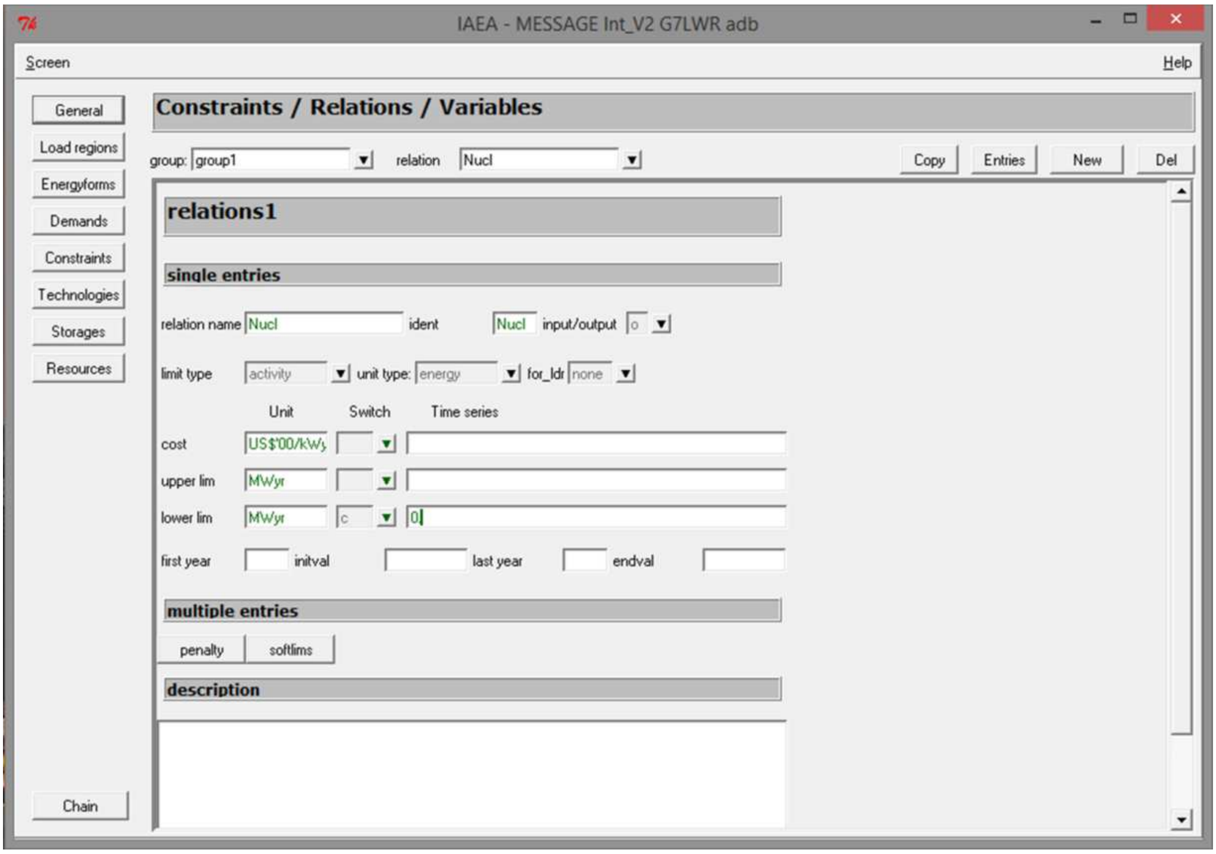


FIG. 96. Entries in Constraints window ('50%').

The technologies that should be under constraints are selected in **other technologies** drop box. The list in the table contains all nuclear and non-nuclear electricity generating technologies. Parameters in column **data -1** for nuclear technology, '**1**' for non-nuclear technology and **0** lower lim correspond to inequality $0 < -1Nucl(activity)\ +1Nonnucl(activity)$.

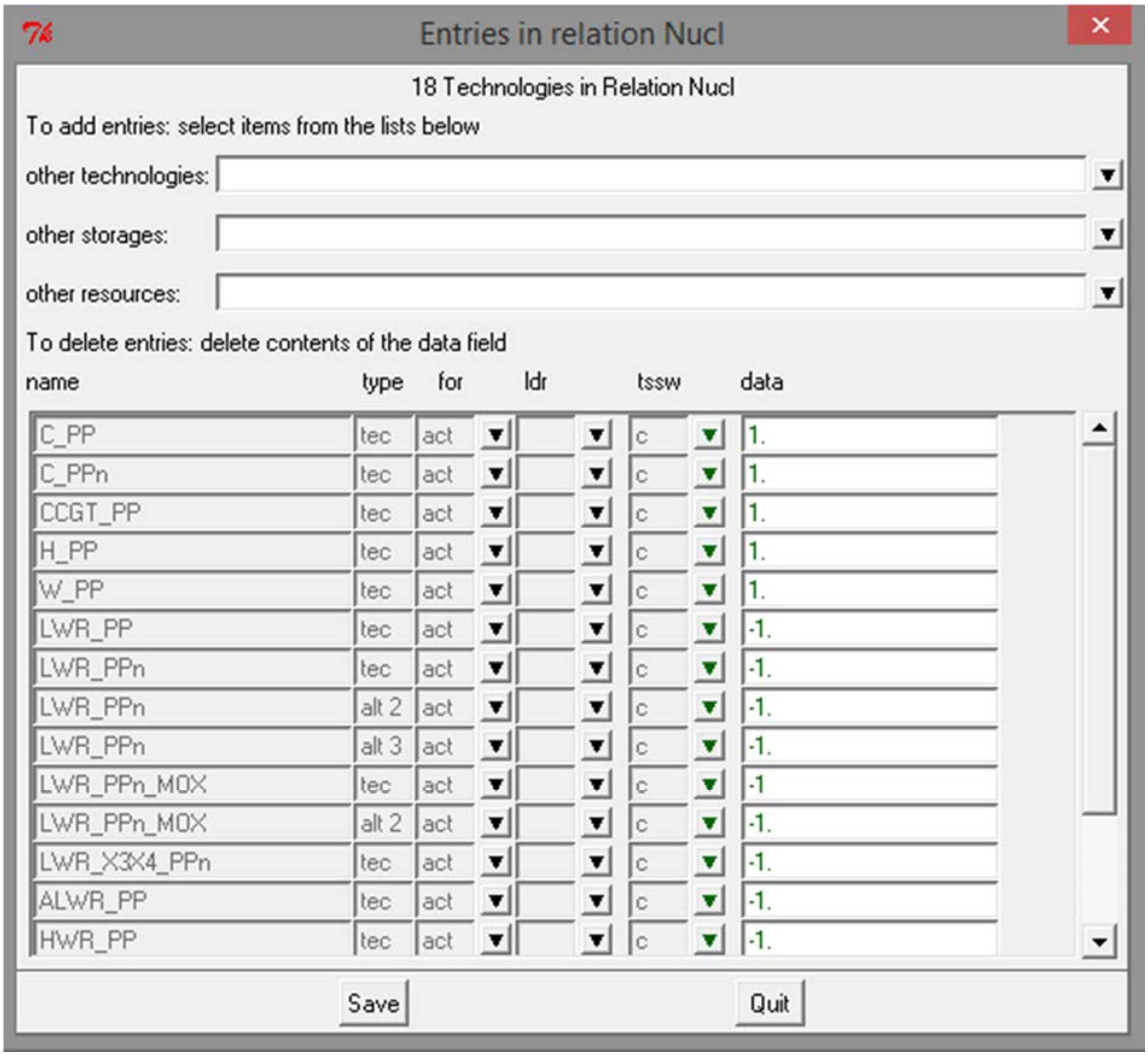


FIG. 97. Technologies under Constraints (‘50%’).

Open fuel cycle

Annual reload for WWER-1200 is modelled through **inp** and **outp** parameters and calculated as 17 265.6/(1120 × 0.9) = 0.017 128 571 428 57 (Fig. 98). Parameter **alag** allows modelling of spent fuel cooling in reactor pool (in this case, cooling time is 5 years).

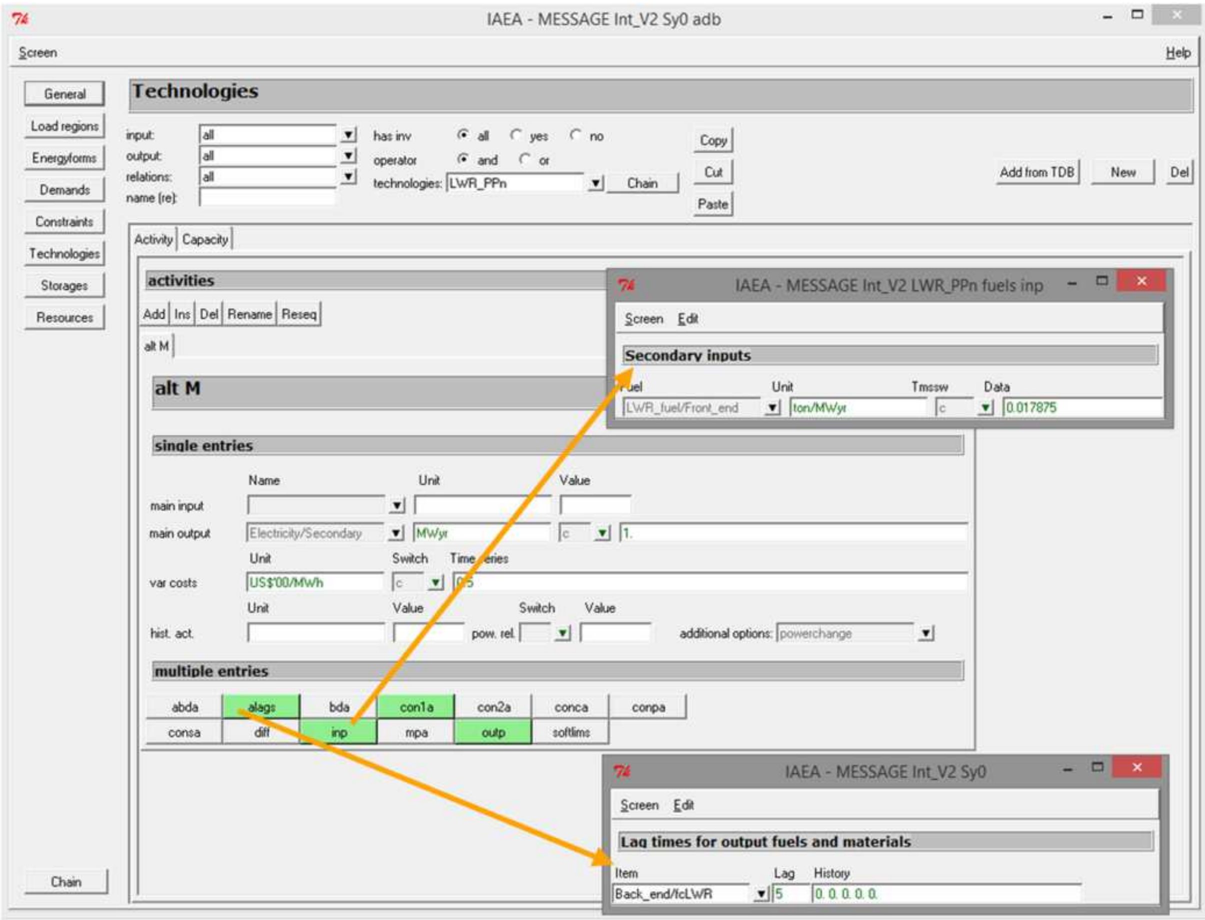


FIG. 98. LWR annual reload.

The first core load and total unload of WWER-1200 are modelled in **corin** and **corout** parameters and calculated as 78.1748/1120 = 0.069 798 928 571 428 57 (Fig. 99).

Active parameter **bdc** (bounds on new capacity addition) reflects additional constraints — ‘construction of new WWER-1200 is allowed after 2030 with the capacity not more than 1200 MW·t/year’. Upper limit (‘not more’) is defined in the drop-down list by option **up**.

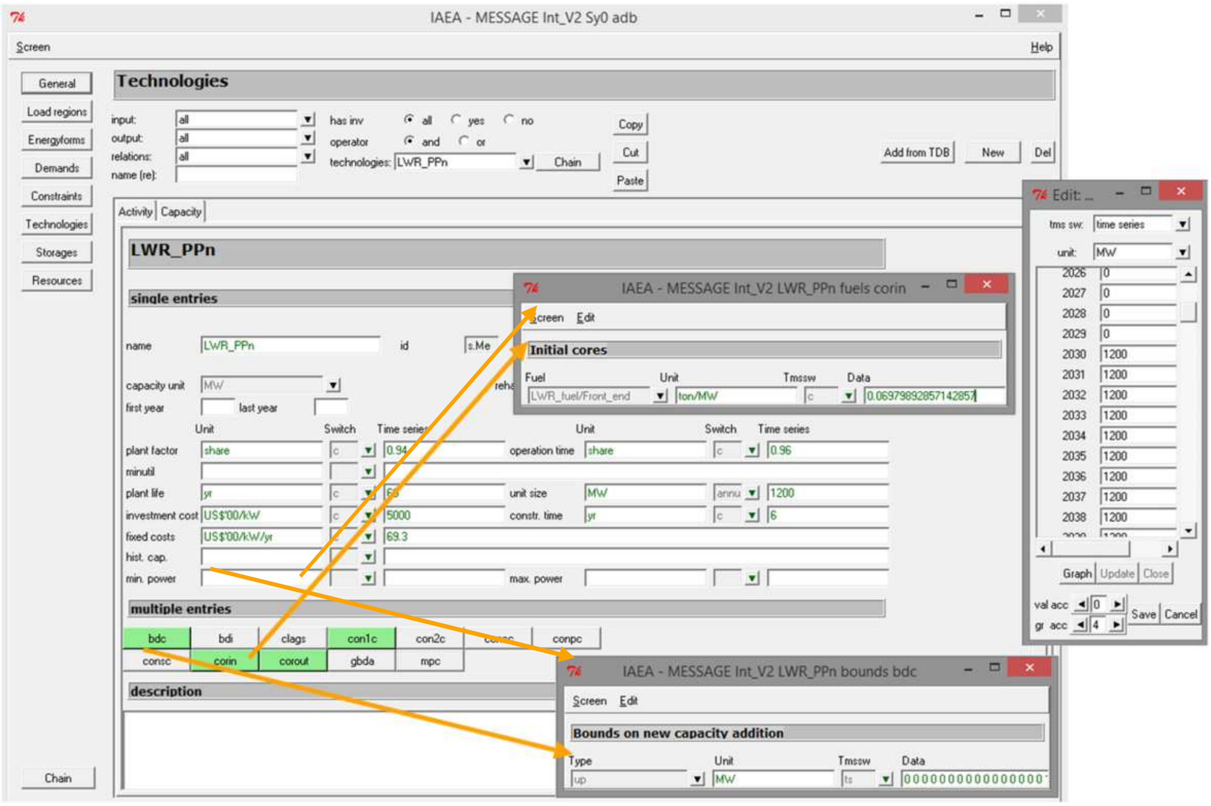


FIG. 99. LWR first load.

Other LWR reactors with UOX fuel are modelled in a similar way.

<u>Supercritical water reactor</u>

Model of the SCWR reactor is constructed in a similar way as the model for the LWR.

SCWR reactor parameters for first core load and unload are calculated as 83.8/1600 = 0.052 375.

Annual reload parameters are calculated as 16.7/(1600 × 0.9) = 0.011 597 2.

<u>Utilization of MOX and ReU fuels</u>

Fuel for the HWR's first load is modelled as UOX fuel from natural uranium.

The HWR's fuel is fabricated from reprocessed uranium. In the model, the technology takes one unit of reprocessed uranium from storage RepU (Fig. 100).

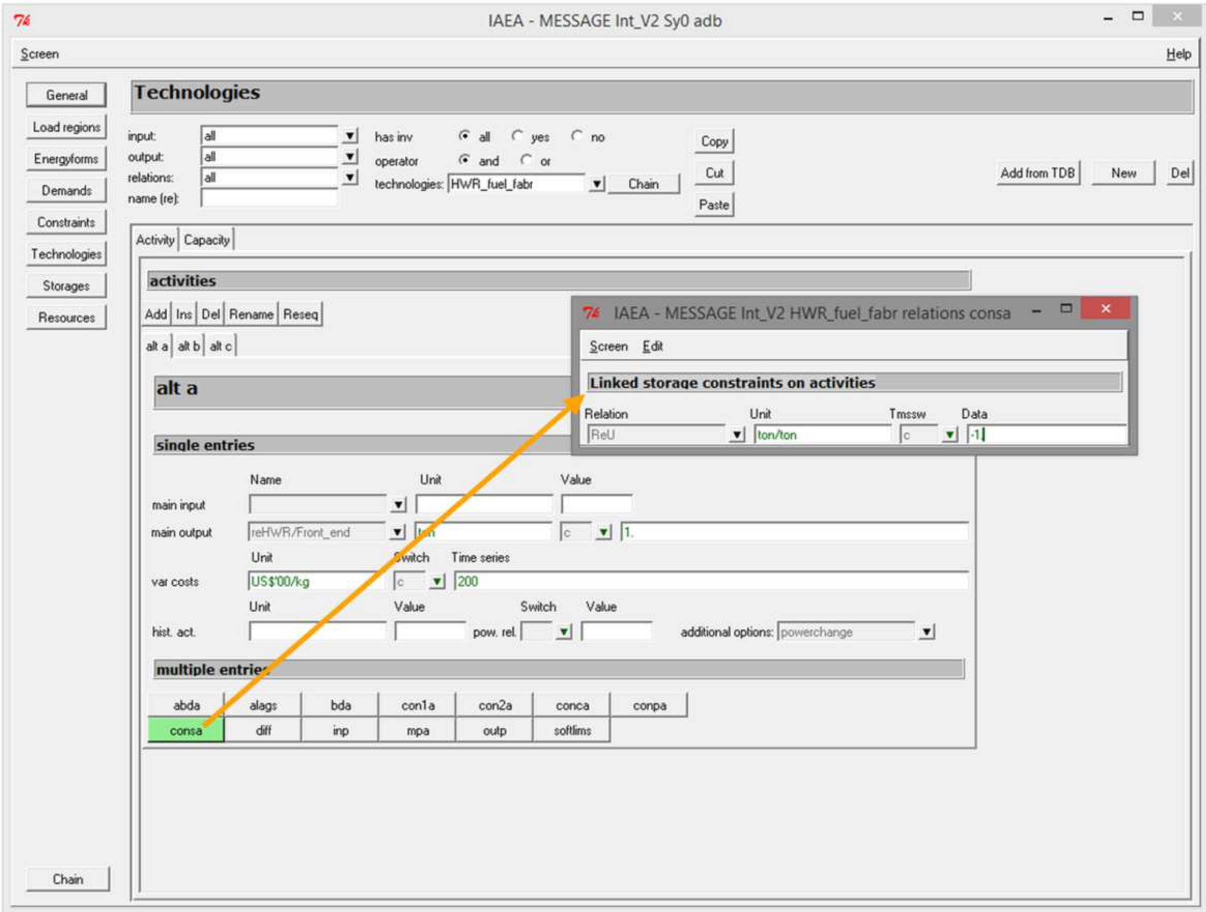


FIG. 100. ReU fuel fabrication for HWR reactor.

Parameter **corin** for the HWR's first load is modelled as 88/728 = 0.120 879.

Mass of fuel reload is calculated as (365 × 728 × 0.9)/(0.353 × 13) = 52.113.

Last discharged fuel is fuel from reprocessed uranium; therefore, the parameter **corout** is calculated as 52.113/728 = 0.071 583 791 208 79.

For annual reload, parameters **inp** and **outp** are calculated as 52.113/(728 × 0.9) ≈ 0.079 (Fig. 101). Parameter **Con1a** is automatically activated after setting **Constraints**.

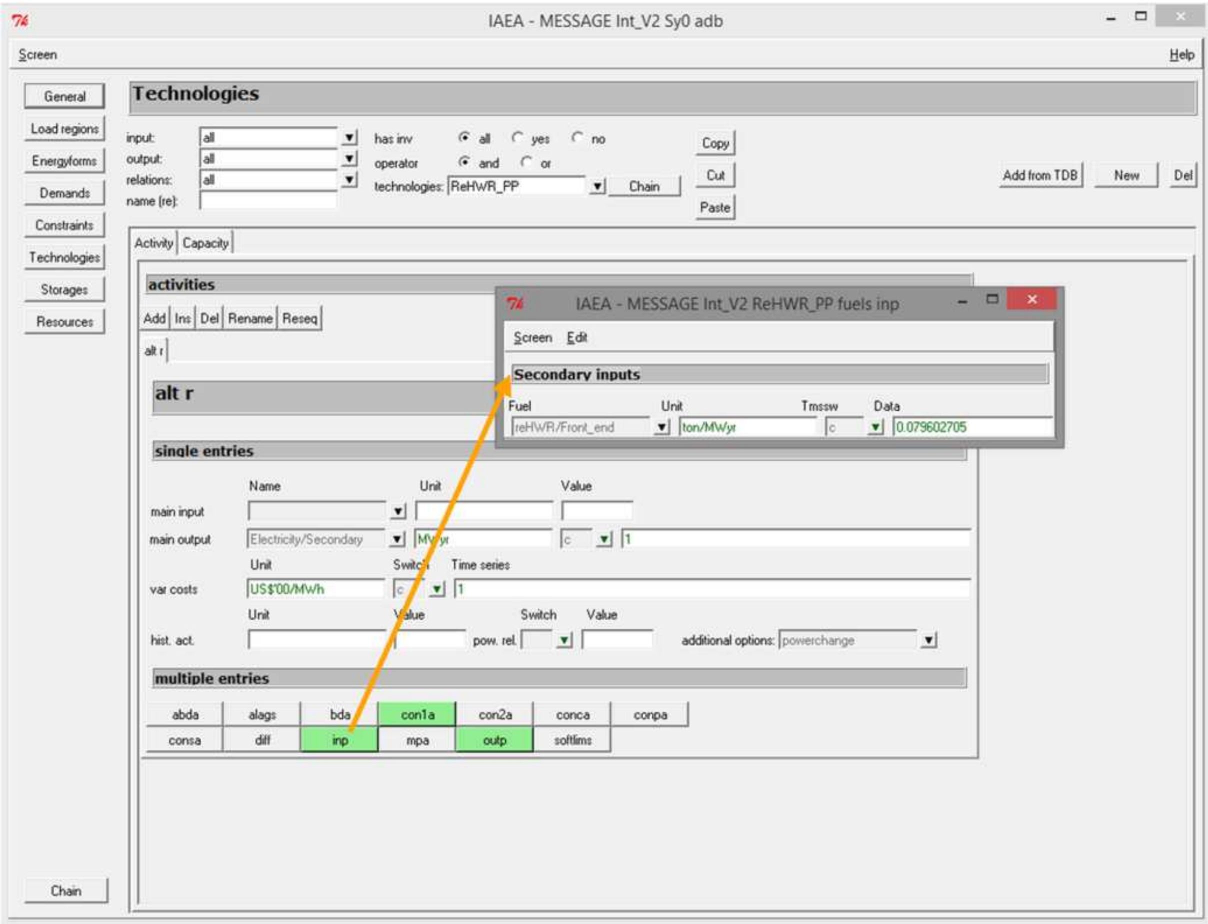


FIG. 101. ReHWR annual reload.

To fabricate MOX fuel for the LWR (Fig. 102) from the storage facilities **DepU** and **Putot**, the depleted uranium and plutonium are taken with a proportion of DepU/Putot = 0.9277/0.0723. Depleted uranium is the uranium accumulated after enrichment and plutonium is accumulated after spent fuel reprocessing.

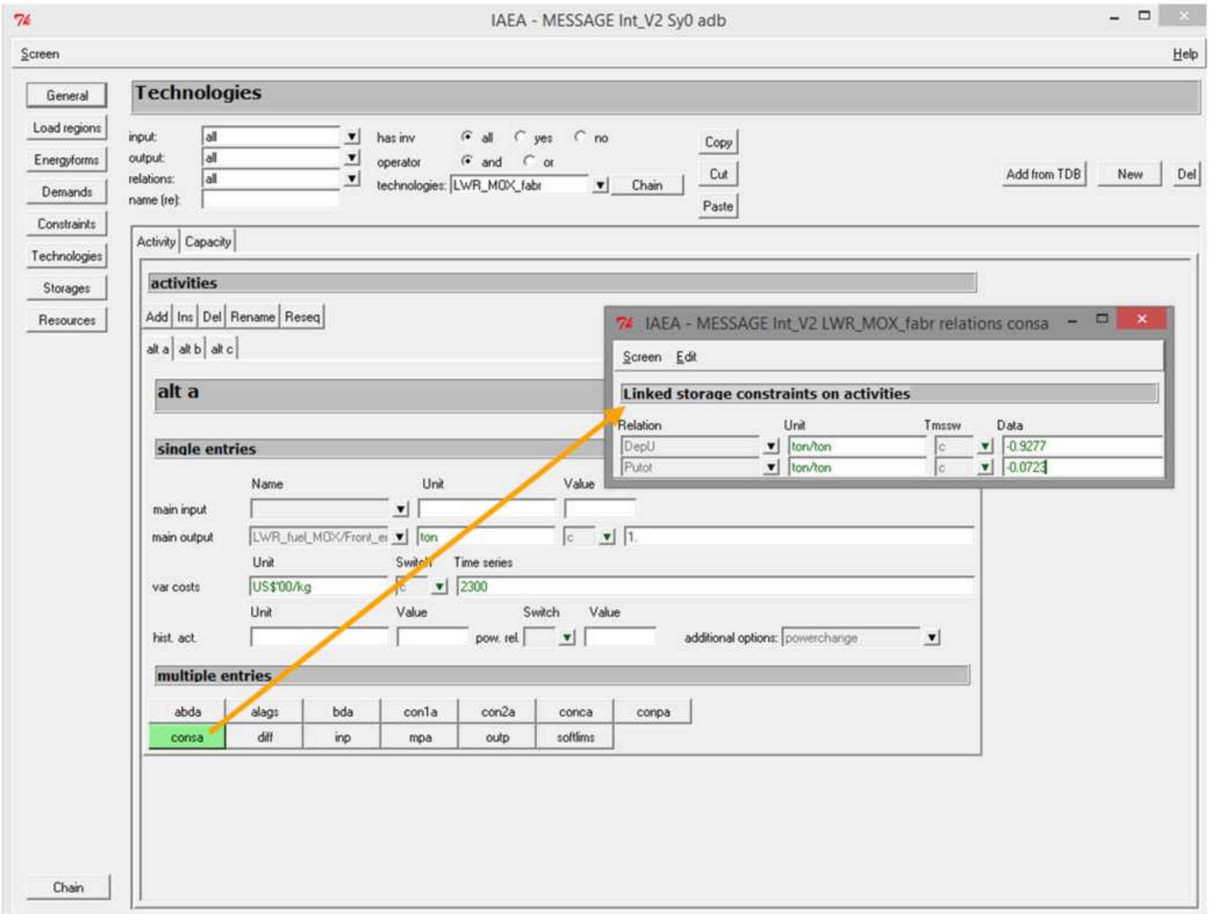


FIG. 102. MOX fuel fabrication.

MOX fuel is loaded in one quarter of the core and in the remaining three-quarters there is UOX fuel. Parameter calculation is shown in Fig. 103. Total load is 78 174.8 tons, out of which one quarter of the core, 19 543.7 tons, is MOX fuel and three-quarters of the core, 58 631.1 tons, is UOX fuel. Parameter **corin** for MOX fuel is 19 543.7/1120 = 0.017 449 732 142 857, and **corin** for UOX fuel is 58 631.1/1120 = 0.052 349 196 428 571. Parameter **Con1a** is automatically activated after setting **Constraints**.

Parameter **bdc** (bounds on new capacity addition) is defined in a similar way as "construction of new LWR_MOX reactors is allowed after 2030 and with capacity not more than 1000 MWt per year". Parameter **bdi** (bounds on total installed capacity) means that "system should have at least 1 reactor after 2050". Lower limit 'should have' is defined in drop-down list by **lo** option.

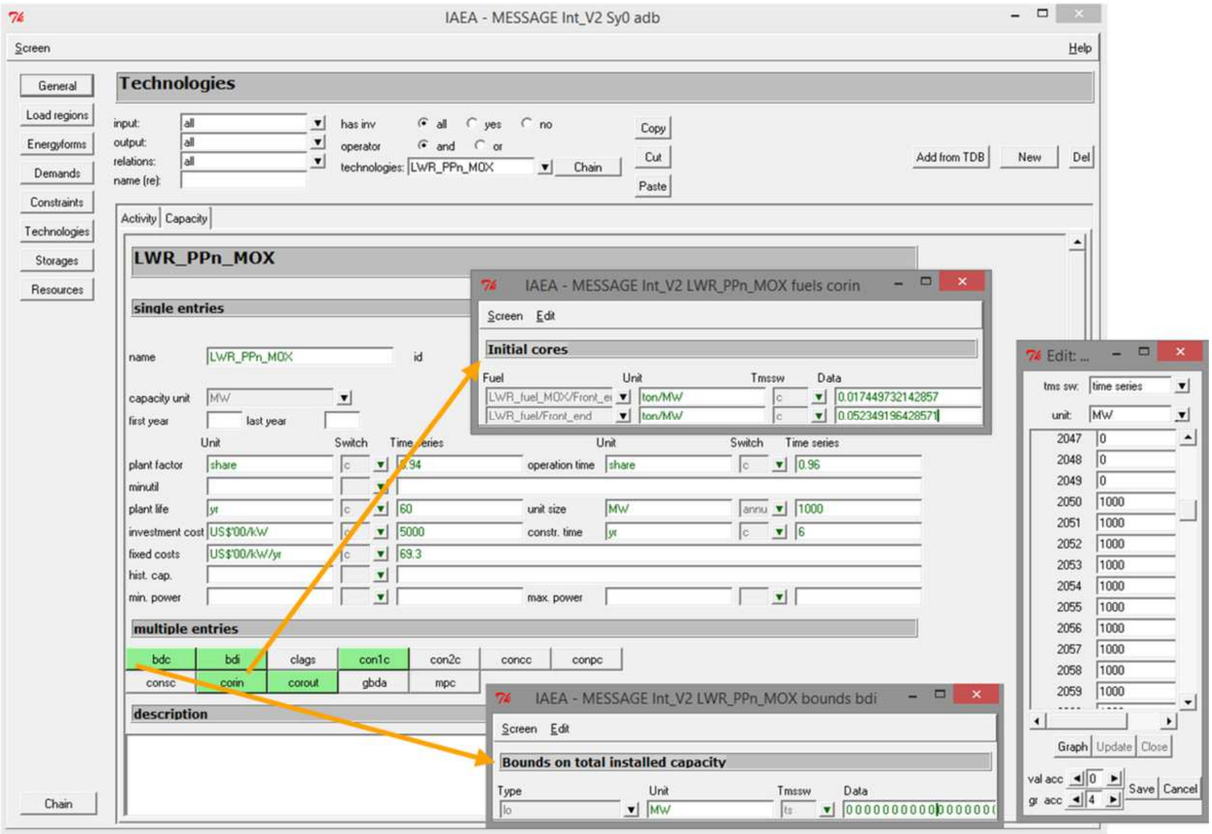


FIG. 103. LWR-MOX first load.

Parameters **inp/outp** for annual reload of MOX fuel are calculated as 4.3164/(1120 × 0.9) = 0.004 281 746 03, and for UOX fuel are calculated as 12.9492/(1120 × 0.9) = 0.0128 464 285 714 285 71. Parameter **Con1a** is automatically activated after setting **Constraints** (Fig. 104).

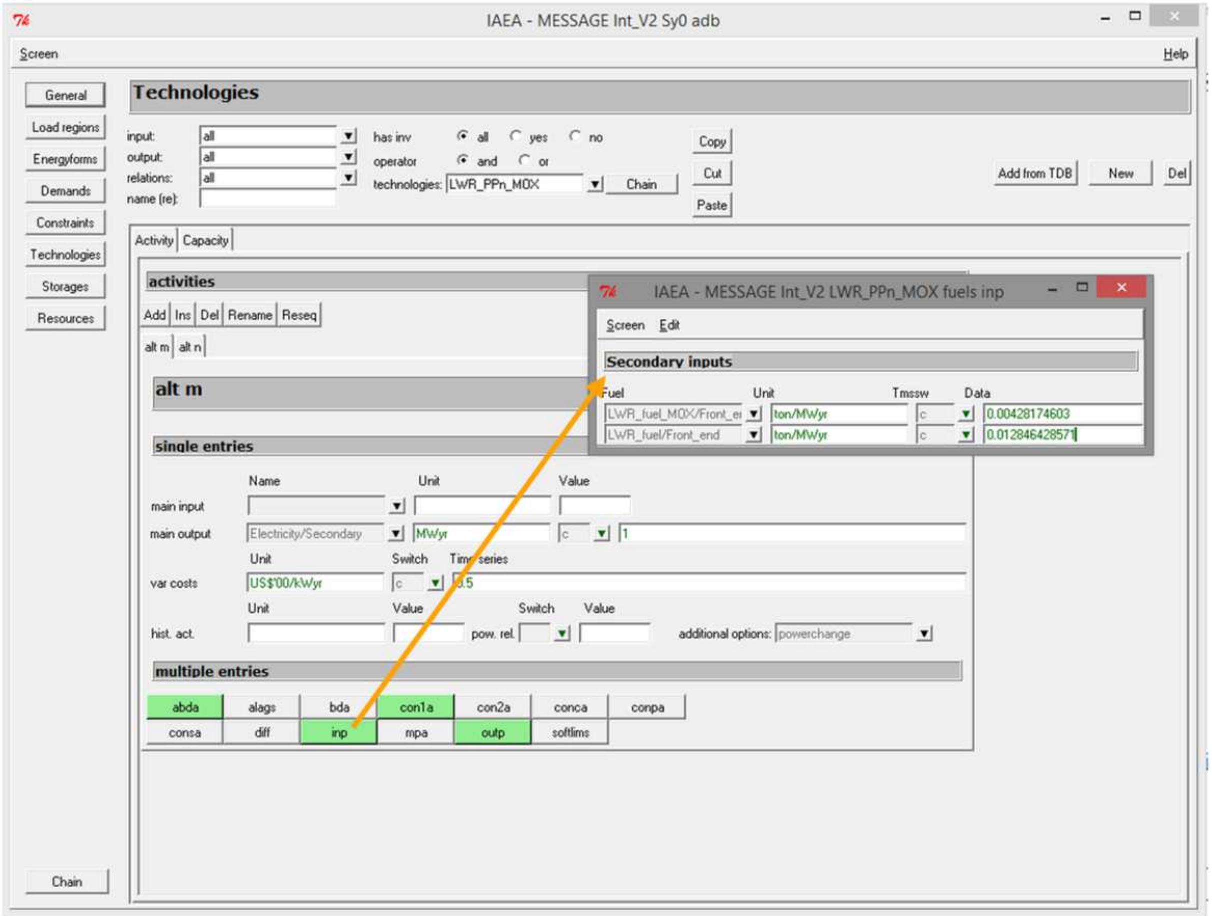


FIG. 104. LWR-MOX annual reload.

To make the model simpler, it was assumed that the spent UOX fuel of the LWR contains plutonium, fission products, minor actinides and reprocessed uranium (Table 41).

TABLE 41. CONTENTS OF SPENT UOX FUEL OF THE LWR

Fraction	**Share**
Plutonium	0.012 131
Fission products	0.051 54
Minor actinides	0.0011
Reprocessed uranium	0.935 18

The modelled technology for reprocessing takes spent fuel from storage (I_LWR) and puts the appropriate fraction into separate storages as Putot (plutonium), FPr (fission products), MAc (minor actinides) and ReU (reprocessed uranium) (Fig. 105).

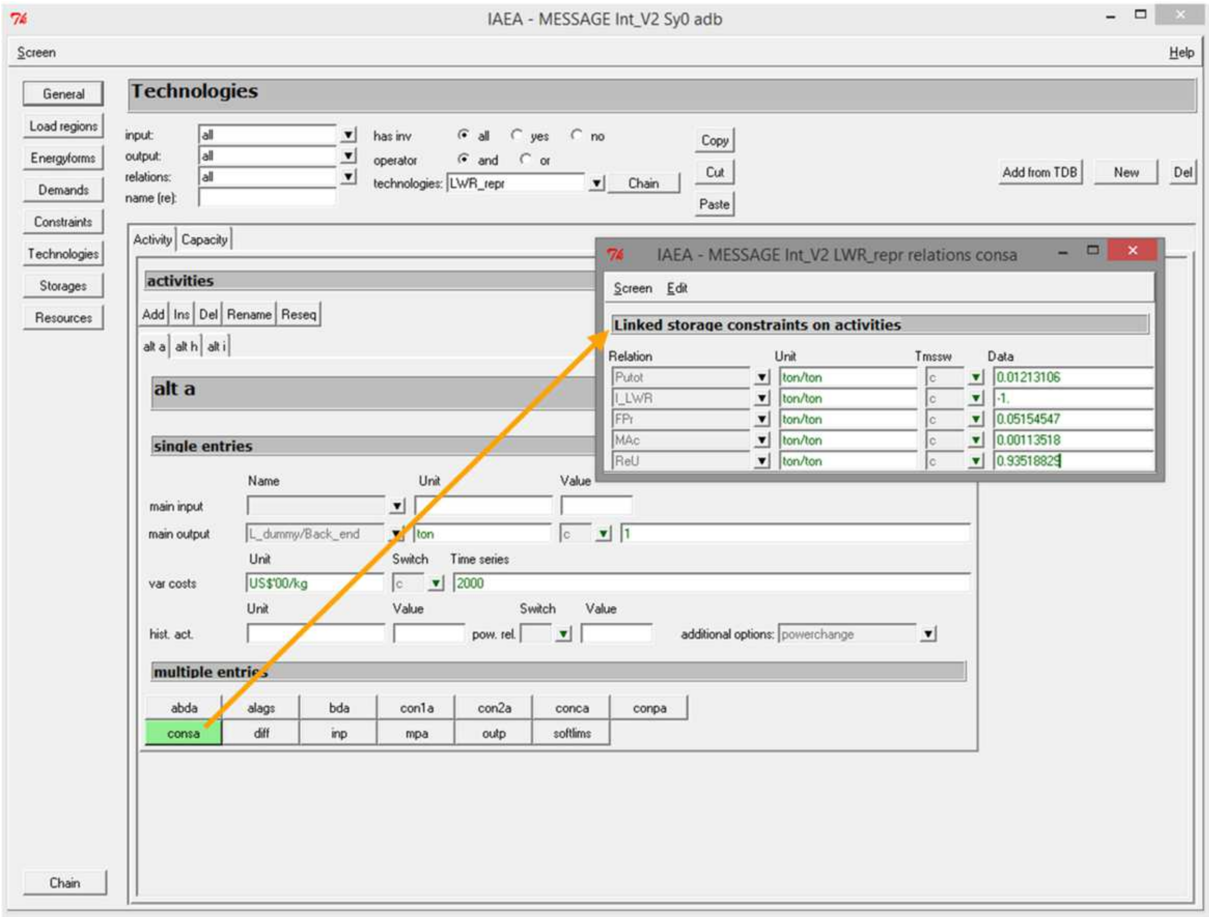


FIG. 105. LWR spent fuel reprocessing.

Modelling of fast reactors

As a rule, blanket and core fuel are modelled for a fast reactor. In this alternative approach one type of fuel is described, because average data are given for fast reactor fuel (Table 42).

Fuel is fabricated from plutonium and depleted uranium. Technology **FR_fuel_fabr** takes plutonium and depleted uranium from storages DepU and Putot with a proportion of DepU/Putot = (-0.718)/(-0.182) and puts one unit of fuel on **main output** (Fig. 106).

Parameters for first core load **corin/corout** are calculated as 41.5/1200 = 0.034 583.

Parameters **inp/outp** for annual reload are calculated as 8.05/(1200 × 0.9) = 0.007 453 703 (Fig. 107). Parameter **Con1a** is automatically activated after setting **Constraints**.

TABLE 42. CONTENTS OF FAST REACTOR SPENT FUEL

Fraction	Share
Plutonium	0.083 09
Fission products	0.0561
Minor actinides	0.003 59
Reprocessed uranium	0.857 22

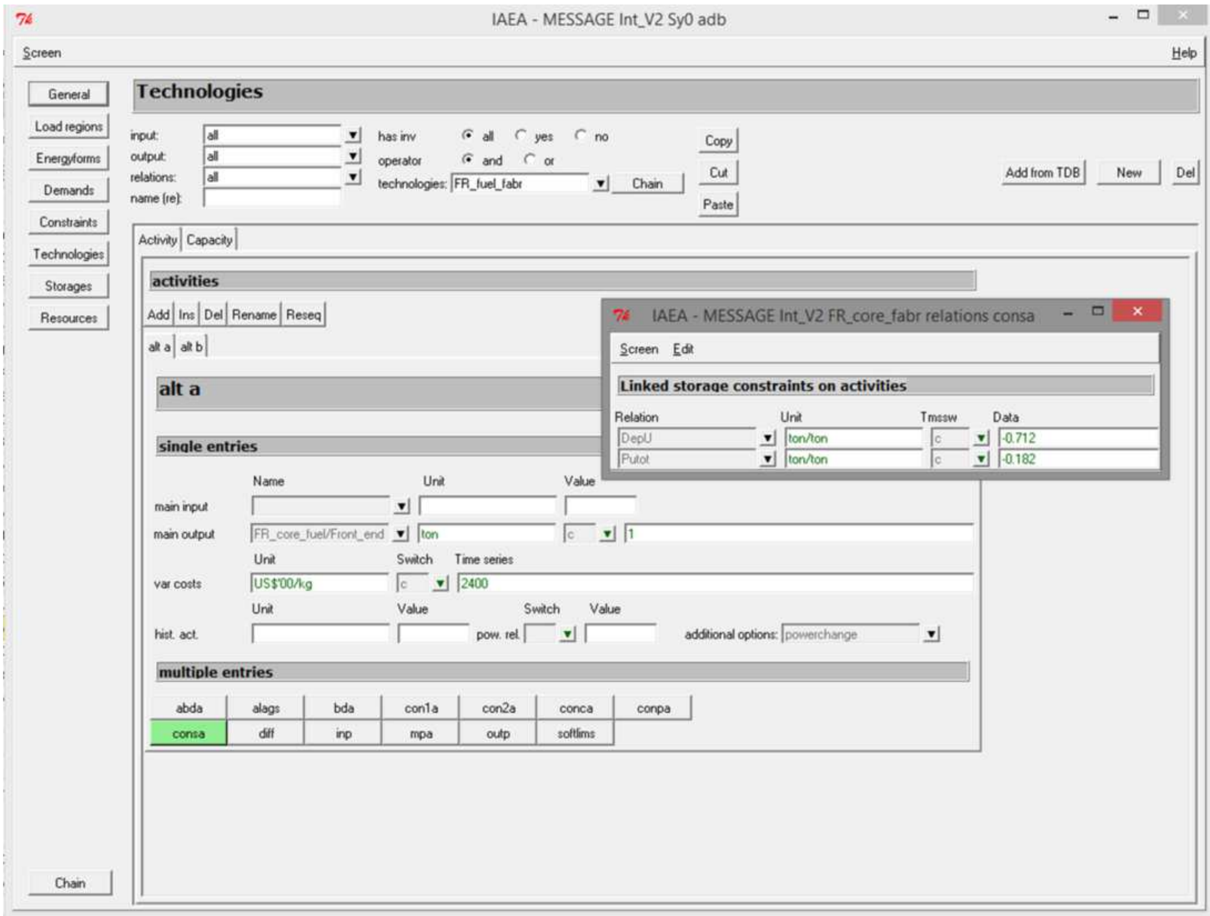


FIG. 106. Fuel fabrication for fast reactor.

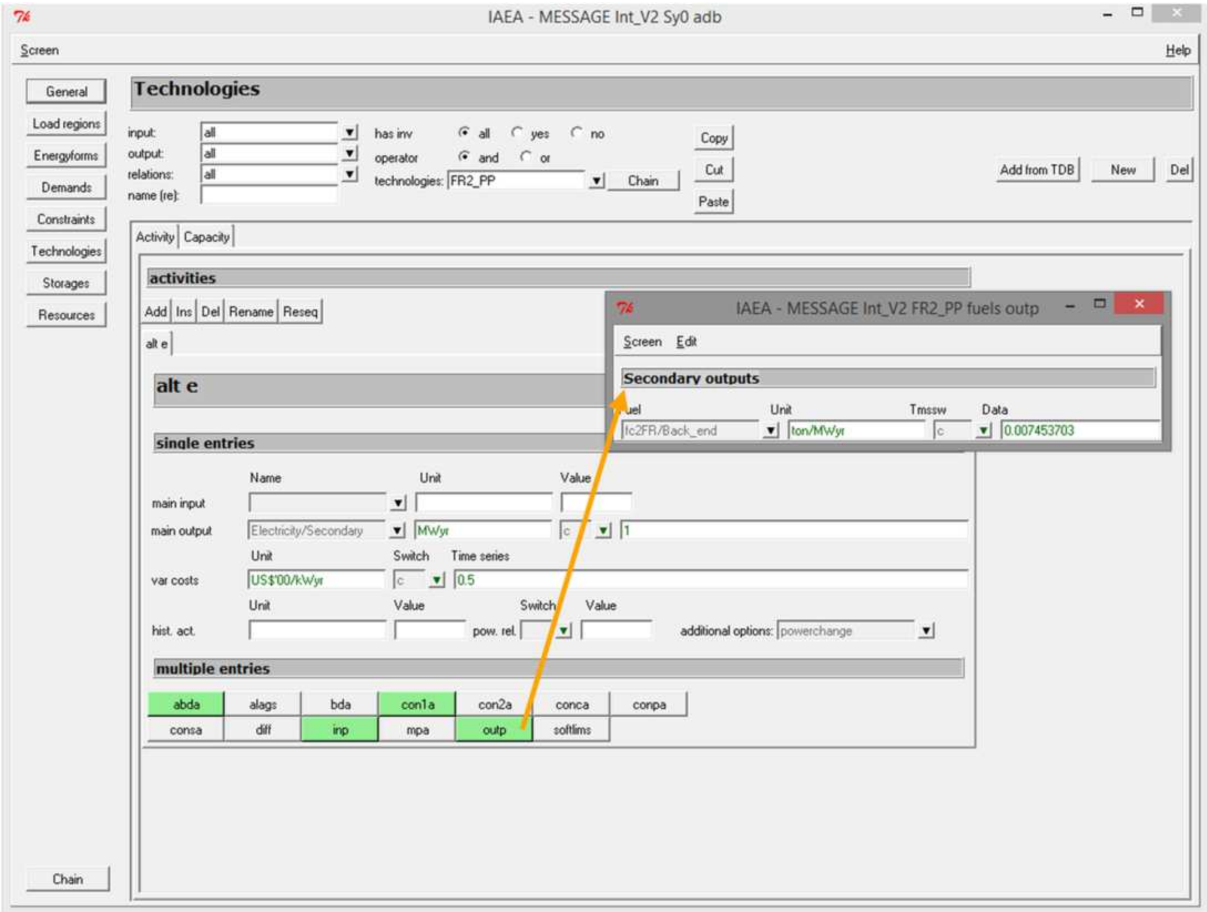


FIG. 107. Modelling of FR annual reload.

Modelled technology for spent fuel transportation from fast reactor to storage (Fig. 108) takes 1 unit of spent fuel from **fc2FR/Back_end** energy level and puts it to storage (I2FR).

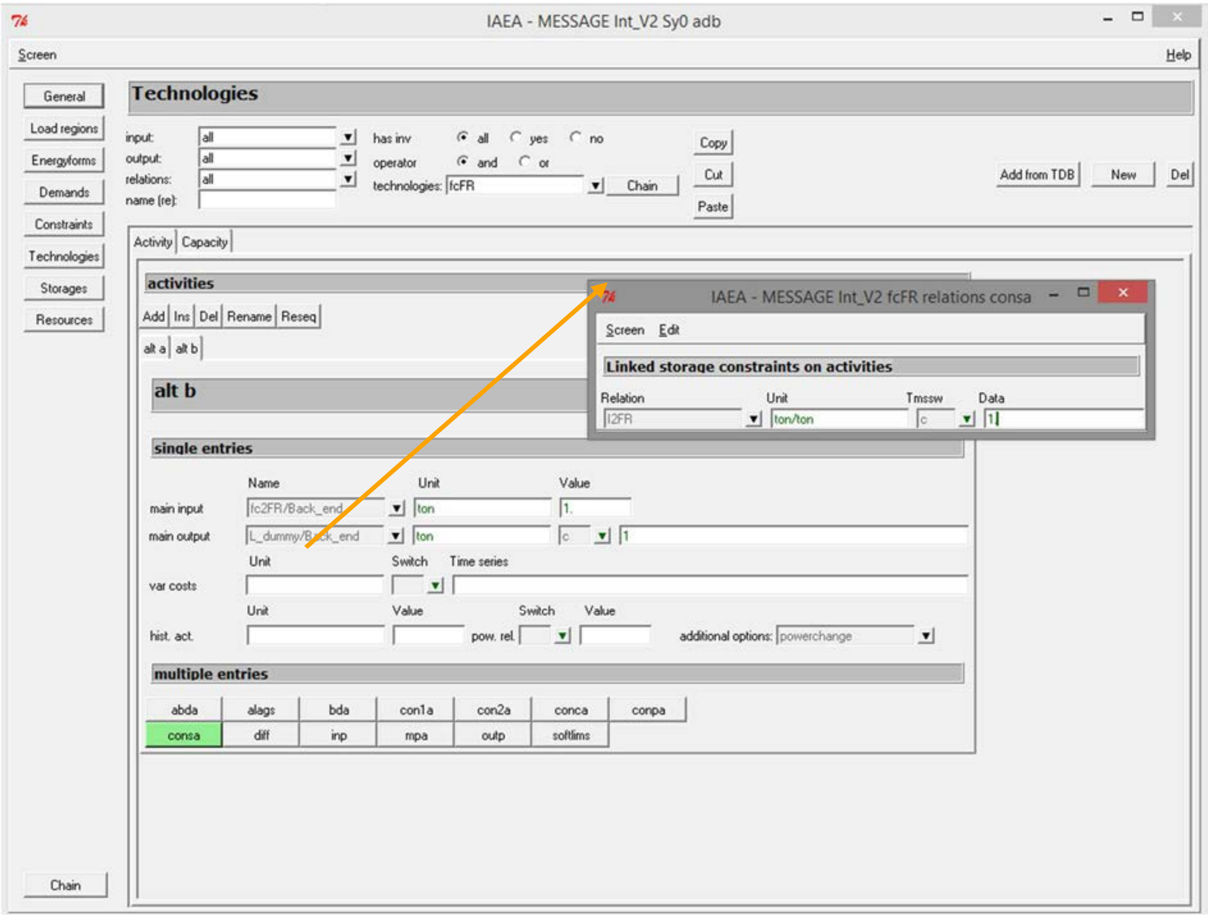


FIG. 108. Spent fuel transportation.

Modelled technology for reprocessing takes spent fuel from storage (I_FR) and puts fractions in separate storages Putot (Plutonium), FPr (Fission products), MAc (Minor actinides), ReU (Reprocessed uranium) (Fig. 109).

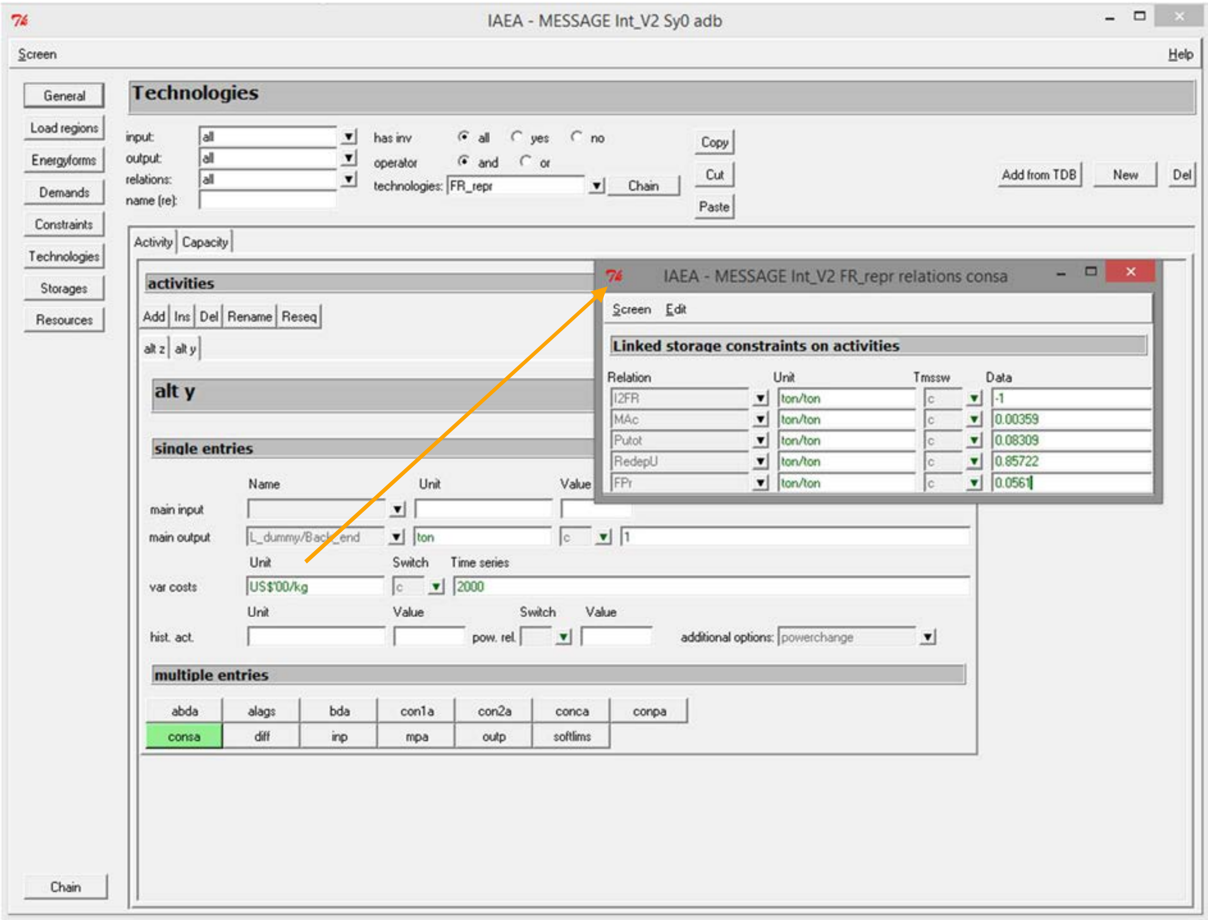


FIG. 109. FR spent fuel reprocessing.

<u>Consideration of load variation in an open fuel cycle</u>

Consideration of daily, weekly and seasonal variations of load would provide a more detailed prediction. However, such MESSAGE calculations require much more computational capacities than were available to the project team. Calculation was, therefore, made considering the load variations only for LWR in the basic scenario.

The schedule of seasonal variations of electricity consumption is presented in Fig. 110 and Table 43. The data provided was averaged over the period from August 2006 to April 2012 in the following way: a year was divided into five periods, in accordance with electricity consumption. The first period covered January, the second covered February and March, the third one covered the months from April to September, the fourth period covered October and November, and the fifth period was December. The duration of these periods was presented in shares of the whole year; electricity consumption for a specific period was presented as a percentage of all electricity consumed during the year. The consumption level shows the average consumption of electricity in a particular month of the period.

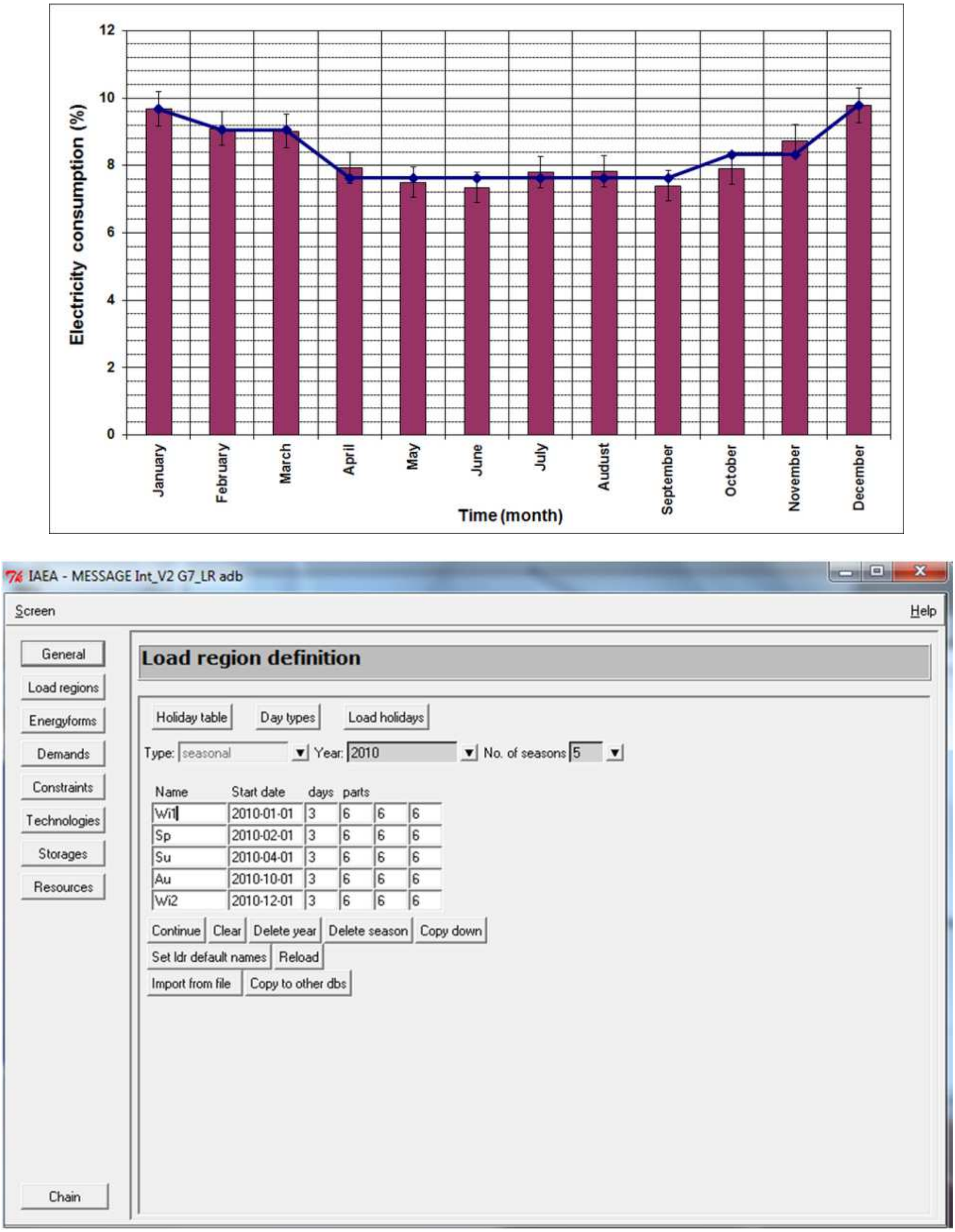


FIG. 110. Seasonal variation of electricity consumption (a line represents a modelling approximation) and its modelling.

TABLE 43. SEASONAL VARIATIONS OF ELECTRICITY CONSUMPTION

Period number	Period duration	Level of consumption in the period (%)	Consumption for the whole period (%)
1	January	9.678 06	9.678 06
2	February–March	9.058 87	18.117 7
3	April–September	7.630 41	45.782 4
4	October–November	8.319 09	16.638 2
5	December	9.783 6	9.783 6
			Total – 100.00

The duration of the day/period was determined as a share of the whole week. The total consumption during the week is 100% and the consumption during the day/period is a share of the consumption during the week (Fig. 111). To perform the calculations, a week was divided into three periods as shown by the column **Period number** in Table 44, working days, Saturday and Sunday, that also complied with the different levels of electricity consumption. Working days of the week were united in one provisional working day, since the form of daily variations in these days does not change significantly.

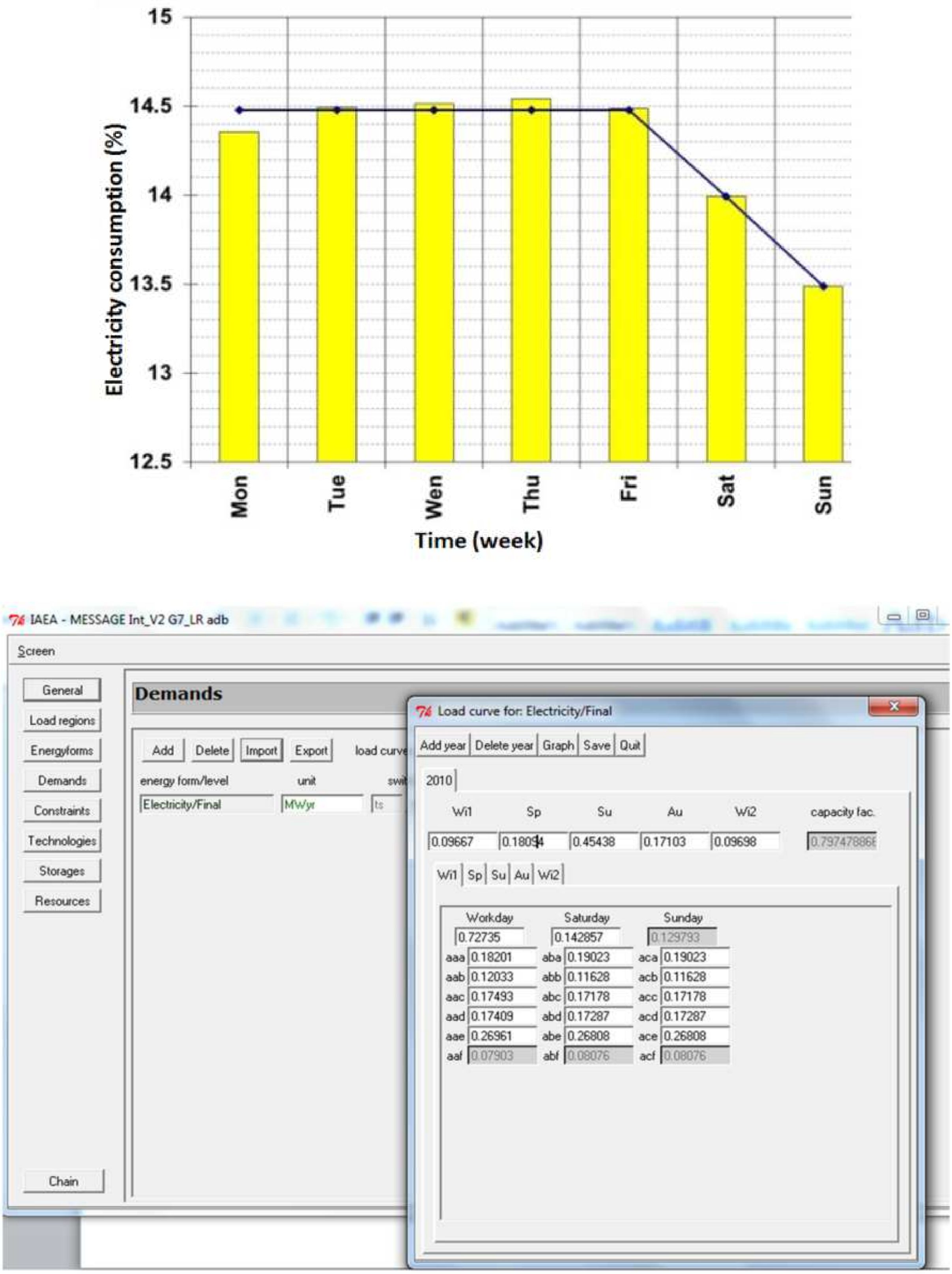


FIG. 111. Weekly variations of electricity consumption (a line represents a modelling approximation) and its modelling.

TABLE 44. WEEKLY VARIATIONS OF ELECTRICITY CONSUMPTION

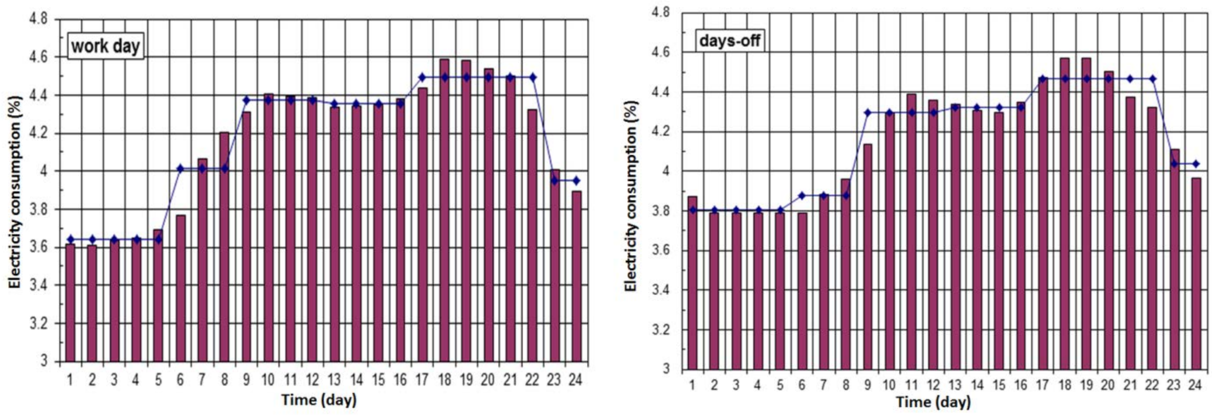
Period number	Period duration	Level of consumption in the period (%)	Consumption for the whole period (%)
1	Monday–Friday	14.516	72.58
2	Saturday	13.98	13.98
3	Sunday	13.45	13.45
			Total – 100.00

Average daily consumption for the working days and days off is presented in Fig. 112. Table 45 shows the split of the day into periods and consumption levels for each period. The indicated data was used in the MESSAGE code.

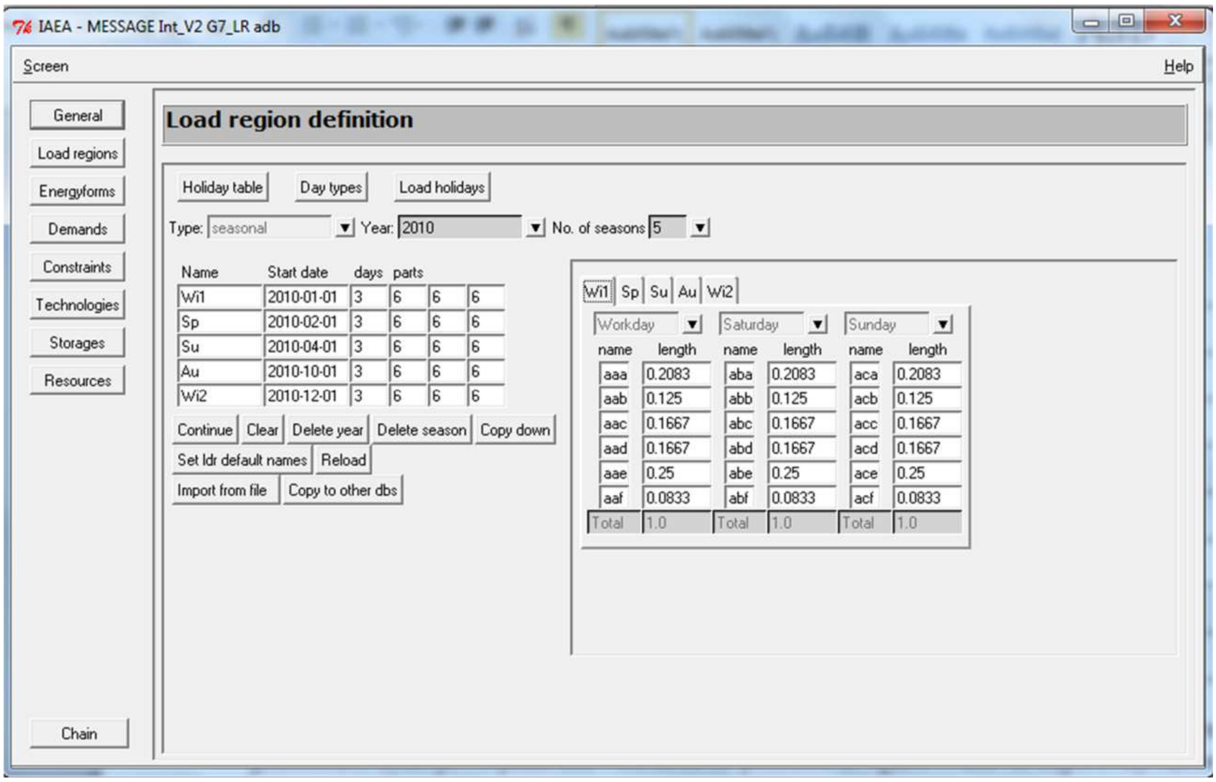
TABLE 45. DAILY CONSUMPTION OF ELECTRICITY (FIG. 112)

Period	Period duration	Daily consumption of electricity (%)	
		Working days	Days off
1–5	0.2083	18.201	19.023
6–8	0.1250	12.033	11.628
9–12	0.1667	17.493	17.178
13–16	0.1667	17.409	17.287
17–22	0.2500	26.961	26.808
23–24	0.0833	7.903	8.076
Total	1	100	100

Electricity generation at hydropower plants and at wind farms is seasonally dependent. Variations in electricity generation at hydropower plants and wind farms are presented in Figs 113 and 114, respectively. As for the hydropower plants, data on the Dnieper River watercourse [59] and open data from State Statistics Service of Ukraine for the period from 2009 to April 2012 were used along with statistical information provided by the Ministry of Energy and Coal Industry of Ukraine [60–62].



(a) (b)



(c)

FIG. 112. Daily consumption of electricity for working days and days off and modelling of day periods in MESSAGE.

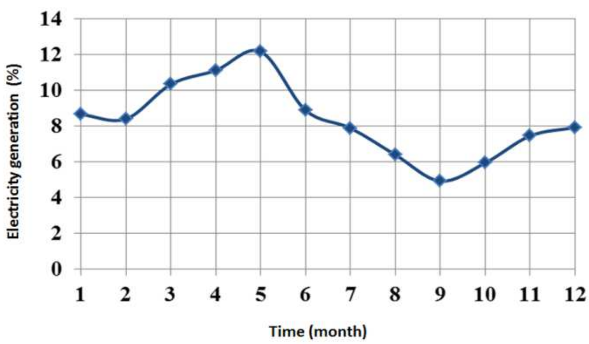


FIG. 113. Seasonal variation of electricity generation at hydropower plants.

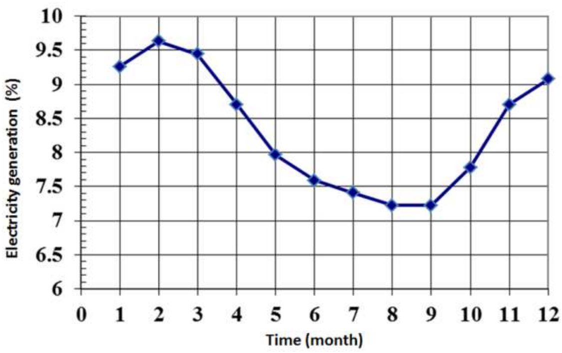


FIG. 114. Seasonal variation of electricity generation at wind farms.

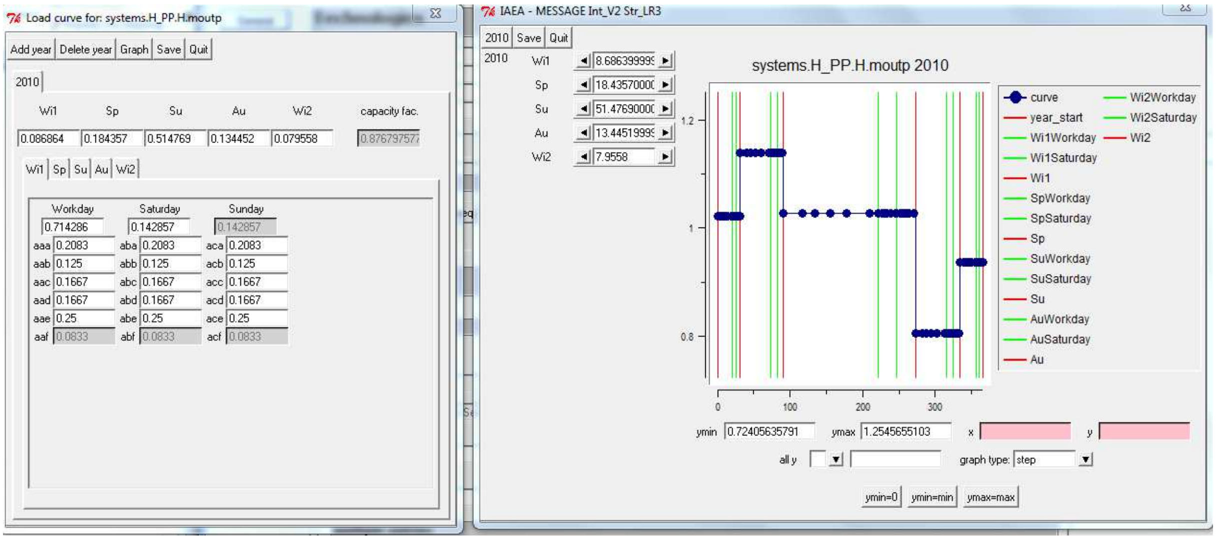


FIG. 115. Modelling of seasonal variation of electricity generation at hydropower plant and wind farms.

Electricity production variation was modelled in the **Technology/activity** tab using the drop box **loadcurves for** with option **moutp** (Figs 115 and 116).

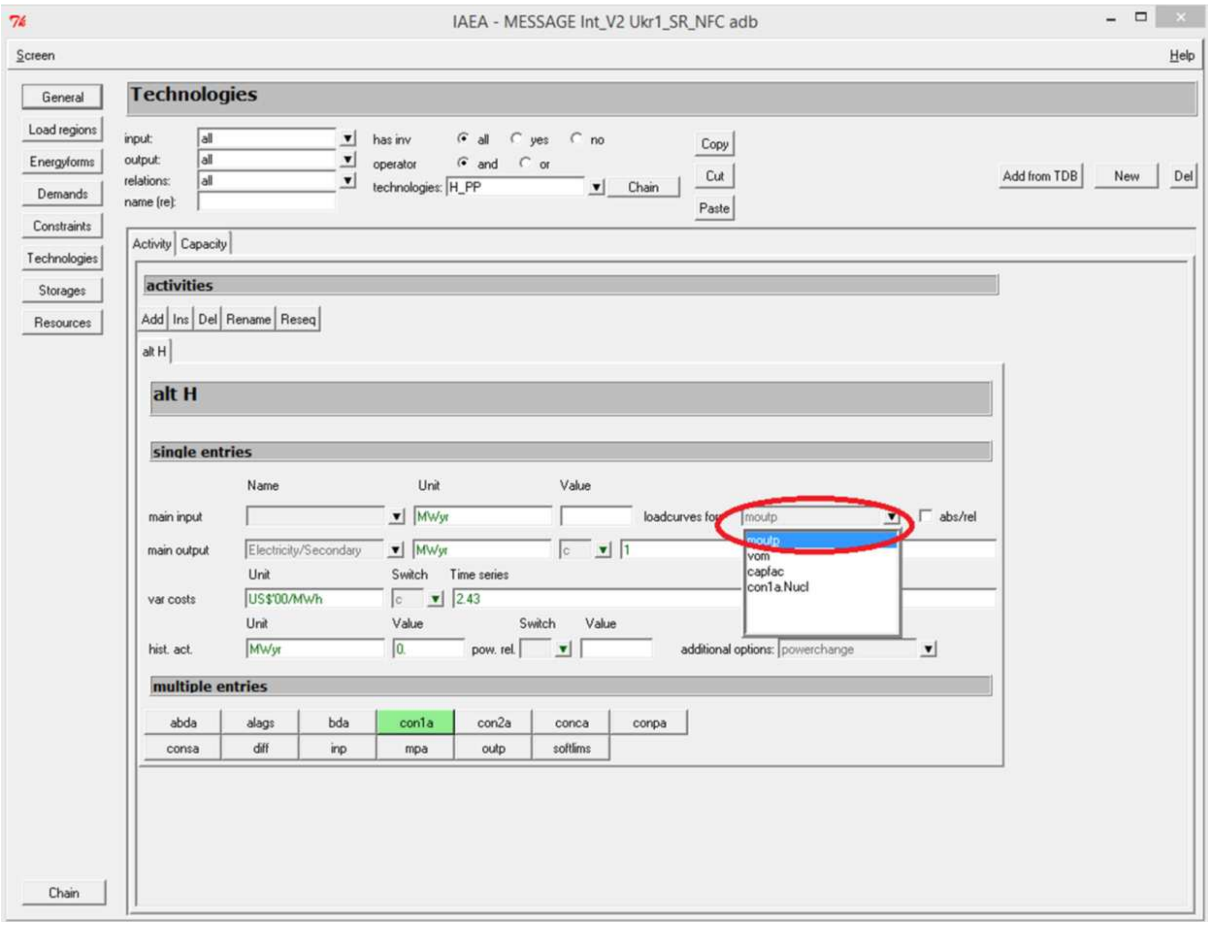


FIG. 116. Modelling of seasonal variation of electricity generation at hydropower plant.

For the wind farms, average annual variations of wind power in Crimea and the southern regions of Ukraine were considered. The impact of intermittent wind power on the energy system was not analyzed.

Electricity generation at solar power plants during the day is presented in Fig. 117.

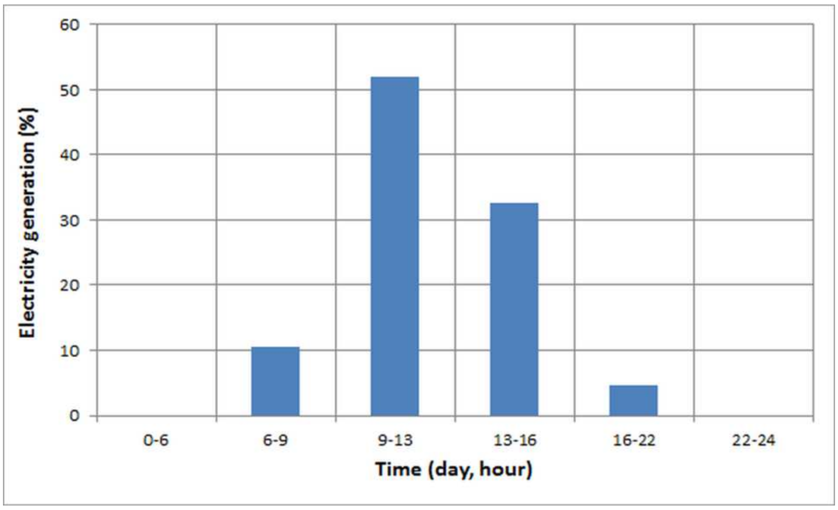


FIG. 117. Daily generation of electricity at solar power plants (annual average).

Table 46 shows the modelling constraints for the power variation rate to create the load diagrams, as well as variations related to electricity generation.

TABLE 46. CONSTRAINTS ON SEASONAL, WEEKLY AND DAILY VARIATIONS OF ELECTRICITY GENERATION

Type	Power change rate during a day (MW/h)	Minimal operational power (%)	Weekly and seasonal variations of electricity generation
NPP	-		No constraints
3–4 KhNPP	10	75	No constraints
LWRn	30	75	No constraints
Coal burning plants	60	75	No constraints
Gas burning plants	150	0	No constraints
Hydropower plants	-	-	Depends on season
Wind farms	-	-	Depends on season
Solar panels	-	-	Depends on time of day

Operating nuclear power plants are not involved in the daily regulation of the load diagram. Constraints are not imposed on any nuclear power plant involved in weekly and seasonal variations. New nuclear power plants are supposed to be able to cover daily variations in consumption, but conservatively the rate of power change is set at the minimal possible level.

Load following mode at coal burning power plants is possible only at the level of 60 MW/h. These plants were assumed to be in half-peak operation without constraints related to the weekly and seasonal variations.

Peak load should be covered by the load following mode of gas turbine power plants. The constraint for this generation type was 150 MW/h.

Hydropower plants, wind farms and solar panels were excluded from the power generation plants that can secure daily load control. Wind and solar energy were excluded due to the intermittent nature of electricity generation from these energy sources. There is no possibility to build large hydropower plants. There is a conservative assumption that hydropower plants will not be able to cover peak loads, considering the increase in consumption and the fact that hydroelectric pumped storage power plants intended to cover peak loads will not be built in time.

2.5.4.2. Discussion on choice and adoption of the MESSAGE tool for case study modelling

The MESSAGE tool was selected as the modelling framework owing to the availability of wide methodological support combined with the possibility of receiving a rapid response from experts at the IAEA.

Available experience of MESSAGE users demonstrates that, once a model is constructed, it could be adopted for specific tasks without significant efforts.

The MESSAGE code can provide a platform for comparison of different nuclear fuel cycles using the approach of cost minimization for entire energy system, taking into account limitation of available resources and availability of fuel market, investment, operating time, waste, etc. The optimal NFC can be defined as a result of the variation in economic and technical parameters. The model is also appropriate for different lengths of the time horizon.

2.5.5. Scope of results and findings of the case study

2.5.5.1. Main outputs calculated with MESSAGE

Open fuel cycle

The scenario considers the possibility of final SNF disposal in a geological repository for LWR SNF. It has no constraints regarding the SNF disposal capacity.

The following assumptions were used when modelling the scenario:

(i) It was assumed that SNF will be transported to the repository (US $600/kg HM) that has no constraints regarding the capacity.

(ii) The CSNFSF was not considered.

The modelling results show that electricity generation at nuclear power plants will increase up to 120 TW.h in the total mix (Fig. 118) if there is a growth of electricity generation at other facilities from 100 TW.h to 180 TW.h. According to their projects, the Kh3 and the Kh4 are the same design as old (installed) reactors. For the Ukraine strategies it is essential to show Kh3/Kh4 separately as new reactors, constructed with proven design. If the electricity consumption in Ukraine increases, a considerable growth of electricity generation at coal-fired power plants will lead to the reduction of NPP share in national energy mix down to 38% (Fig. 119).

In order to maintain the share of nuclear power at the level of 50% in national energy mix, 13 GW of new installed capacities should be commissioned as nuclear power plants in 2030–2050. It causes large financial burdens on the country's economy. To solve the problem, the Updated Energy Strategy 2030 of fuel and energy sector development in Ukraine should be revised and financial expenses should be optimized through the commissioning of more nuclear reactors by 2030.

The commissioning of a significant number of new reactors starting from 2050 will result in NPP share of electricity generation increased up to 50% and this share will not change till 2100 (Figs. 119).

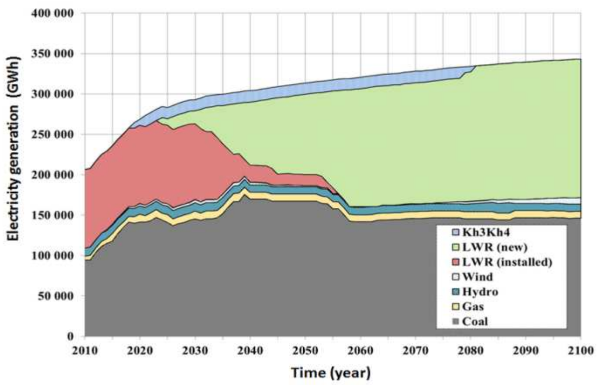


FIG. 118. *Electricity generation structure in total mix for open nuclear fuel cycle scenario.*

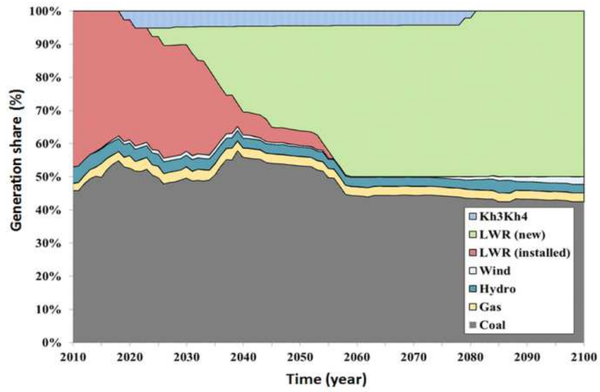


FIG. 119. *Generation share of different electric power plants in energy system for open nuclear fuel cycle scenario.*

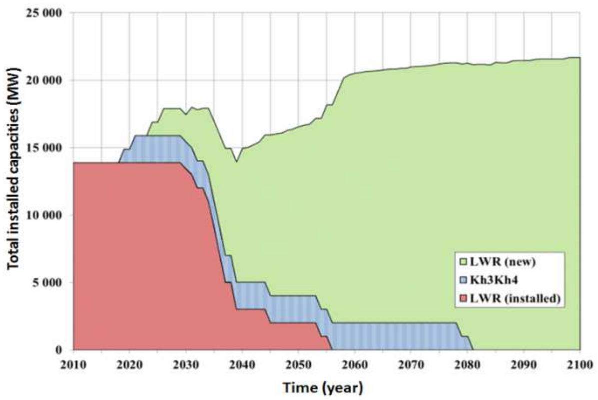


FIG. 120. *Total installed capacities of nuclear power plants for open nuclear fuel cycle scenario.*

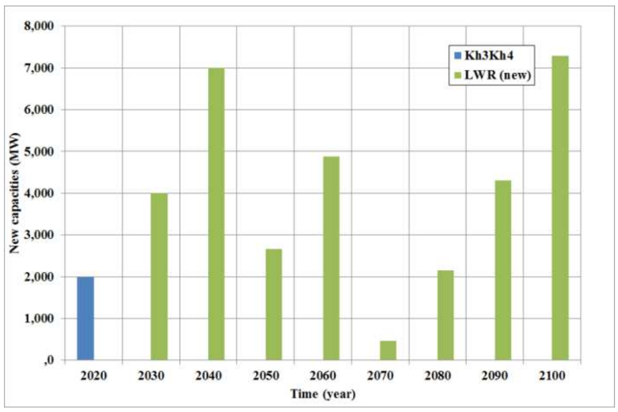


FIG. 121. *Commissioning schedule of new capacities of nuclear power plants for open nuclear fuel cycle scenario.*

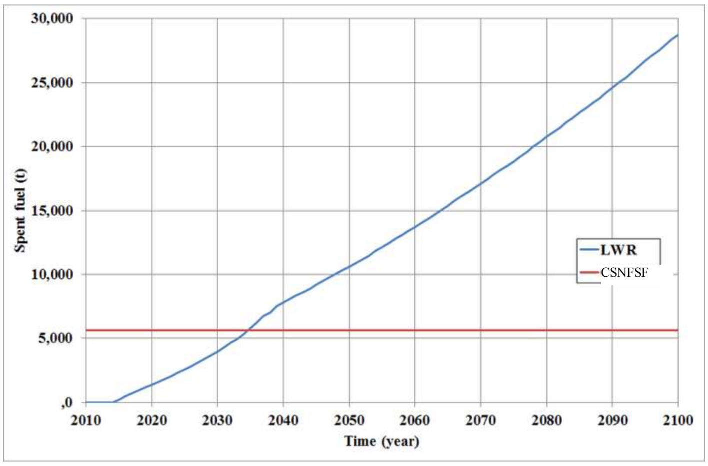


FIG. 122. SNF accumulation and volume of planned CSNFSF for open nuclear fuel cycle scenario.

Large quantities of SNF will be accumulated (up to 30 000 t HM) in the case of a once-through NFC (Fig. 122). This fact may be considered as a deviation from the concept of a sustainable NFC and requires an appropriate solution because SNF disposal will cost approximately the same amount of money as could be spent on six new facilities having the same storage capacity as the CSNFSF.

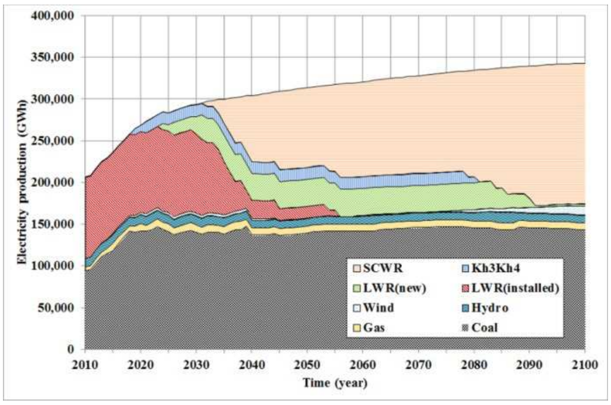
Modelling of super critical water reactor in an open fuel cycle

Significant growth in capital construction costs of nuclear reactors that belong to Generation III and III+ makes fossil-fuelled power plants economically more attractive for the system. The growth of capital construction costs may be related to the fact that safety systems have become more complicated, more time is required for commissioning, while construction delays and fluctuation in exchange rates may also occur.

The construction and operation of SCWR may be considered as a possible solution to this issue. SCWR commissioning is supposed to take place not earlier than 2030.

Owing to the advanced technical specifications of the SCWR, nuclear power's share in electricity generation will remain at the 50% level in 2030–2040. The capacity of new supercritical water reactors that will be commissioned in 2030–2040 will comprise up to 10 GW due to the construction and operational costs optimization and constraints regarding the necessity to have 50% of nuclear power in the energy system of Ukraine (Figs 123–126).

The total amount of accumulated SNF will amount to 25 000 t HM by 2100, as the result of improved nuclear fuel utilization (Fig. 127). This amount of accumulated SNF is similar to the one accumulated in the partially-closed and closed NFC options, although it is much less than the SNF accumulation in a once-through NFC option (up to 30 000 t HM). This is an important outcome, since it does not require expenses for reprocessing and infrastructure development for minor actinides and plutonium storage. Both LWR SNF and SCWR SNF accumulations are found to reach an approximate level of 10 000 t HM by 2100.



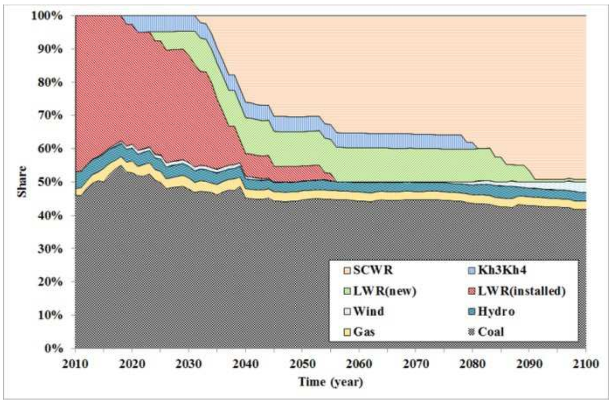
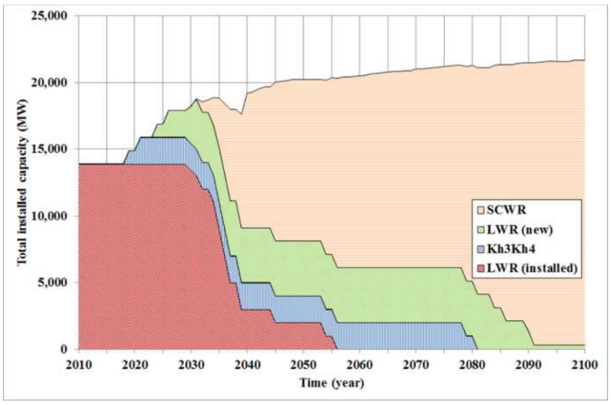


FIG. 123. Electricity generation structure in total mix with conventional LWR and SCWR introduction.

FIG. 124. Generation share for different electric power plants in energy system for scenario of SCWR introduction in open fuel cycle.



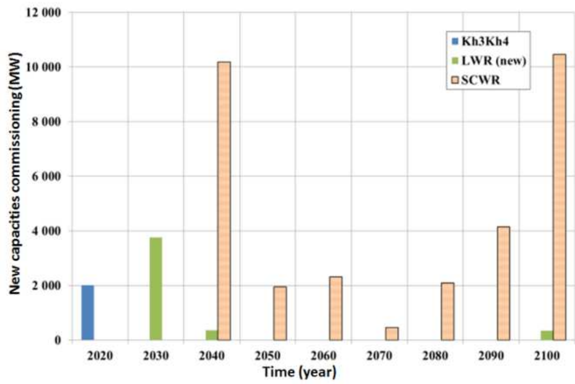


FIG. 125. Total installed capacities of nuclear power plants in energy system for scenario of SCWR introduction in open fuel cycle.

FIG. 126. Commissioning schedule of new capacities of nuclear power plants for scenario of SCWR introduction in open fuel cycle.

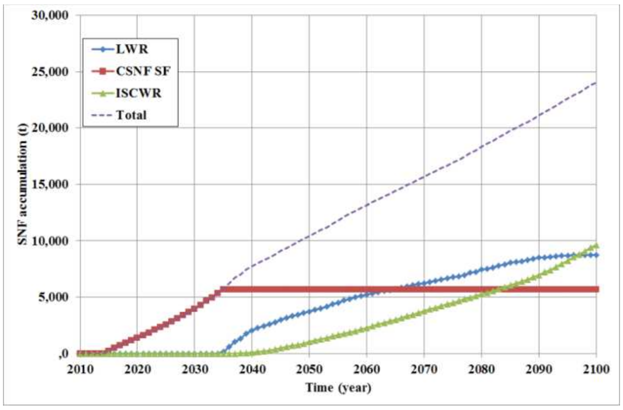


FIG. 127. SNF accumulation for scenario of SCWR introduction in open fuel cycle; CSNFS — accumulation of LWR SNF in CSNFSF; LWR — accumulation of LWR SNF above CSNFSF capacity; ISCWR — accumulation of spent fuel from SCWR.

Utilization of MOX and ReU fuels

This section refers to the scenario of 'partially-closed' NFC, based on a new LWR with MOX fuel and an HWR with fuel made of reprocessed uranium (ReU).

The following constraints were used in the scenario modelling:

(i) SNF reprocessing is possible.

(ii) MOX fuel application is possible after 2030 at new LWR. ¼ of the core will be loaded with this type of fuel.

(iii) The commissioning of the HWR with ReU fuel is possible after 2030, owing to the economic viability of new NFC infrastructure deployment in Ukraine, although only for utilization of the products derived from the LWR SNF reprocessing, as there is no solution to commercial operation of ReU fuel. The impact of CANDU reactors' deployment on the economics of the NFC in Ukraine in the case of UOX fuel operation should also be studied.

(iv) SNF is transported for disposal at disposal cost of US $600/kg HM. The repository capacity is not limited.

The scenario for the optimized model considers the option where several directions of system development may be selected: (a) once-through NFC, (b) supplement of the system with LWR using MOX fuel and/or HWR using ReU fuel with no constraints on the number of reactors using MOX fuel and ReU fuel, and (c) complete transition of the system to the partialclosure of NFC with MOX and/or ReU fuel with no constraints regarding the number of reactors using MOX fuel and ReU fuel.

The modelling results show that there are no reactors with MOX fuel in the system, i.e., LWRs with MOX fuel are 'squeezed out' from the system under initially selected conditions. Additional 'prioritized' (compulsory) commissioning of reactors with MOX fuel is modelled in order to assess potential changes in the nuclear generation structure in favour of partial closure of the NFC. The commissioning of reactors with MOX fuel has a high priority, i.e., one reactor should be commissioned in 2050 since the system itself does not show 'the application viability' of this technology. After 'prioritized' commissioning of one reactor with MOX fuel, their number in the system will grow. MOX fuel is not widely used owing to the high cost of its fabrication and expensive LWR SNF reprocessing.

Nuclear power's share in electricity generation will be reduced in 2040–2050 (Figs 128 and 129) owing to the decommissioning of operating LWR and the financial expenses of commissioning of new reactors with the total capacity of 7 GW after 2030 (Fig. 131).

The results of this study demonstrate that the deployment of the first CANDU reactor can be expected in 2050 are a result of LWR SNF reprocessing and availability of regenerated uranium at zero cost. A reactor of 1 GW with MOX fuel may be commissioned in the same period due to the necessity for plutonium utilization. The optimization model based on MESSAGE code does not consider many reactors with MOX fuel (under given assumptions) because it is not economically viable when there are considerable reserves of natural uranium at costs less than US $120/kg and the MOX fuel fabrication costs at about US $1500/kg HM.

The commissioning of HWRs with ReU fuel is possible after 2030. Since there is plentiful accessible uranium, nuclear power's share will increase up to 50% (Fig. 130). The main reactor type in the system is LWR. Their commissioning is the result of optimization and is related to the availability of regenerated uranium after LWR SNF reprocessing.

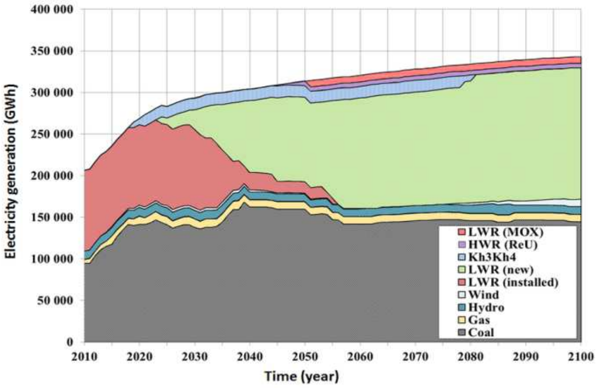


FIG. 128. *Electricity generation structure in total mix for scenario of MOX and ReU fuel utilization; LWR consume UOX and MOX fuel; HWR consume ReU fuel.*

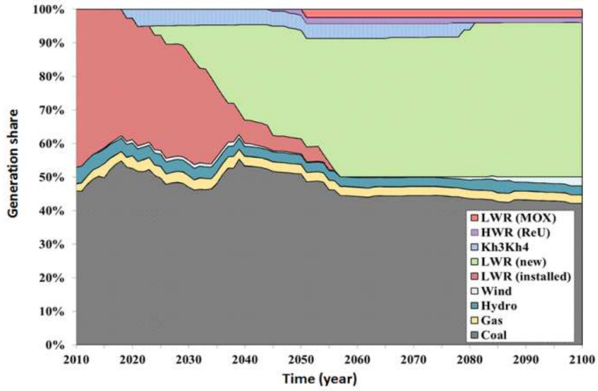


FIG. 129. *Generation share for different electric power plants in energy system for scenario of MOX and ReU fuel utilization.*

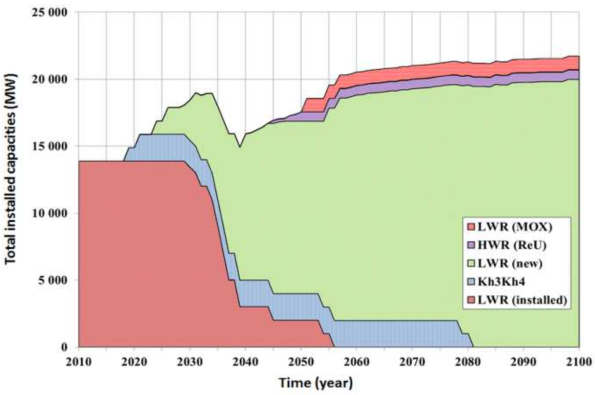


FIG. 130. *Total installed capacities of nuclear power plants in energy system for scenario of MOX and ReU fuel utilization.*

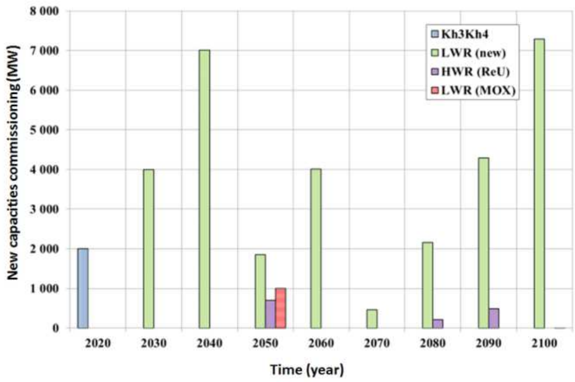


FIG. 131. *Commissioning schedule of new capacities of nuclear power plants for scenario of MOX and ReU fuel utilization.*

The model considers MOX fuel utilization in all WWER reactors starting from 2030 with obligatory condition that more than one reactor will be in operation in 2050. It requires SNF reprocessing to extract enough plutonium for MOX fuel fabrication and, as a result, there will be regenerated uranium available at zero cost. The LWR SNF reprocessing based on current assumptions regarding the reactor and NFC technical and economical parameters, as indicated in the Table 37, is not economically viable. An additional study needs to be performed regarding the issue of inventory balance distribution and the economic viability of MOX fuel utilization at nuclear power plants in Ukraine.

SNF accumulation for this option is presented in Fig. 132. LWR SNF is reprocessed and the spent MOX fuel and HWR ReU fuels are accumulated. There is not much spent MOX fuel because only one reactor is in operation (one quarter of the core is loaded with MOX fuel). The model considers 'separate' disposal for spent ReU fuel. The construction cost of the repository is US $600/kg HM.

Regenerated uranium may initially get accumulated before HWR commissioning. It is extracted from LWR SNF in reprocessing and later is used as fuel. The projection for reprocessing of the accumulated products is presented in Fig. 133.

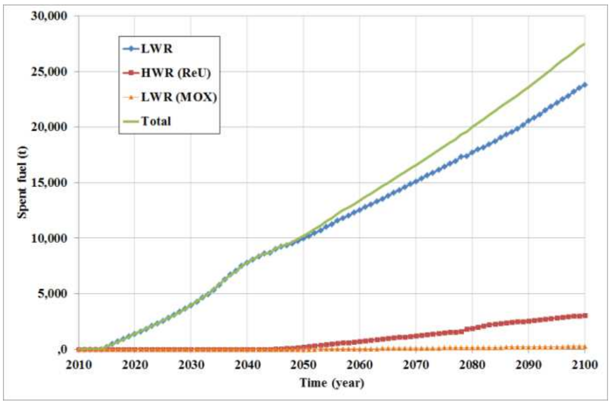


FIG. 132. SNF accumulation for scenario of MOX and ReU fuel utilization; LWR: accumulation of UOX spent fuel from LWR reactors; HWR (ReU): accumulation of HWR spent fuel; LWR (MOX): accumulation of MOX spent fuel from LWR reactors.

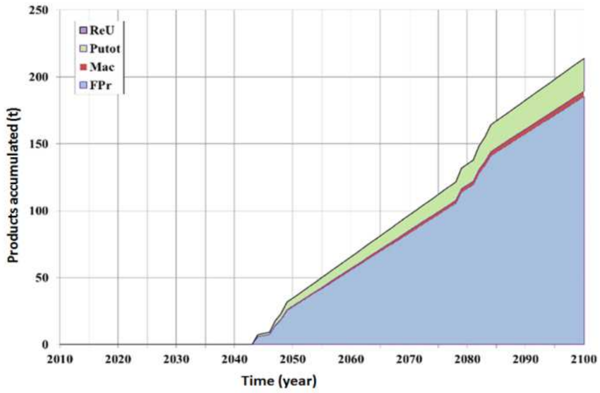


FIG. 133. Accumulation of products derived from reprocessing for scenario of MOX and ReU fuel utilization; Specified accumulated volumes of regenerated uranium (ReU), extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr).

Modelling of fast reactors — LWR SNF disposal

The configuration considers commissioning of reactors of all types: LWR with UOX and MOX fuel, HWR with ReU fuel and FR with MOX fuel. The model considers the possibility of LWR SNF disposal.

The following constraints were used in the scenario modelling:

(i) LWR and FR SNF reprocessing is possible;

(ii) MOX fuel use is possible after 2030. One quarter of the core will be loaded with this type of fuel;

(iii) The commissioning of HWR with ReU fuel is possible after 2030;

(iv) The commissioning of FR is possible after 2030;

(v) The opportunity for LWR SNF disposal is considered (US $600/kg HM), with no constraints regarding the repository capacity;

(vi) The opportunity for spent MOX fuel disposal is considered (US $600/kg HM), with no constraints regarding the repository capacity;

(vii) HWR SNF (ReU fuel) is transported for disposal at the cost of US $600/kg HM,capacity of the repository is not limited.

The modelling results show that only LWR will be in the system if the selected initial conditions and assumptions are considered. This is conditioned by the low commissioning capital costs, low cost of UOX fuel fabrication, high costs of SNF reprocessing services and considerable reserves of natural uranium.

To assess potential impact of MOX fuel and FR deployment on the system, obligatory commissioning of one LWR with MOX fuel and of one FR is considered by 2050. The LWR with UOX fuel remains the main reactor type in the system.

Considering the model requirement that necessitates MOX fuel reprocessed from LWR SNF to be used in the LWR, the NFC is automatically complemented with HWR with the ReU fuel that can be commissioned not earlier than 2030.

The modelling results show a reduction of the nuclear power's share to 40–43% from the existing level as a result of the decommissioning of operating reactors and of the low tempo of commissioning of the replacement reactors, both as considered in the updated energy strategy of fuel and energy sector development in Ukraine until 2030 (Figs 134–137). This result complies with the previously obtained results for the once-through NFC and the partially closed NFC, which proves the model correctness.

A condition to maintain a 50% nuclear share in the energy system of Ukraine requires commissioning of a significant amount of nuclear capacities in 2030–2040, which would impose a significant financial burden on the country's economy and which cannot be considered as a realistic scenario. The total installed capacity of new LWR will make up 7 GW in this period.

The operation of reactors with MOX fuel and of one FR with plutonium fuel in 2050 requires LWR SNF reprocessing in the NFC with the deployment of one HWR with ReU fuel in the indicated period (Fig. 137). It should be noted that there are no limitations regarding the number of LWR with MOX fuel and FR in the model of this study. However, taking into account technical and economic parameters of the reactors and NFC, the commissioning of these reactors is performed at a minimal level and is related to the absence of restrictions regarding the amount of accumulated LWR SNF, the natural uranium reserves and the related costs.

The results regarding the accumulation of SNF and reprocessing products are similar to the option based on a partially-closed NFC due to a low share of FR in NFC. The total amount of accumulated SNF will make up to 28 000 t HM including 4 000 t HM of HWR SNF and 24 000 t HM of LWR SNF. The total amount of accumulated spent MOX fuel and FR SNF will be less than 1 000 t HM by 2100 (Fig. 138). Thus, the main contributors to SNF accumulation are spent fuel from the reactor options of LWR with UOX fuel and HWR with ReU fuel. Spent MOX fuel from LWR and spent fuel from FR are produced in negligible quantities as compared to the total amount of the spent nuclear fuel.

The small amount of reprocessed LWR SNF corresponds to the small amounts of the obtained reprocessing products (up to 200 t HM). The amount of extracted plutonium is about 20 t HM. The impact of plutonium storage costs on the NFC economy needs to be analysed in additional study (Fig. 139).

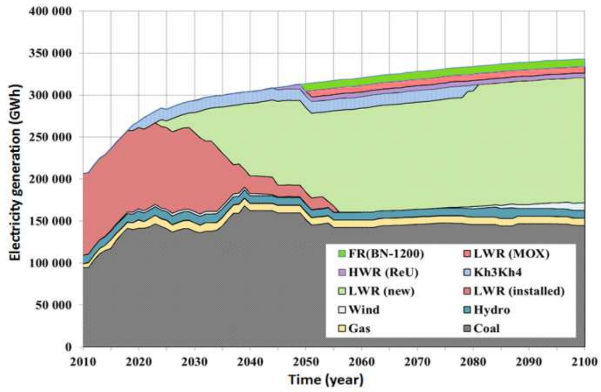


FIG. 134. *Electricity generation structure in total mix for modelling scenario of FR with LWR SNF disposal.*

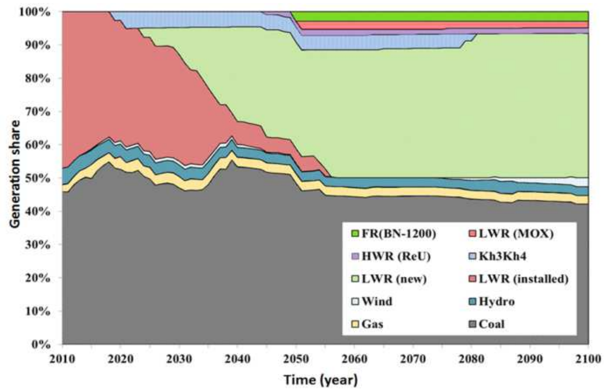


FIG. 135. Generation share for different electric power plants in energy system for modelling scenario of FR with LWR SNF disposal.

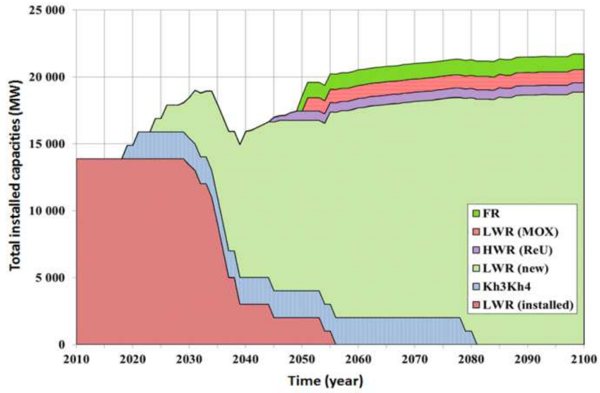


FIG. 136. Total installed capacities of nuclear power plants in energy system for modelling scenario of FR with LWR SNF disposal.

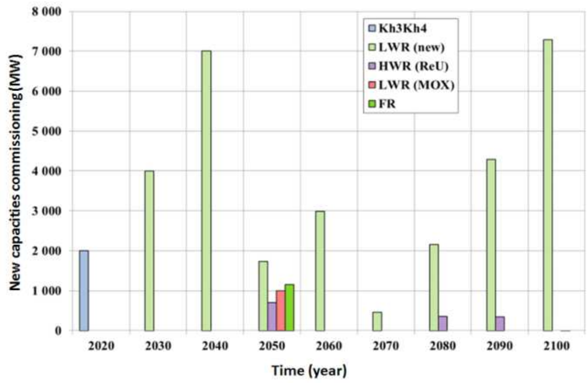


FIG. 137. Commissioning schedule of new nuclear capacities for modelling scenario of FR with LWR SNF disposal.

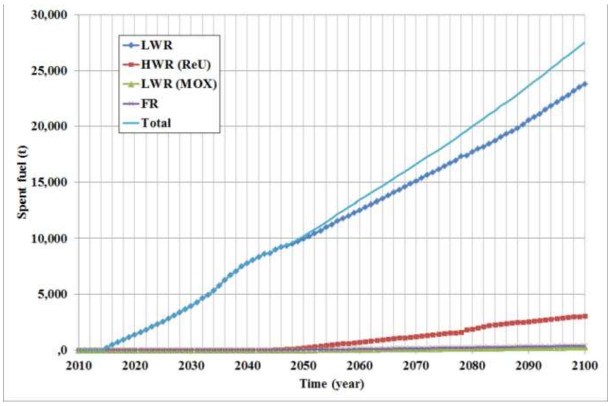


FIG. 138. SNF accumulation in the system for modelling scenario of FR with LWR SNF disposal.

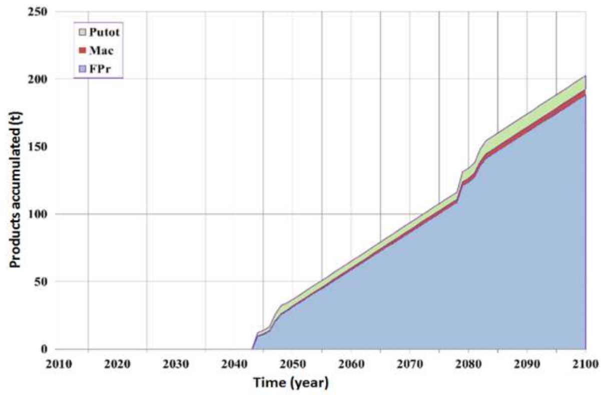


FIG. 139. Accumulation of products derived from reprocessing for modelling scenario of FR with LWR SNF disposal; Specified accumulated volumes of extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr).

Modelling of fast reactors — CSNFSF commissioning and LWR SNF disposal

This scenario considers the impact of the CSNFSF costs and capacity on the general indicators of the NFC.

Taking into account the modelling results, it should be noted that the nuclear share in electricity generation (Figs 140 and 141), the schedule of new/replacement reactors commissioning (Figs 142 and 143), and the SNF accumulation up to 2100 are similar to the previously studied scenario.

According to the scenario, the total amount of SNF to be accumulated by 2100 will be 27 000 t. In the case when CSNFSF is commissioned in 2015, it will be filled completely by 2035 (Fig. 144).

If SNF is reprocessed, 150 t of high level waste will be accumulated (Fig. 145). LWR with UOX fuel is the main reactor type in the system. The amount of accumulated SNF will not change as it will in the scenario without CSNFSF construction.

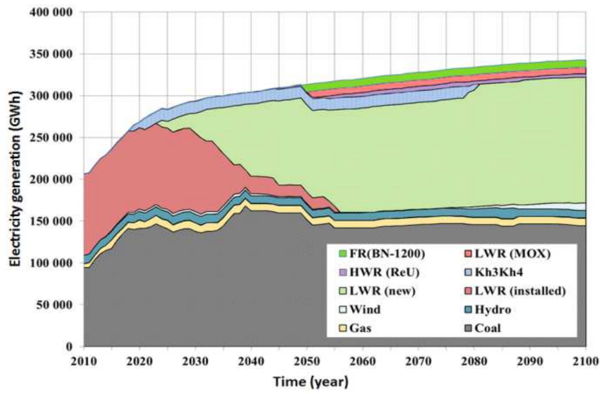


FIG. 140. Electricity generation structure in total mix for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal.

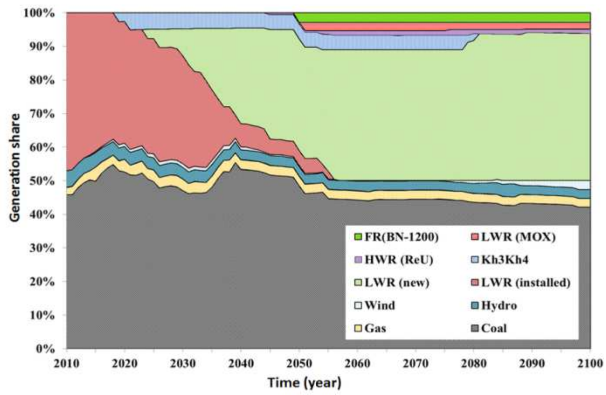


FIG. 141. Generation share for different electric power plants in energy system for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal.

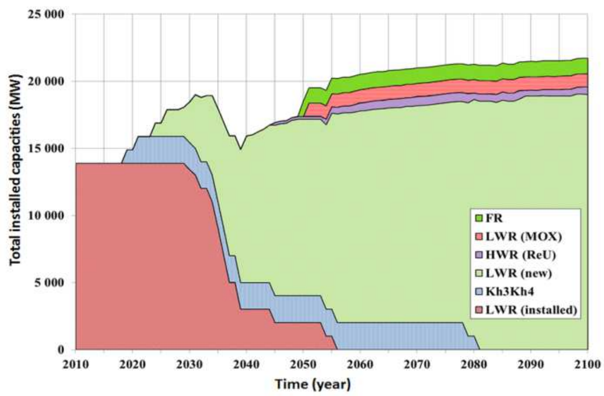


FIG. 142. Total installed capacities of nuclear power plants for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal.

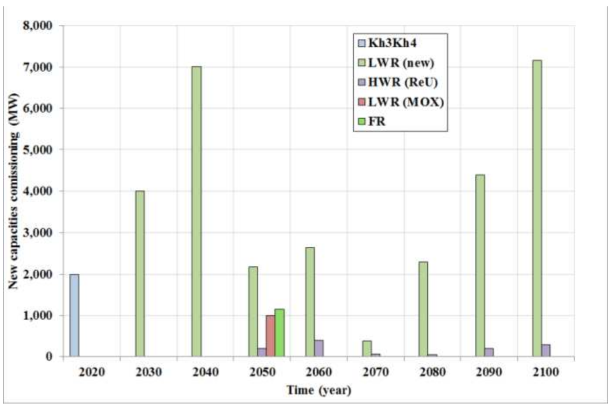


FIG. 143. Commissioning schedule of new nuclear capacities for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal.

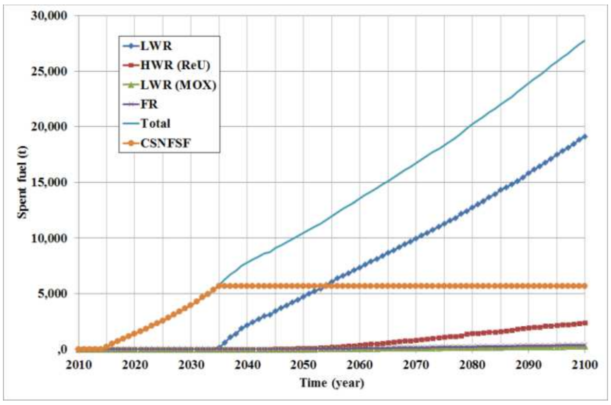


FIG. 144. SNF accumulation for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal.

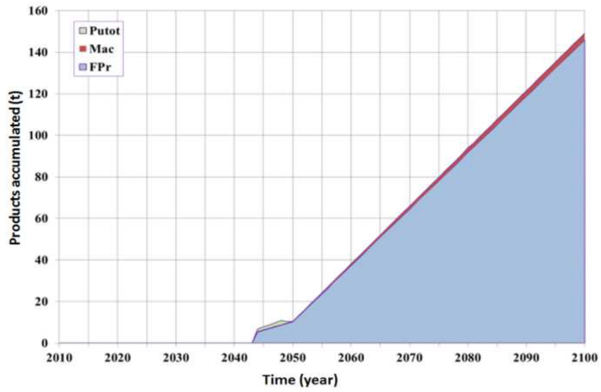


FIG. 145. Accumulation of products derived from reprocessing for modelling scenario of FR with CSNFSF commissioning and LWR SNF disposal. Specified accumulated volumes of extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr).

2.5.5.2. *Consideration of load variations in the open fuel cycle*

The difference between the basic scenario (without load variation) and the option where NPP installed capacities consider load variations is provided in Figs 146 and 147.

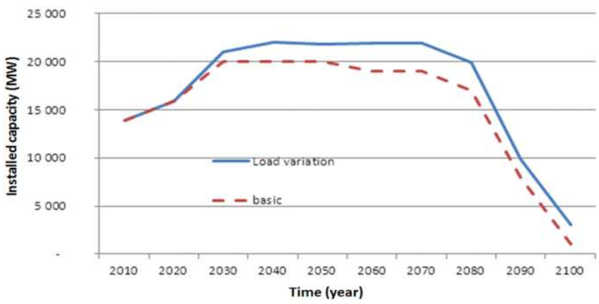


FIG. 146. Comparison between scenarios with load variation and without load variation (basic) regarding installed capacities of NPP.

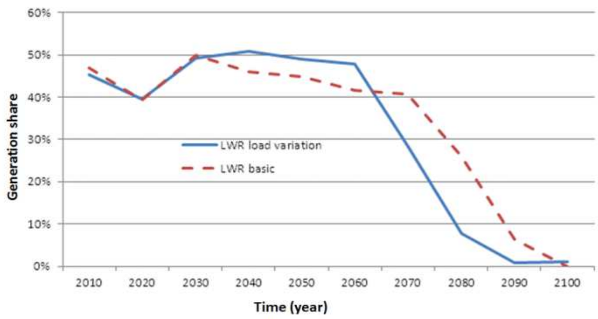


FIG. 147. Comparison between scenarios with load variation and without load variation (basic) regarding nuclear share of electricity generation in total mix.

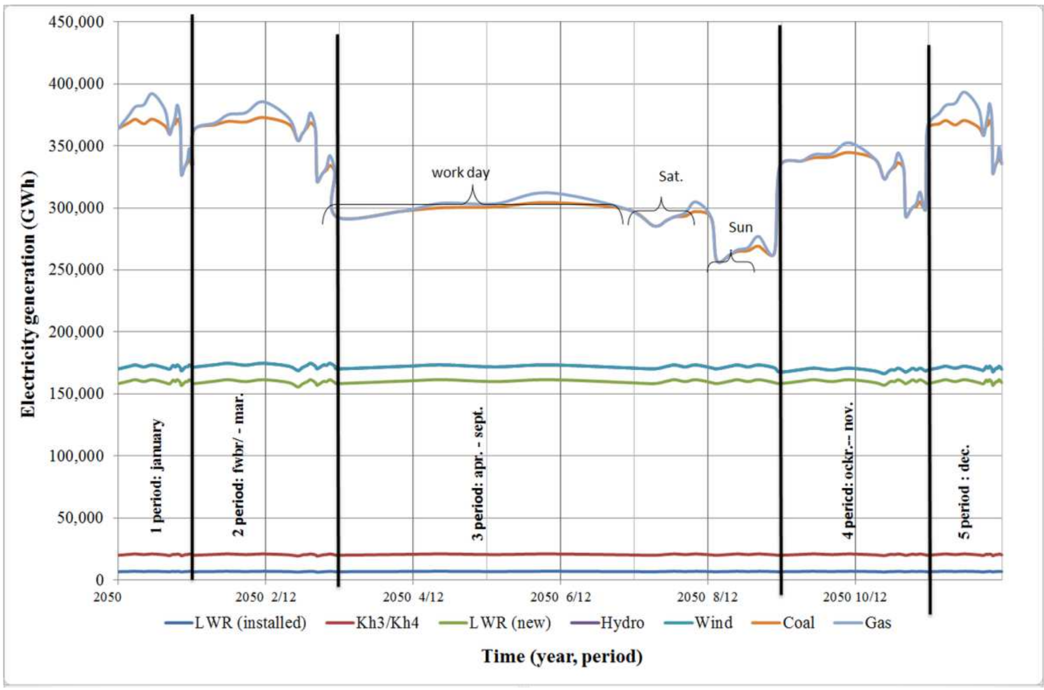


FIG. 148. Energy mix in 2050 for scenario with load variation (average annual data).

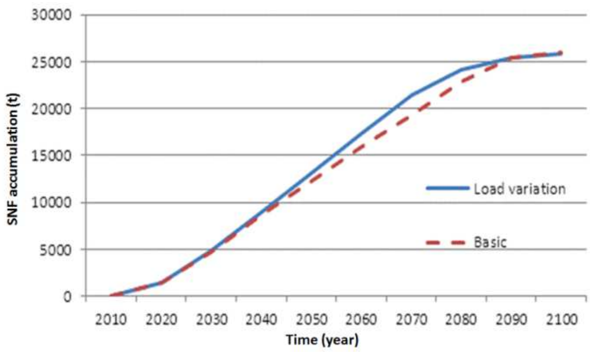


FIG. 149. Comparison between scenarios with load variation and without load variation (basic) regarding SNF accumulation.

Nuclear generation provides a stable level of electricity generation throughout the whole year. However, at times, when electricity consumption is low, the nuclear share exceeds the share of other generation sources (third period in Fig. 148, including Saturday and Sunday). It contributes to an increase in nuclear share as compared to the calculation with no account of load variations, as well as to a corresponding increase of the installed capacities (Figs 146 and 147) and SNF accumulation (Fig. 149).

2.5.5.3. Main conclusions and findings of the case study

Major findings of the case study

Once-through nuclear fuel cycle

If the concept of 'postponed decision' regarding SNF management is implemented, electricity generation at nuclear power plants with a once-through NFC would remain competitive.

Nuclear power's share would be maintained at the 50% level if nuclear power units are operated with a higher capacity factor (up to 80% and more) and fuel burnup rate is more than 60 MW·d/kgU. However, the implementation of this concept will lead to a non-compliance with the United Nations concept of sustainability [1] and result in accumulation of large quantities of the SNF, thus, increasing the burden for future generations who will then have to deal with its final disposal.

The operational nuclear power plants are expected to be decommissioned in 2030–2040. To keep the NPP share at 50% in the Ukraine's energy mix, about 7 GW of new capacity will have to be commissioned. This would impose a financial burden on the country's economy and cannot be considered a plausible scenario. Thus, the reduction in NPP share in electricity generation in Ukraine has to be considered, or relevant amendments should be made to the updated energy strategy for fuel and energy sector development in Ukraine after 2030, in order to envisage the commissioning of a large number of new reactors by 2030.

It is reasonable to consider the revision of lifetime extension approach in relation to operating nuclear power plants of 1 GW electrical capacity. This would make it possible to optimize financial expenditures for the construction and operation of new reactors, by commissioning of the reactors with larger installed capacity.

A large amount of SNF is produced in a once-through NFC — about 27 000 t HM.

As it can be seen, CSNFSF commissioning with the capacity of 5650 t HM does not allow to fully implement the strategy of 'postponed decision'. If nuclear share in electricity generation remains at 50% and electricity consumption increases in a once-through NFC, considerable amount of SNF will be produced and the CSNFSF will be filled out completely by 2035. Under such circumstances, there will be no reduction in the rate of SNF accumulation. SNF will have to be removed from 2065 to 2085 and the SNF transportation rate may also increase in this period. By 2035, following decisions should be made:

(a) Construction of additional intermediate storage facility that will make it possible to save time for making the final decision;

(b) Final disposal or reprocessing of the LWR SNF.

Products derived from WWER-400 SNF reprocessing are returned to Ukraine under the contract. This approach will probably be applied to WWER-1000 SNF as well. It would require construction of relevant infrastructure for HLW management

<u>Utilization of MOX fuel</u>

According to the calculations performed by means of the MESSAGE code, a partially closed NFC, based on LWRs with MOX fuel and plutonium utilization, is not economically viable under the indicated initial conditions (natural uranium price, costs of LWR SNF reprocessing services and MOX fuel fabrication costs). Reactors with MOX fuel are 'squeezed out' from the energy system. However, it is possible to consider a partially closed NFC in the case of MOX fuel utilization in all LWRs, with the assumption that reprocessing costs will be low; an option when reprocessing services are provided not with the purpose of yielding income but because it is necessary to maintain the loading of reprocessing capacities (French option) or to provide nuclear generation with additional fuel resources (Japanese option).

A partially closed NFC may be required when constraints are imposed on the volume of LWR SNF storage and disposal. In this case, HWRs with regenerated uranium may be beneficial in comparison to LWRs with MOX fuel. Taking into account the initial data, four LWRs can provide regenerated uranium for one HWR.

In the partially closed NFC, the SNF volume does not change in comparison to a once-through NFC, when one SNF type is replaced by another. The partially closed NFC does not solve the problem of the 'postponed decision'; the SNF problem is postponed for future generations. Reprocessing leads to the accumulation of 800 t of the reprocessing products and minor actinides.

In the case of a partially closed NFC, as in the option based on a once-through NFC, retention of 50% of the nuclear share requires the commissioning of a significant number of new reactors in 2030–2040 with total capacity of 7 GW.

The SNF volume does not change significantly when compared to the open fuel cycle option — the total amount would be up to 30 000 t HM with the 4000 t accumulation of the HWR SNF. Regardless of the option of a partially closed NFC (with or without plutonium utilization, different numbers of HWRs), in the case of the CSNFSF, its design capacity will be filled out by 2035 which would require building a second storage facility or SNF transportation for reprocessing.

Closed NFC

With reference to the calculations made under the accepted input data and constraints, the NFC closure based on FRs is not economically viable until 2100 and should be postponed to a later period. The main reasons for this are the availability of large uranium reserves and high costs of the FR construction, the SNF reprocessing and the fresh fuel fabrication for FR.

Closed NFC deployment in Ukraine takes place with a considerable share of LWR with UOX fuel under the unattractiveness of commissioning of the LWR with MOX-fuel, the insufficiency of one FR and with a number of heavy-water reactors with ReU-fuel, depending on the amount of SNF subject to reprocessing.

As for the NFC economics, the availability of a considerable amount of regenerated uranium at 'zero' cost makes it possible to increase the nuclear power's share in electricity generation up to 50% and to rearrange the commissioning of new reactors in 2030–2040 with a total capacity of 4.5 GW. This may be considered as a more realistic scenario.

The restricted capabilities for SNF disposal (limited capacities of repositories), the reduction of uranium reserves and the decrease in costs of technologies related to the closed NFC may be necessary reasons for a transition to the closed NFC.

The closed NFC based on FR will significantly reduce the amount of SNF accumulation. In the case when LWR and FR operation is balanced (LWR SNF is reprocessed to provide FR with nuclear fuel), the ratio of the FR installed capacities to the LWR installed capacities will be 1:10.

Conclusions of the case study

Once-through NFC

For the Ukrainian conditions, a once-through nuclear fuel cycle is defined as a basic scenario for nuclear power development, assuming a large scale decommissioning of operating nuclear reactors in 2020–2040. Provided that nuclear generation accounts for 50% of power demand, a sizeable number of new nuclear capacities (about 7 GW(e)) should be commissioned during this period, imposing a substantial financial burden on the State's economy. With regard to the experience gained elsewhere, there is a definite need for additional activities to assess the capability to optimize financial costs allocated for the deployment of replacement units (e.g., early decommissioning of older reactor facilities, lifetime extension beyond design limits of 5–10 years with further decommissioning).

In a once-through NFC, the amount of SNF accumulated is anticipated to significantly increase up to 25 000–30 000 t by 2100. In view of the estimated power demand growth, provided that nuclear share is maintained at 50%, the CSNFSF will be fully loaded with spent fuel by 2035. This will require either commissioning of additional dry storage capacities or a return to the SNF export model. The first phase of the CSNFSF commissioned in 2015 along with potential commissioning of the second phase will result in a reduction of expenses for SNF management, although it will not entirely solve the problem of final SNF disposal (i.e., the problem of a deferred decision will remain). In 2065–2085, the fuel assemblies delayed in the second phase of the CSNFSF will begin to be removed either for reprocessing or for final disposal that would result in a higher rate of SNF exports to the country of origin.

By 2035, decisions will need to be taken concerning:

(a) Establishment of either domestic or international complementary interim storage facility which will provide additional time for making a final decision;

(b) Final disposal of the SNF from LWR or its reprocessing.

The capacities of an international interim storage facility, if applied, should house 15 000 – 20 000 t taking into account also the CSNFSF. If the interim storage capacities are limited, the need will arise to reprocess SNF. By 2100, the required capacities for geological disposal of the high level reprocessing products (minor actinides, fission products) could account for about 800–1000 t. Given that the capacities on SNF storage/disposal are limited and that SNF should be reprocessed in a once-through fuel cycle, the NPP generation share could decrease down to 30% (owing to high reprocessing cost).

If the once-through NFC is further developed in Ukraine, international cooperation in the NFC will be limited only to enrichment of uranium hexafluoride and fuel pellet sintering (until those are implemented at the domestic nuclear fuel fabrication plant). As for the NFC back end, it seems reasonable to address the capability of establishing a regional complex for long term SNF storage, so as to optimize economic expenditures and minimize the deployment of dry SNF storage facilities at each NPP.

Partially closed NFC

The partially closed NFC with MOX and ReU fuels, used in LWRs and HWRs, respectively, is one of the options for building a fuel cycle to efficiently combine different technologies in order to attain the best economic results. The major advantage of this option is a more effective use of natural uranium resources to generate electricity and the capability to reduce the amount of SNF reprocessing products.

The partially closed NFC, as well as the once-through fuel cycle with the nuclear share maintained at 50%, requires the commissioning of a significant number of new reactors of 7 GW capacity in the period of 2030–2040. The decrease in the number of new/replaced reactors in this time period could be observed when involving the use of regenerated uranium without the reactors running on MOX fuel. The feasibility of storing plutonium recovered through reprocessing of SNF from LWRs requires separate studies to be performed.

The partially closed NFC, based on LWRs with MOX fuel and plutonium, is deemed not to be feasible under the normal conditions. Therefore, the reactors with MOX fuel are excluded from the energy mix.

The need for partial closure of the NFC may arise if limitations are imposed on capacities for storage and disposal of SNF from LWRs. HWRs may have the advantage over LWRs with MOX fuel under ‘zero’ cost of regenerated uranium. In accordance with the input data accepted, four LWRs in the equilibrium operation may provide regenerated uranium in the amounts necessary for operation of one HWR.

The reprocessing of SNF from LWRs may be incorporated into the existing NFC, subject to a decrease in reprocessing costs. The decision on reprocessing of SNF from LWRs is postponed owing to the availability of the substantial uranium ore reserves and their reasonable cost. The reprocessing of LWR SNF may be required if SNF disposal capacities are significantly limited. Given the flexibility of the NFC described above, the nuclear share in a partially closed NFC may account for up to 50%. Owing to the long research period and small storage capacities, there is no significant difference between an NFC with CSNFSF, an NFC with CSNFSF and SNF geological disposal, or an NFC with plutonium.

The partially closed NFC will not lead to a change in the amount of SNF compared to the once-through fuel cycle, although it will lead to one SNF type being replaced by another. The partial closure does not solve the issue of a deferred decision; the SNF problem solution will be just postponed. The reprocessing will result in a production of up to 800 t of reprocessing products and minor actinides.

In the case of a partially closed NFC, international cooperation could be based on reprocessing of SNF from LWRs and fabrication of the MOX and ReU fuels. This is determined by the lack of implementation of these technologies at the domestic fuel assembly fabrication plant (given the limited capacities commissioned on MOX and ReU fuels, the re-equipment of the fuel fabrication plant with respective hot cells and SNF handling equipment is not deemed to be economically feasible). The construction of a long term storage facility for ReU fuel will also be of great significance.

Closed NFC

The commissioning of fast reactors is deferred for a later term owing to the availability of abundant uranium resources, the high cost of fast reactors and the high reprocessing cost. According to optimization estimates and in consideration of the restrictions and input data provided in Annex 1, the closed NFC based on FRs is not deemed to be feasible for the conditions of the Ukrainian power grid until 2100 and is, therefore, deferred for a distant future. The major reasons are as follows:

(i) Availability of large uranium reserves;

(ii) High cost of FR construction;

(iii) High cost of SNF reprocessing;

(iv) High cost of fresh fuel fabrication for FR.

When considering a closed NFC under the Ukrainian conditions, the specific features are a significant share of LWRs on UOX fuel and lack of economic attractiveness for commissioning of LWRs on MOX fuel. Commissioning of one FR with different numbers of HWRs on regenerated uranium depends on the scope of SNF reprocessing.

When considering the economics of the NFC, a significant amount of regenerated uranium of ‘zero’ cost will increase the NPP share up to 50%, while decreasing the rate of commissioning of new reactor capacities in the period of 2030–2040, which could be considered a more feasible scenario.

It would be reasonable to ensure reprocessing of SNF for FR operation owing to a higher content of fissile materials. The closing of the NFC based on FR will significantly decrease the amount of SNF accumulated. In the equilibrium operation of LWRs and FRs (SNF from LWRs is reprocessed to provide fuel for FRs), the ratio of FR to LWR installed capacities will be approximately 1:10.

The transfer to closed NFC could be preconditioned by limited capacities for SNF disposal (limited storage capacities), decrease of uranium reserves and decrease in the cost of technologies for closing of the NFC.

The input data on the cost (price range) of FRs and reprocessing needs to be discussed with manufacturers and services suppliers. The modelling results depend significantly on price parameters. In addition, sensitivity analysis needs to be performed regarding the dependence on costs of the technologies and services.

To provide one FR with fuel requires reprocessing SNF from 10 LWRs. However, reprocessing of SNF increases the cost of the fuel cycle. On the basis of the obtained results it becomes obvious that reprocessing of SNF from FRs (instead of SNF from LWRs) is feasible owing to the much higher content of fissile material.

In this case, the most prospective way is to develop international cooperation in the NFC back end in several domains as follows:

— Reprocessing of SNF from LWRs;

— Fabrication of MOX and ReU fuels.

Generation IV reactors: supercritical reactors

Supercritical reactors are being viewed as a prospective trend. The supercritical reactors can produce a significant share of electricity in the power system owing to higher technical parameters (increased values of the capacity factor, efficiency and fuel burnup rate). Taking into account economic attractiveness within the technical and economic characteristics applied in this study, the introduction of supercritical reactors may significantly increase the share of nuclear generation in Ukraine.

It is reasonable to consider the development of a supercritical reactor fleet as a component of a once-through NFC.

2.5.6. Feedback from the case study on NES modelling with the MESSAGE tool

2.5.6.1. Aspects in which the MESSAGE model was useful in this study

Important results were obtained for this case study by using the MESSAGE tool including the dynamics of NPP decommissioning and the schedule for new capacity construction. The initial assumptions and the possibility of scenario realization were also discussed in line with the MESSAGE model.

Another important area regarding the NES modelling with MESSAGE is the study of spent nuclear fuel accumulation. The scenarios analyzed give important information on the required capacities of storages complete with the schedule of storage construction to meet the scenario assumptions.

2.5.6.2. Benefits of NES modelling with MESSAGE

Application of the MESSAGE tool for energy system modelling provides an opportunity to analyze different short and long term scenarios of energy system development (set of initial conditions, assumed strategy and output data), as well as challenges and steps for scenario realization.

The results of comparative assessment of NFC facilitate strategy formulation for nuclear energy generation deployment up to 2100, keeping in view the available nuclear infrastructure as initial data. Technical parameters of different reactors are used in the scenario realization. The results define the prospective directions of international collaboration in different areas of the nuclear fuel cycle.

2.5.6.3. Suggestions for further elaboration of the model

The experience of using the MESSAGE tool for energy system modelling shows that some input parameters or switches in the user interface could change their values or states.

For example, the input and output energy levels for uranium conversion technology are defined in weight-units as **ton**. When updating the model, the main input unit changes from **ton** to **MWyr** (Fig. 150).

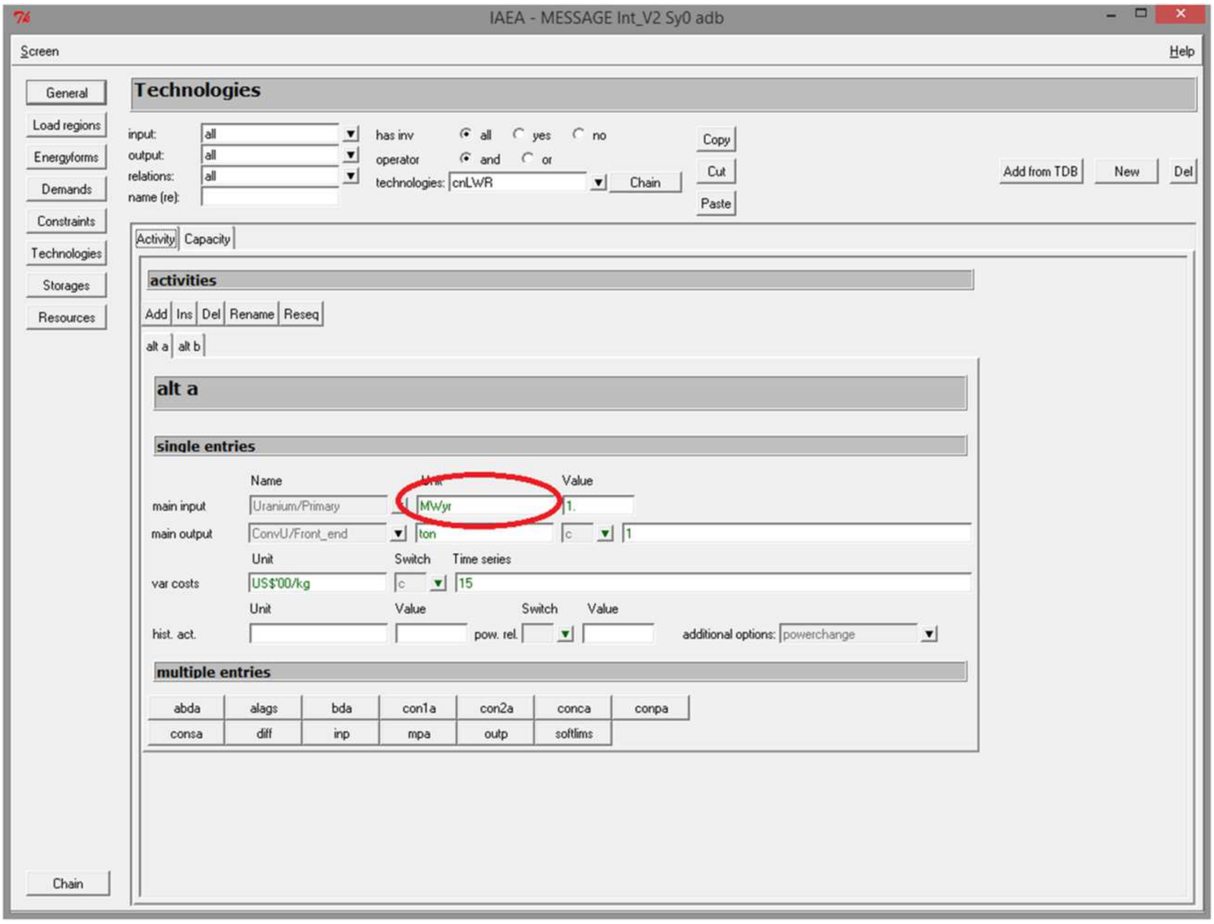


FIG. 150. Example of changing parameter in user interface of MESSAGE.

Such changes may provide unexpected outputs. The only way to track such changes is to check all parameters one by one. Creating a ‘log’ for changed parameters or an option, such as ‘return to previous parameters’, could help solve this operational problem.

3. ELABORATION OF MESSAGE FOR SIMULATION OF HETEROGENEOUS WORLD MODEL, THORIUM FUEL CYCLE AND MINOR ACTINIDE TRANSMUTATION

3.1. SIMULATION OF HETEROGENEOUS WORLD NUCLEAR ENERGY SYSTEM WITH MULTI-REGIONAL MESSAGE MODEL

3.1.1. Introduction

The IAEA's INPRO Section has performed several studies at global and regional levels to understand key issues in a transition to future sustainable nuclear energy systems. In particular, the INPRO collaborative project on Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) [3, 63–65] developed the internationally verified analytical framework for assessing transition scenarios to future sustainable nuclear energy systems and applied it in sample analyses. The framework defined major scenario elements, including: scenarios for nuclear power evolution, a heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle, plausible architectures for nuclear energy systems, data on nuclear reactors and associated fuel cycles, metrics for scenario analysis and evaluation and sample scenario studies.

The GAINS project defined architecture as a NES with different types of reactors and associated fuel cycle installations, including also interactions between NES components, altogether intended to serve a common goal. Sample analysis of selected nuclear energy system scenarios using the framework has shown quantitatively that a synergistic nuclear energy system architecture, based on technological and institutional innovations as well as proven technologies, offers the potential for a mutually beneficial collaboration among technology holders and users, facilitating nuclear energy production, resource preservation, minimization of waste and direct use material inventory, as well as improved economics.

Most of the studies on the future of nuclear energy have been based on a homogeneous global model, which suggests the world would rapidly converge towards global solutions for meeting the economic, social and environmental challenges. This model emphasizes the opportunities for creation of a common global nuclear architecture, such as unification of reactor fleets and associated technologies, infrastructure sharing, multinational fuel cycle centres and innovative approaches to financing and licensing. However, it does not take into account the barriers to cooperation existing between different parts of the world, or national preferences and capabilities.

To complement this model, the GAINS project developed a heterogeneous model based on grouping of countries with similar fuel cycle strategies. This model can facilitate a more realistic analysis of transition scenarios towards achieving a globally-sustainable architecture of innovative nuclear energy systems. It can also illustrate the global benefits that would result from some countries introducing the innovative nuclear technologies, while limiting the exposure of the majority of countries to the financial risks and other burdens associated with the development and deployment of such innovative technologies.

The heterogeneous world model developed by GAINS organizes countries into different nuclear strategy groups (NGs) according to their strategies for SNF management: NG1 countries recycle SNF and pursue a national fast reactor programme, NG2 countries directly dispose of SNF or send it for reprocessing to NG1, and NG3 countries, typically newcomers, send their SNF to NG1 or NG2 countries. Rather than assigning individual countries to groups, the methodology applied in the analysis allocates a fraction of future global nuclear energy generation to each group, as a function of time, to explore hypothetical scenarios. For the GAINS studies, the NG1:NG2:NG3 ratio was fixed at 40:40:20 by the end of this century. Sensitivity analysis was performed to variations of the NG fractions. The heterogeneous model may involve some degree of cooperation between groups (synergistic case), or it may not involve any cooperation (non-synergistic case).

The INPRO collaborative project SYNERGIES applied and amended the analytical framework developed in GAINS to examine, more specifically, various forms of regional collaboration among nuclear energy suppliers and users. The project focused on short and medium term collaborative actions that could help develop pathways to long term NES sustainability.

The SYNERGIES project investigated collaborative scenarios and architectures of interest to participants, involving, *inter alia*, fuel cycle infrastructure development with shared facilities [4, 66]. Within SYNERGIES, the focus was on the studies of regional collaboration among countries. Case studies performed by the participants were grouped into families of scenarios as follows: 'business as usual' scenarios and scenarios with mono-recycling of U/Pu in thermal spectrum reactors; scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in light water reactors and fast reactors; fast reactor centred scenarios with reprocessing of thermal reactor fuel to enable a noticeable growth rate of fast reactor capacity; scenarios of transition to Th/^{233}U fuel cycle and scenarios with U/Pu/Th fuel cycles.

The SYNERGIES project explored various issues related to synergies in technology and synergistic collaboration among countries, including the selection of reactor and fuel cycle options, uncertainties in the scale of nuclear energy demand growth, possible modes of collaboration among countries and sensitivity studies [66] to the shares of countries with different nuclear fuel cycle policy, etc.

3.1.2. Objectives and problem formulation

This section presents selected case studies performed in the GAINS and SYNERGIES collaborative projects to illustrate a heterogeneous model of the global nuclear energy system based on grouping of the countries according to their policy regarding the fuel cycle back end.

More specifically, the following two aspects have been be considered in those studies: (i) positive effects of technology innovation for minimization of radioactive waste and increase of natural resource base and (ii) cooperation among countries which could amplify the positive effects of technology innovation in achieving sustainable nuclear energy and bring the sustainability benefits from innovations in technology holder countries to countries that do not pursue innovation programmes domestically. The specific objective was to illustrate and identify short term and medium term options for collaboration capable of facilitating the transition to long term sustainability. Such collaboration could provide benefits in terms of economics, security of supply, resource allocation, infrastructure requirements, radioactive waste management and in other key areas defined by the GAINS framework. Another specific objective was to identify and clarify challenges which may need to be overcome in order to realize the associated benefits.

The studies presented in this section have been carried out to explore the impact of cooperation among three groups of countries on NES infrastructure, fuel cycle services, nuclear material resources, discharged fuel, radioactive waste and minor actinides. The country groups included NG1 which recycles spent nuclear fuel and pursues a fast reactor programme, NG2 which directly disposes spent nuclear fuel or sends it for reprocessing to NG1, and NG3 which sends spent nuclear fuel to NG1 or NG2.

The studies also included sensitivity analysis of possible impacts to the market shares of countries with a different nuclear fuel cycle policy and to the scale of collaboration among countries. The goals of the sensitivity studies were to determine the impact of changing the country group shares on key output parameters and to identify when stresses appear within particular portions of the global nuclear energy system. The change in the NG1:NG2 ratio takes into account possible transition from one group to another. NG3 share variation considers the possibly changing market share of NG3. The impacts of NG3 share on the NG1/NG2 fuel cycle front end requirements, including enrichment and fuel fabrication, and on the NG1/NG2 fuel cycle back end requirements, including reprocessing, storage and disposal, have been evaluated.

The sensitivity studies also explored how cooperation between technology holder (NG1) and technology user (NG3) countries impacts the structure of electric energy generation growth in the technology-holder group of countries (NG1) and how change in the NG1 electric energy production structure would affect the NFC structure from mining to reprocessing. The short term advantages of sharing long term storage facilities were also evaluated. Accumulation of UOX spent fuel in long term storage of NG3 will steadily increase, resulting in significant amounts by the end of the century in the non-synergistic case. Cooperation between NG1 and NG3 could resolve the issue of SNF accumulation in both regions.

3.1.3. Model description and input data and prospects for nuclear power evolution

Heterogeneous world model of global nuclear system and prospects for nuclear power evolution

The case study explored a heterogeneous scenario comprising the once-through fuel cycle strategy in NG2, a closed fuel cycle strategy in NG1 and the use of thermal reactors in a once-through mode in NG3. This scenario includes both synergistic and non-synergistic cases. In the synergistic case, NG3 receives fresh fuel from NG2 and NG1 and returns the associated SNF to those groups (Fig. 151). Solid lines indicate required functions and actions, while dotted lines indicate additional options. The heterogeneous synergistic framework cases build on the basis of non-synergistic cases. All of the primary input parameters are the same. The key difference consists in allowing the movement of material between the NGs (synergism), an action that may result in improving the ability of each group to follow their selected fuel cycle strategies.

World energy demand is based on the GAINS high case and assumes 1500 GW(e)/year in 2050, 5000 GW(e)/year in 2100, then flat to the end of the modelled period. In 2008, 50% of world nuclear power generation is in the recycling fuel cycle group (NG1) and 50% in the once-through fuel cycle group (NG2). In the reference (or nominal) cases, the shares of nuclear energy generation in groups NG1:NG2:NG3 were fixed in the ratio 40:40:20 for total nuclear energy generation by the year 2100. The nominal case explored non-synergistic and synergistic nuclear energy development to consider the mutual benefits and issues of cooperation.

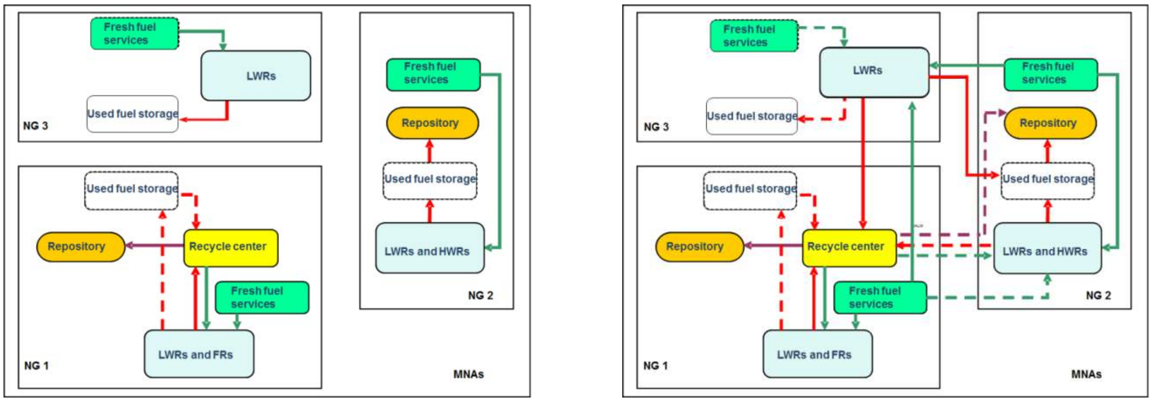


FIG. 151. Heterogeneous world for the business as usual plus fast reactors (BAU-FR) scenario (Non-synergistic, Synergistic cases).

Variations of these shares were considered in sensitivity studies. The first part of the sensitivity studies included variations of power shares NG2/NG3 and kept fixed the nuclear power in NG1. NG2/NG3 share variation considers possible market share change of NG2/NG3 for the back end fuel cycle services provided by NG1. NG2/NG3 share in 2100 was varied as 50/10, 40/20 (base case), 30/30, 20/40 and 10/50. The second part of the sensitivity studies included variations of power shares NG1/NG2 and kept fixed the nuclear power in NG3. The change in NG1:NG2 proportion takes into account the possible transition from one group to another and its impact on the reactor mix and the NFC infrastructure in NGs.

Uranium resources

The data on uranium resources for this study were taken from Ref. [67] and divided in five grades: a, b, c, d and e, according to their cost. Grades a–e refer to identified and undiscovered resources of various costs comprising 17.5 million tons of natural uranium, as shown in Table 47. Grade f is associated with uranium in phosphates and has a deposit of 21 600 000 t U with a recovery cost in the range >US $400/kgU. The total natural uranium resources are 39 million tons in all grades. Resources of grade g are associated with uranium in seawater. Theoretically, grade g has a practically unlimited resource, with the cost of recovery higher than US $450/kgU.

TABLE 47. URANIUM RESOURCES

Recovery (US $/kg U)	Identified resources (t)		Undiscovered resources (t)		Phosphates (t)
	Reasonably assured resources	Inferred resources	Prognosticated resources	Speculative resources	21 600 000 (f)
<40 (a)	493 900	187 000			
40–80 (b)	1 520 900	876 700	1 624 100		
80–130 (c)	1 440 700	808 000	1 073 900	3 543 800	
130–260 (d)	923 200	846 200	143 300	318 300	
Cost range unassigned (e)				3 733 200	
Total	7 096 600		10 436 600		
	17 533 200				
	39 133 200				

Reactor and fuel input data

Three reactor types: LWR, HWR and FR (BR ~1.0) were considered in the case study. General characteristics of the thermal and fast reactors used in scenario simulations are shown in Table 48.

A typical LWR design was assumed with an average burnup of 45 GW·d/t and a fuel enrichment of 4%. A nominal HWR design was considered which has an average burnup of 7 GW·d/t and natural uranium loading. A break-even FR was selected which has a breeding ratio close to 1.0. Corresponding to the reprocessing strategy planned in many countries, core fuel and radial blanket subassemblies were assumed to be dissolved together and reprocessed at the same time.

The plant lifetime and load factor for both LWRs and HWRs were 60 years and 85%, respectively. Plant lifetime and load factor of FRs were 60 years and 85%, respectively, the same as for LWRs and HWRs. The cooling time of spent fuel (SF) from thermal reactors (LWRs and HWRs) in nuclear power plant storage was 5 years. The out of reactor time of FRs was 3 years, which consists of 2 years' cooling in nuclear power plant storage and a process time of 1 year for reprocessing and fuel fabrication. The tails assay was 0.3% and remained constant during the whole period of modelling.

In order to model the spent fuel reprocessing option, it is necessary to specify the isotopic composition of spent fuel discharged from the reactor. The composition data of fresh fuel and discharged fuel are shown in Table 49. The composition data of discharged fuel correspond to immediate discharge from the reactor. Thus, the composition change during cooling, storage and processing periods should be adequately calculated using other analytical tools.

Data on historical capacities of LWR and HWR were taken from the IAEA's Power Reactor Information System (PRIS) database. The data on reactor and fuel cycle costs were taken from the outputs of the SYNERGIES project [4]. The study was not considering to optimize NES with respect to the total discount cost as is usual with the MESSAGE model. The task was to simulate the introduction of fast reactors to the system initially consisting of LWRs and HWRs. There were assumptions imposing a constraint on the power production by fast reactors in the years between 2030 and 2050 taken into account by specifying a maximum deployment rate resulting in a total electricity production rate of 10 GW(e)/year from fast reactors in 2030 and a total of 400 GW(e)/year in 2050 for the high scenario case. After 2050, the deployment rate of fast reactors was considered to be maximized and limited only by the amount of plutonium available and the overall nuclear growth rate. The investment in FRs was assumed to be lower than in LWRs to simulate the maximum possible number of FRs commissioning after 2050. Therefore, the MESSAGE model was applied in this study to simulate a given innovative NES without actual economic optimization.

TABLE 48. GENERAL CHARACTERISTICS OF THERMAL AND FAST REACTORS

Parameter	Unit	LWR	HWR	FR (BR~1)		
Fuel type	-	UOX	UOX	MOX depleted U		
Electric capacity	MW(e)	1000	600	870		
Thermal efficiency	%	33	30	42		
Load factor	%	85	85	85		
Life time	year	60	60	60		
Core fuel burnup	MW·d/kg	45	7	65.9		
Construction time	year	5	5	5		
Uranium enrichment	%	4	0.711	-		
Cooling time	year	5	5	2		
Reprocessing time	year	1	1	1		
				core	axial blanket (depleted U)	radial blanket (depleted U)
Fuel residence time	EFPD	1168	292	420	420	490
Mass of the core	t HM	78.7	83.4	12.6	5.5	6.2
Pu content in fresh fuel	-	-	-	0.22	-	-

TABLE 49. NUCLIDE GROUP COMPOSITION OF UOX SPENT FUEL FROM LWR AND MIX MOX AND BLANKETS SPENT FUEL FROM FR

	U tot	Pu tot	MA	FP
LWR	0.942 19	0.010 40	0.000 10	0.046 39
FR and blanket	0.840 45	0.120 09	0.000 11	0.038 41

Fuel cycle options and schemes

Country groups NG1, NG2 and NG3 were assumed to have fuel cycle schemes in accordance with their strategies for SNF management. The NG1 group adopted a combined once-through fuel cycle based on LWRs and an FR closed cycle system. This combined system has all front end and back end facilities, including a reprocessing facility for recycle of plutonium and storage for the MA, uranium and radioactive waste (Fig. 152). Fuel reprocessing was assumed to have no losses of heavy metal isotopes. The plutonium inventory in storage was targeted to be kept close to zero.

NG2 continues implementing the BAU (business as usual) strategy of a once-through fuel cycle based on LWRs and HWRs without recycling. The HWRs were assumed to retain a 6% share of the total generation. The once-through fuel cycle system consists of steps in uranium mining, conversion, enrichment, depleted uranium storage, fuel fabrication, nuclear power plant, SNF nuclear power plant storage and SNF long term storage. In the case of HWRs, the steps of conversion, enrichment and depleted uranium storage do not exist because HWRs use natural uranium as the fuel (Fig. 153). The fuel cycle conditions for the BAU scenario assumed 0.3% uranium enrichment tails assay.

NG3 starts with no NESs and introduced LWRs in 2008. The fuel cycle scheme is presented in Fig. 154 with LWRs in a once-through fuel cycle.

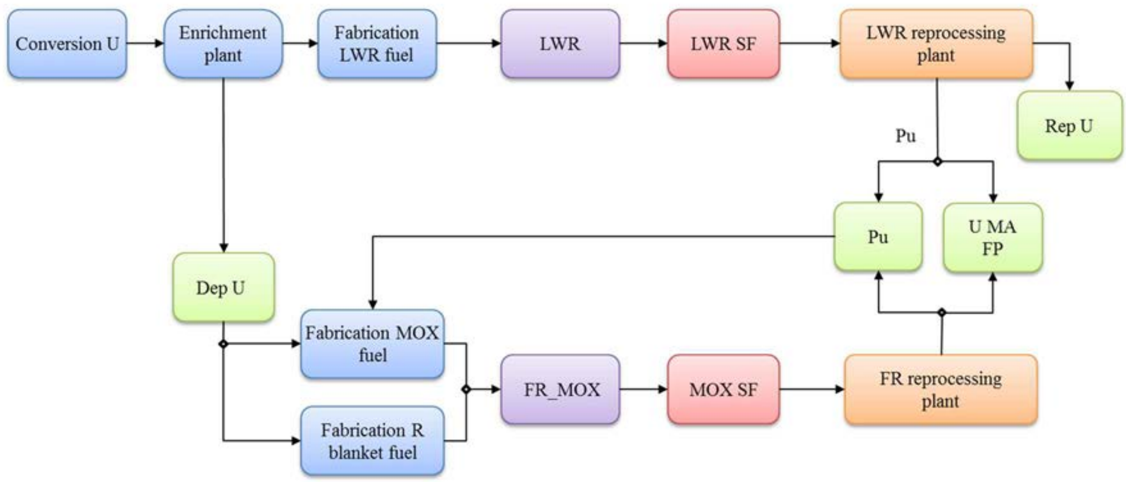


FIG. 152. Fuel cycle options and scheme for NG1.

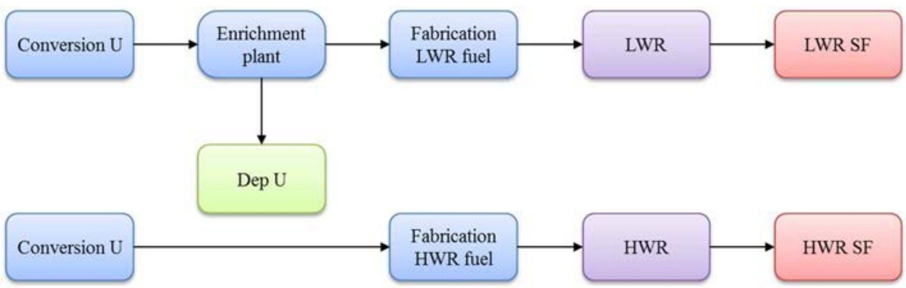


FIG. 153. Fuel cycle options and scheme for NG2.

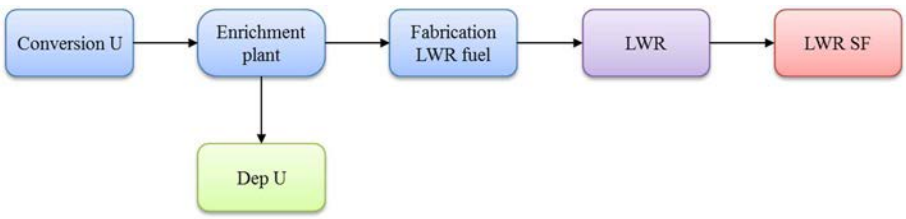


FIG. 154. Fuel cycle options and scheme for NG3.

Metrics (indicators) for scenario analysis

Analysis of scenarios was performed with a key indicator set developed in the GAINS framework. It reflects sustainability areas related to power production, nuclear material resources, discharged fuel, radioactive waste and minor actinides, fuel cycle services, system safety, and costs and investment (Table 50).

TABLE 50. METRICS FOR SCENARIO ANALYSIS AND ASSESSMENT

Power production	
	Nuclear power production by reactor type
	New and total installed capacities by reactor type
Nuclear material resources	
	Annual and cumulative natural uranium demand
	Pu production, consumption and accumulation
	Depleted uranium accumulation
Discharged fuel inventories	
	Discharged fuel inventories
	Spent nuclear fuel in storage
Radioactive waste and minor actinides	
	FP inventories
	Minor actinide inventories
Fuel cycle services and NFC infrastructure	
	Uranium conversion, uranium enrichment, fresh fuel requirement, fuel reprocessing requirement and capacity
	Annual quantities of fuel and waste material transported between groups
Costs and investment	
	Levelized unit of electricity cost (LUEC)

3.1.4. Modelling of selected NES elements with MESSAGE

The starting point for multi-region modelling of a heterogeneous world nuclear energy system is a homogeneous world NES model developed in Ref. [2]. This publication provides detailed guidance on how to build mathematical models representing complex nuclear energy systems within the framework of the MESSAGE tool.

3.1.4.1. General comments on multi-region modelling with MESSAGE

The MESSAGE tool allows to build a multi-region model. A multi-region model comprises a model for one main region and models for sub-regions. The tool considers the main region and each of the sub-regions also as an independent case study. The user may optimize each case study for a sub-region independently. For the main region and each sub-region, in addition to the name of the case study, the user needs to provide a synopsis which comprises a brief name of the case study which is used for identification of the study in other parts of the tool. There are two methods to create a new multi-region case study in MESSAGE:

- Create a new case study from a scratch.
- Copy the existing case studies.

Figure 155 depicts the basic structure of the MESSAGE multi-region model for the main region and three sub regions.

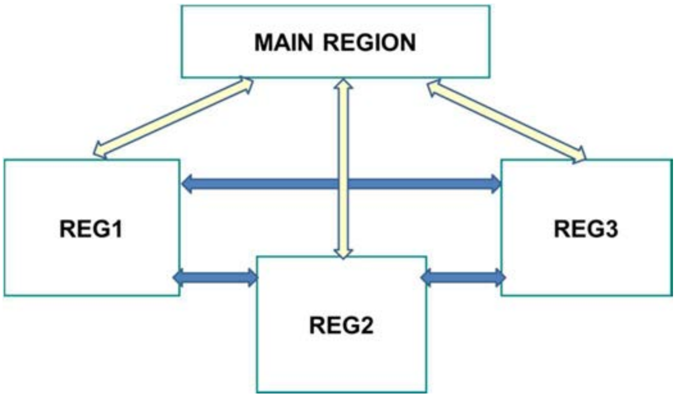


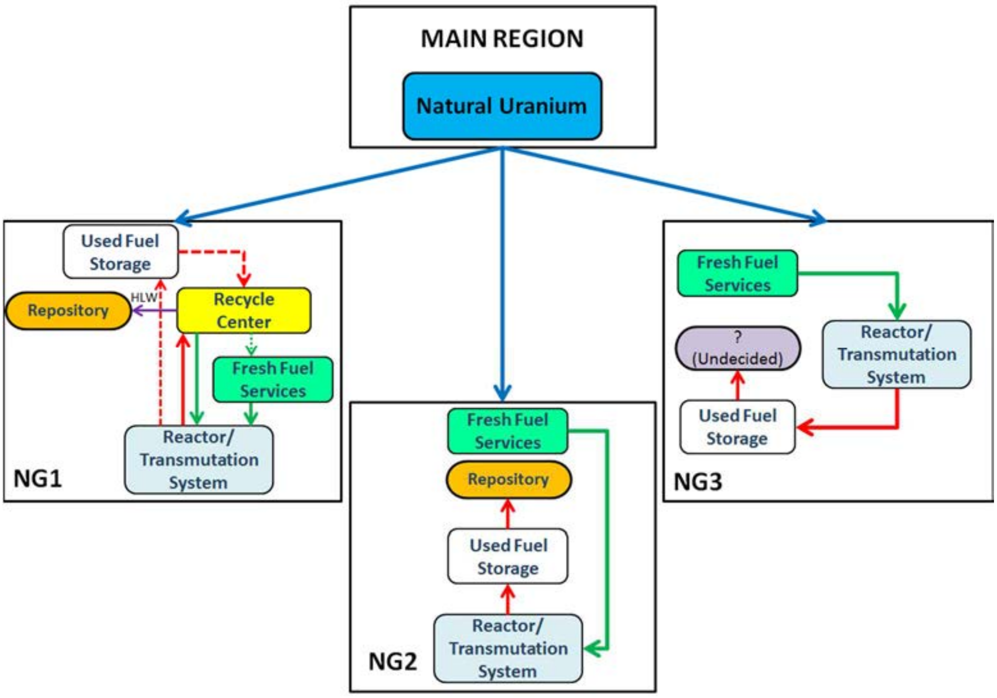
FIG. 155. Basic structure of the MESSAGE multi-region model.

Multi-region modelling requires an equal timeline of study period and an equal discount rate for all sub-regions and the main region. Regions can be optimized independently only if they have self-sufficiency. The name of a region can only exist one time, independent of whether it is a 'single region', a 'main region' or a 'sub-region'.

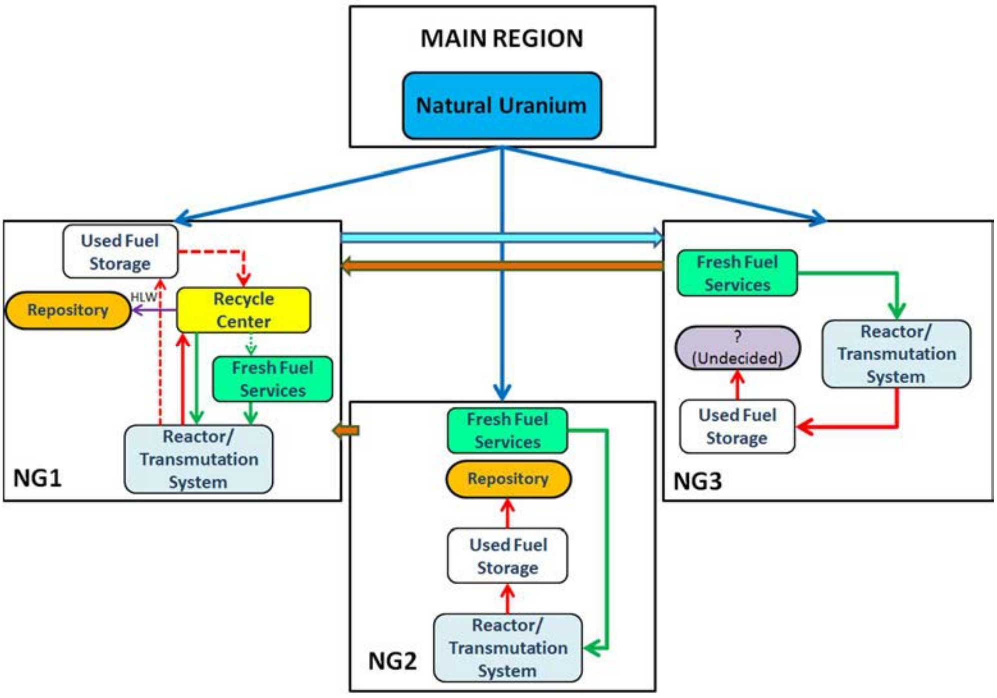
3.1.4.2. Multi-regional MESSAGE model for the heterogeneous world nuclear energy system

The MESSAGE model was built for the heterogeneous world nuclear energy system using the GAINS framework. The reason to use the multi-region MESSAGE model was to analyze regional cooperation in nuclear services and to provide sensitivity analysis of the heterogeneous world nuclear energy system comprising the three groups of the non-personified (generic) countries grouped according to their different different nuclear fuel cycle policies.

The multi-regional model comprises the main region and three sub regions NG1, NG2, NG3 (Fig. 156). NG1 countries recycle spent nuclear fuel and pursue a national fast reactor programme.



(a)



(b)

FIG. 156. Structure of MESSAGE multi-region model for heterogeneous world nuclear energy system comprising the main region and three sub-regions (NG1, NG2, NG3).

The NG1 group has a closed NFC and can provide front end and back end fuel cycle services to other country groups. NG2 countries use the once-through fuel cycle based on thermal reactors. The general group strategy is either to directly dispose the used fuel or to reprocess it in NG1. The NG3 group comprises countries intending to incorporate nuclear energy into their energy mix, as newcomers. The general strategy of this group is to obtain fuel cycle services from NG1 and NG2. The main region is the obvious part of the MESSAGE multi-region model. It includes natural uranium resources common for all sub-regions.

3.1.4.3. Creation of a multi-region case

The multi-region study for the heterogeneous world nuclear energy system was created from a set of the single region studies for NG1, NG2 and NG3 as discussed previously. These single region studies were copied from the GAINS framework base case for BAU with the introduction of fast reactors (BAU–FR) [3] with some related modifications. The details of the BAU–FR modelling are presented in Ref. [2] in the section on a global NES based on thermal and fast reactors with plutonium multi-recycling. The reactors and fuels considered for this case were: HWR using natural uranium fuel; LWR using UOX fuel; fast reactor using MOX fuel for the core and depleted uranium for the blankets. The timeframe under consideration was 2009–2160.

The first step is the creation of new multi-region case and definition of only one dummy sub-region R1 which needs to be deleted later (Fig. 157). The directory name is defined as GRh20f1GRAL00U and the main region is defined as h20f1GRAl00U.

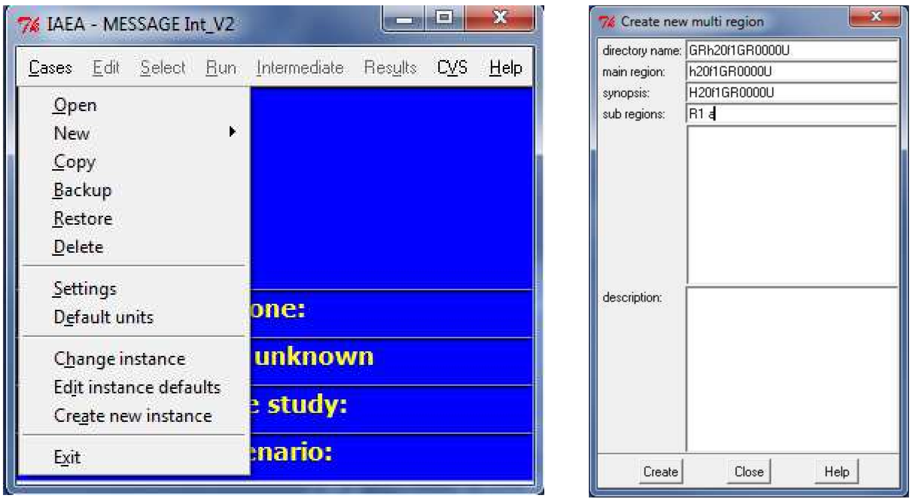


FIG. 157. Creation of a multi region case.

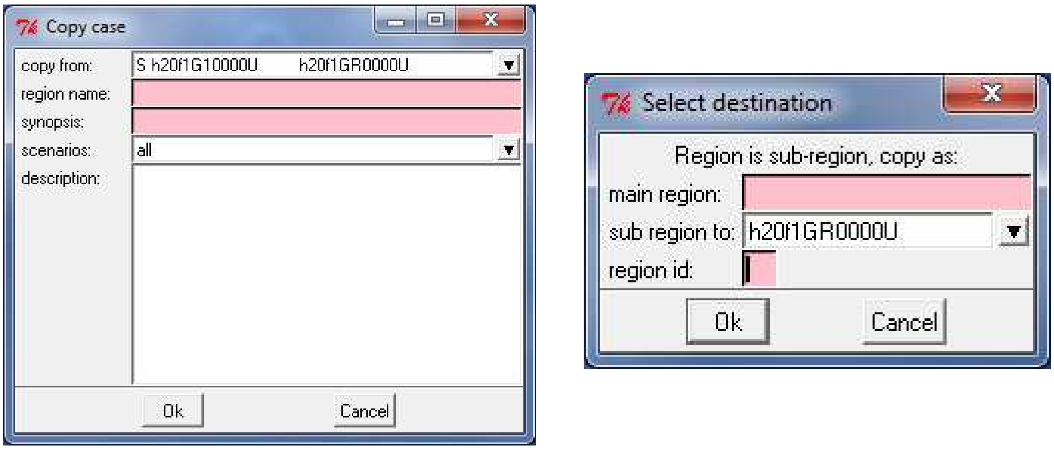


FIG. 158. Copying the existing single-region studies for NG1, NG2 and NG3 into an existing multi-region study.

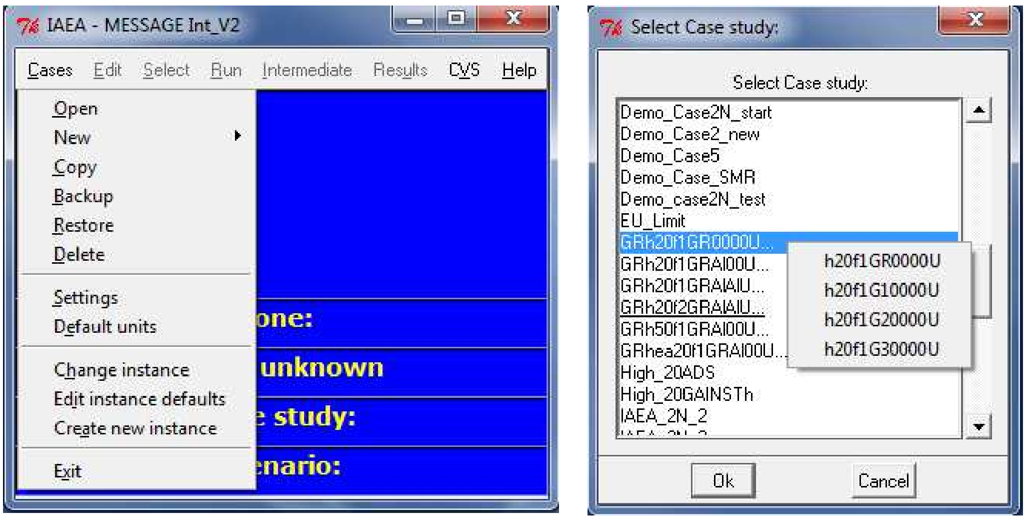


FIG. 159. Opening the multi-region case.

The second step is copying the existing single region studies for NG1, NG2 and NG3 into an existing multi-region study defined as h20f1G1Al00U for sub-region NG1, h20f1G2Al00U for sub-region NG2 and h20f1G3Al00U for sub-region NG3 (Fig. 158). The next step is opening and updating the multi-region case (Fig. 159). The main region is updated by adding resources (Fig. 160(a)) and a dummy level; the latter is obligatory for the main region. Natural uranium from the main region (h20f1GRAl00U) should be linked to NG1 (h20f1G1Al00U), NG2 and NG3 (Fig. 160(b)). There are no technologies in the main region.

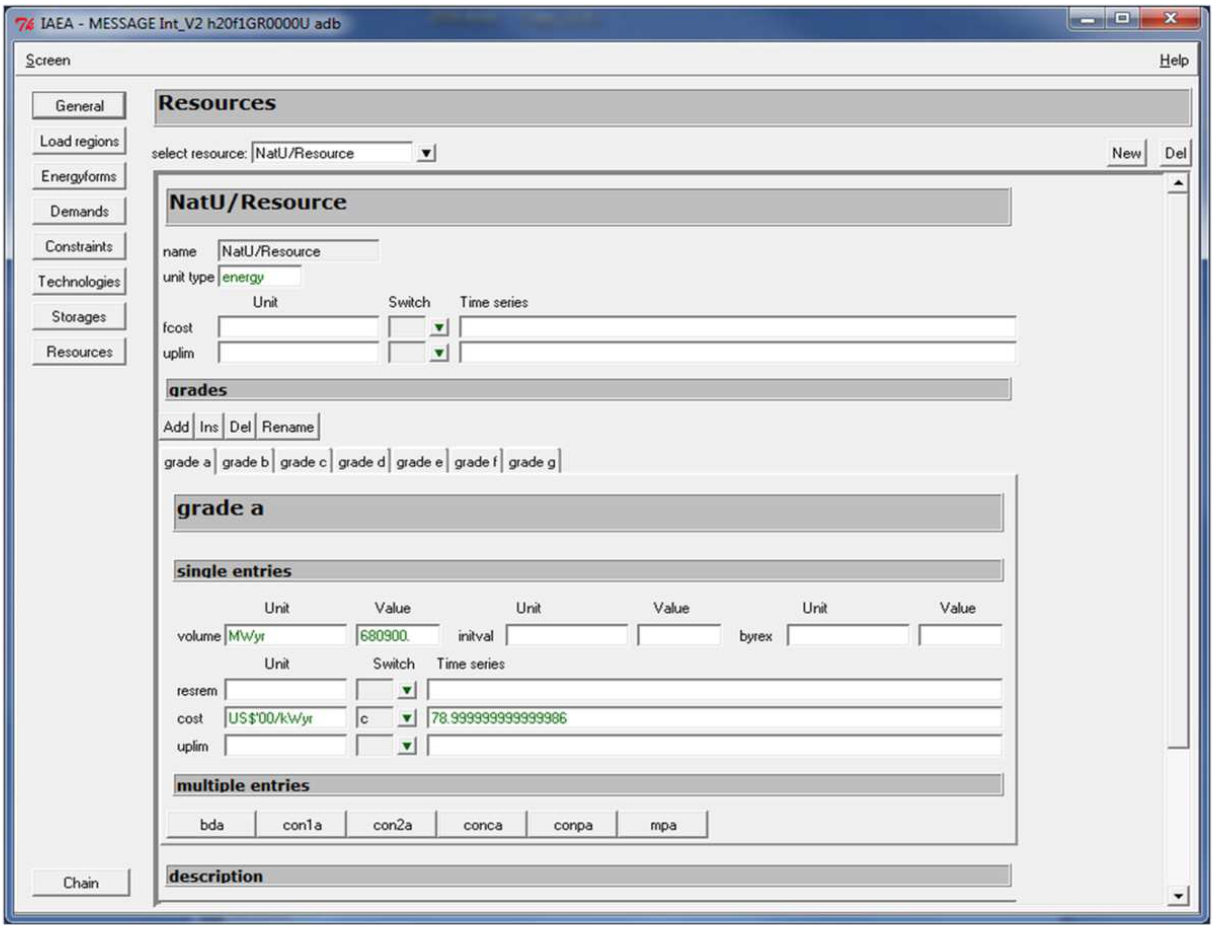


FIG. 160(a). Uranium resource in main region.

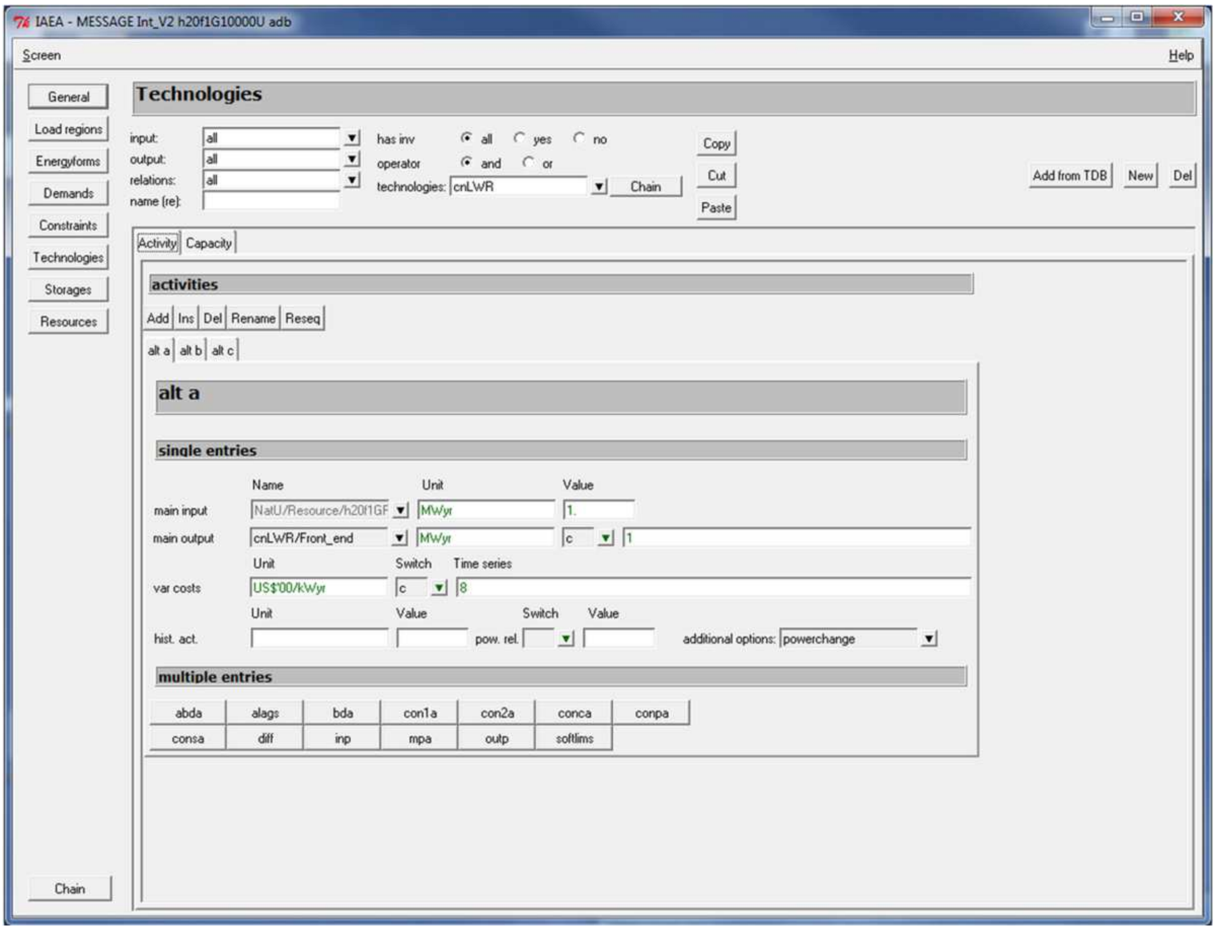


FIG. 160(b). Link to uranium resource in NG1 region.

Updating of the NG1, NG2 and NG3 sub-regions includes adjusting the NE demand, the reactor park, the reactor rates and the reactor historical capacities. Commissioning of FRs in NG1 and HWRs in NG2 is restricted by the related constraints (Figs 161 (a) and (b)).

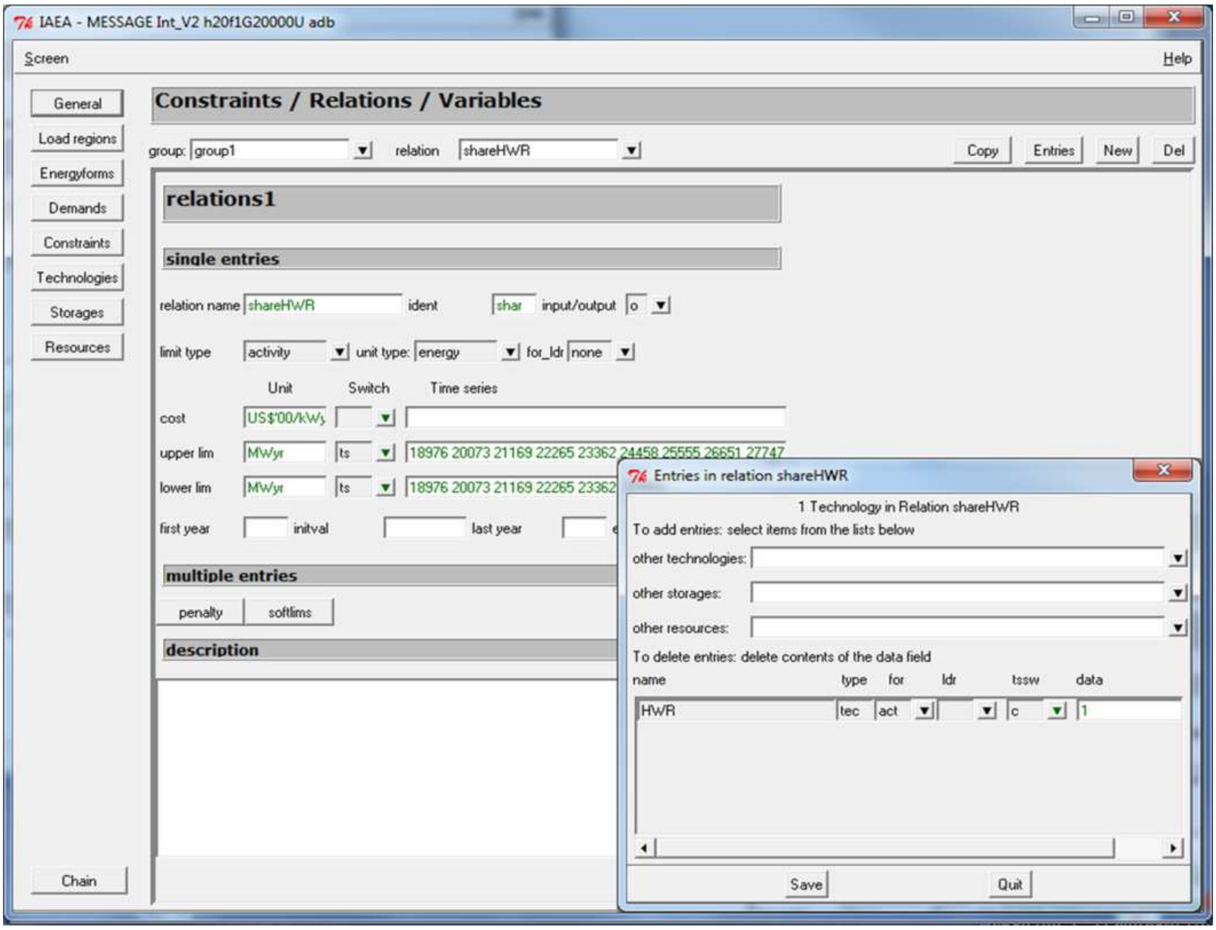


FIG. 161(a). Constraint on HWRs.

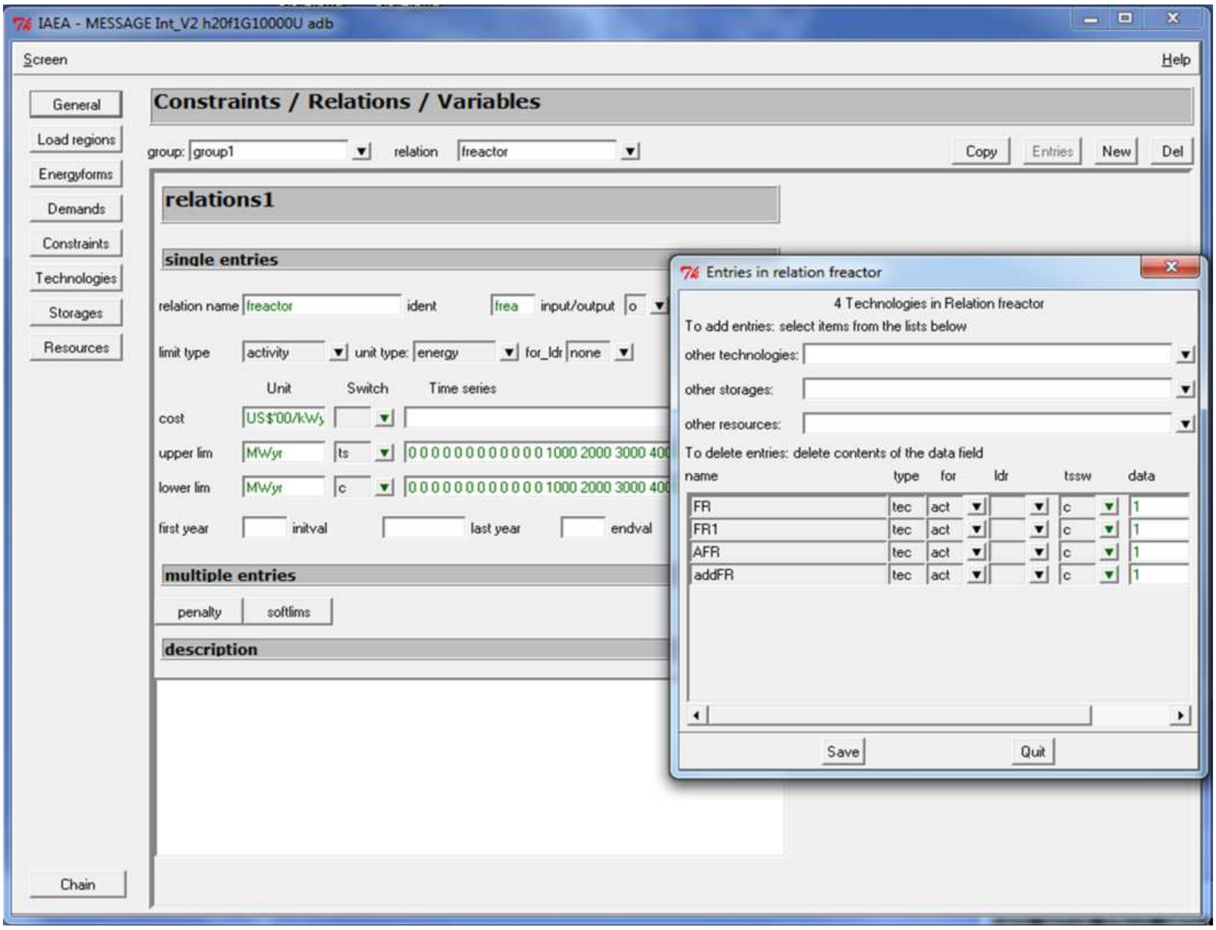


FIG. 161(b). Constraint on FRs.

In the heterogeneous non-synergistic cases, there is no movement of materials between NGs. Each group has its own fuel cycle facilities to mine, convert, enrich and fabricate fresh fuel and to store and/or dispose spent fuel. The only fuel available to reprocess for fast reactors is the fuel in NG1. Modelling of NG1 and NG3 cooperation is illustrated in Fig. 162. Fresh fuel moves from NG1 (Sub region NG1 h20f1G1Al00U) to NG3 (Sub region NG3 h20f1G3Al00U) (Fig. 163). Spent fuel is shipped from NG3 (Sub region NG3 h20f1G3Al00U) to NG1 (Sub region NG1 h20f1G1Al00U) (Fig. 164).

The fuel available to reprocess for fast reactors is NG1 and NG3 fuel modelled as alternatives. MESSAGE allows imposing a constraint on the introduction of reprocessing facilities (Fig. 165). The introduction of a new LWR reprocessing capacity is limited to up to 0.850 kt HM/year spent fuel till 2050 and up to 3.0 kt HM/year spent fuel after 2050. Fix mode on capacity page means that the reprocessing facility must operate for its full lifetime, at full capacity.

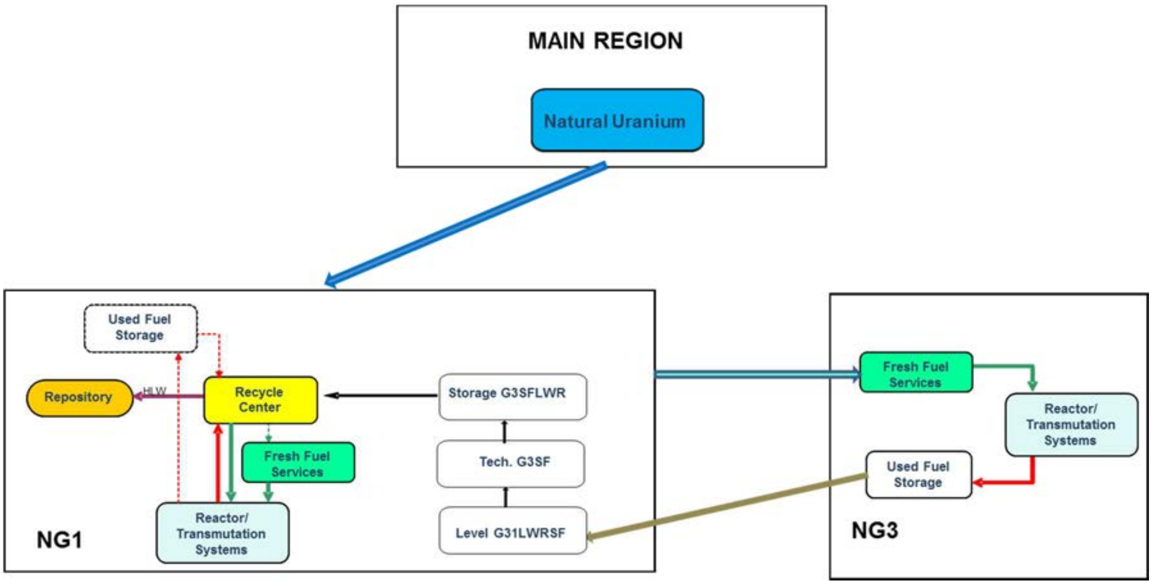


FIG. 162. Modelling of NG1 and NG3 cooperation.

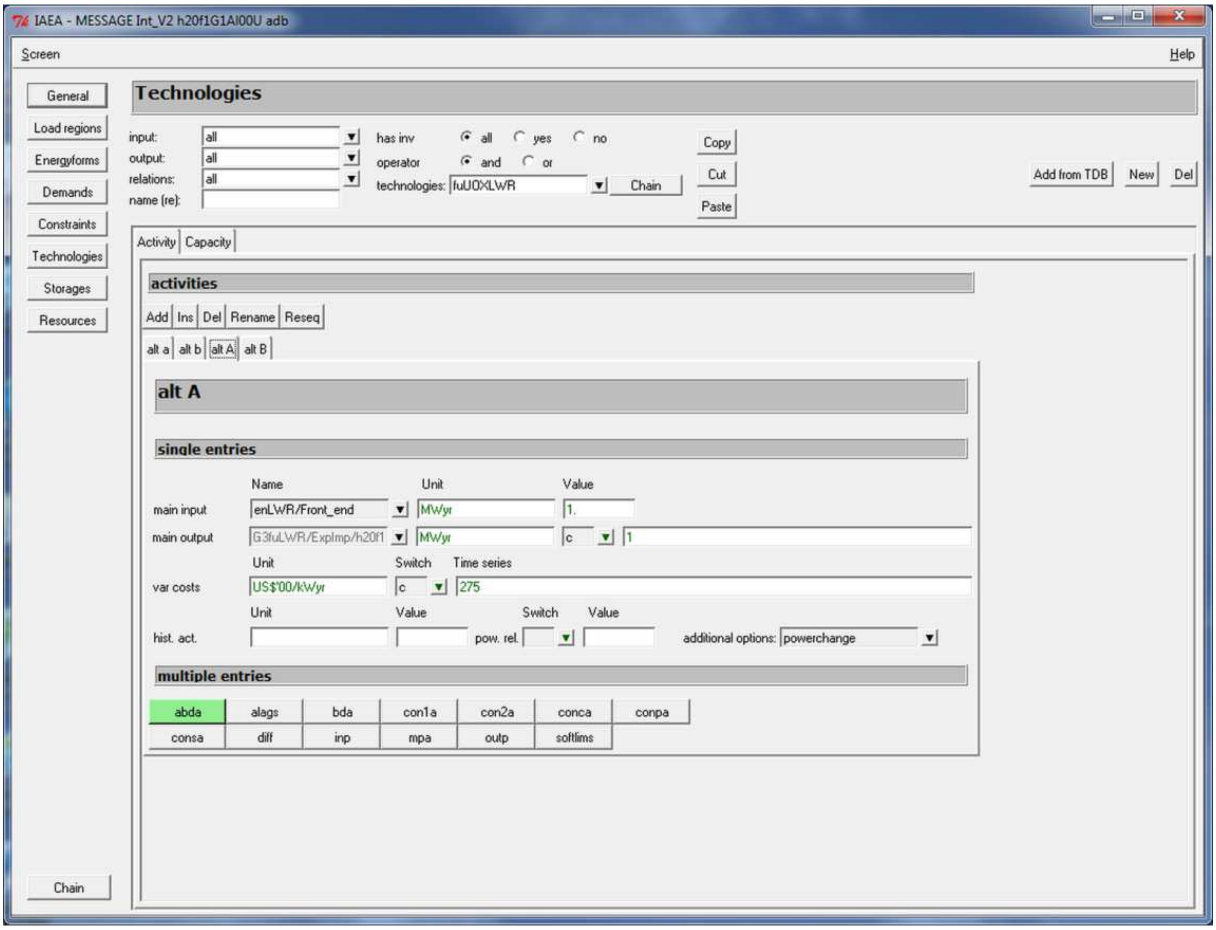


FIG. 163(a). Moving of fresh fuel from NG1 to NG3.

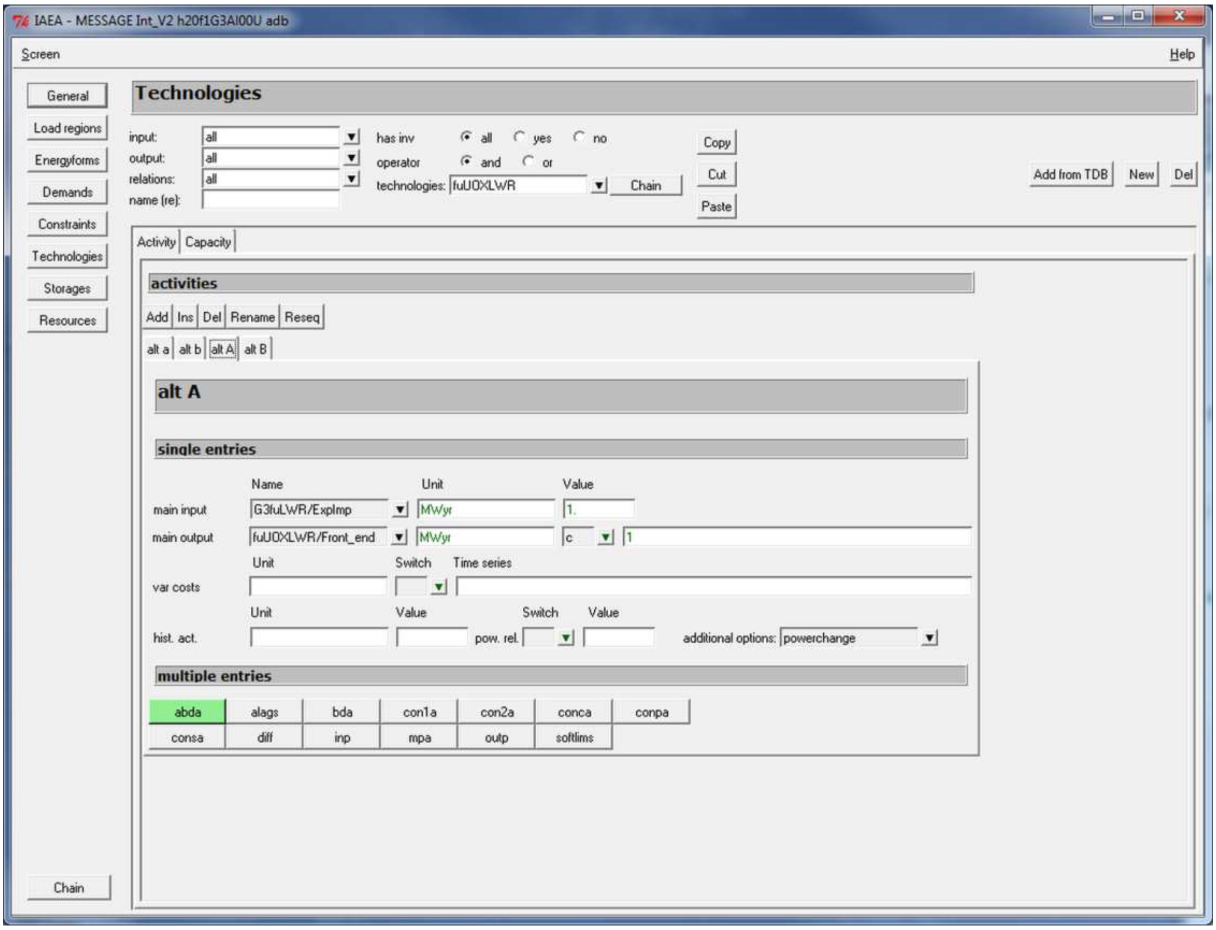


FIG. 163(b). Moving of fresh fuel from NG1 to NG3.

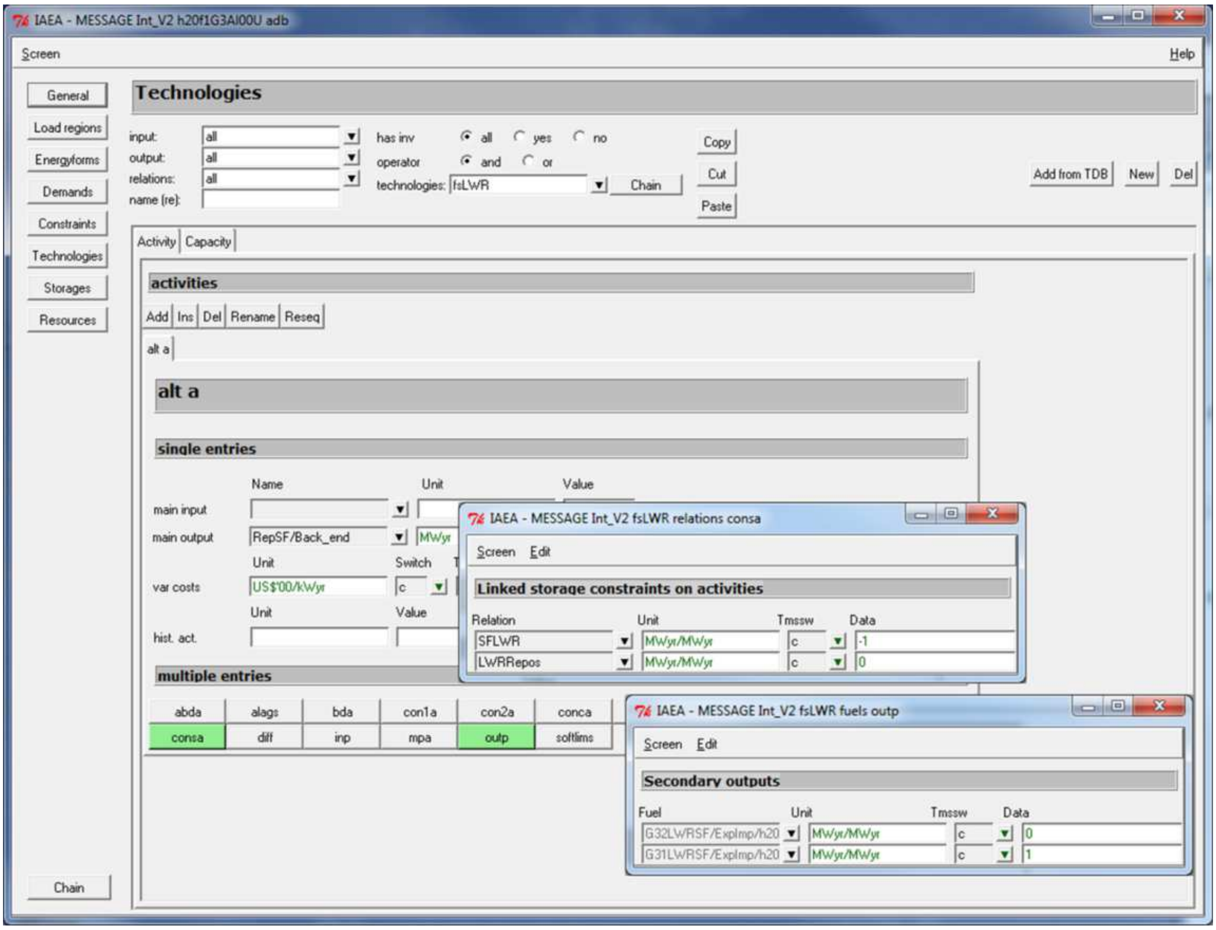


FIG. 164(a). Shipping spent fuel from NG3 to NG1.

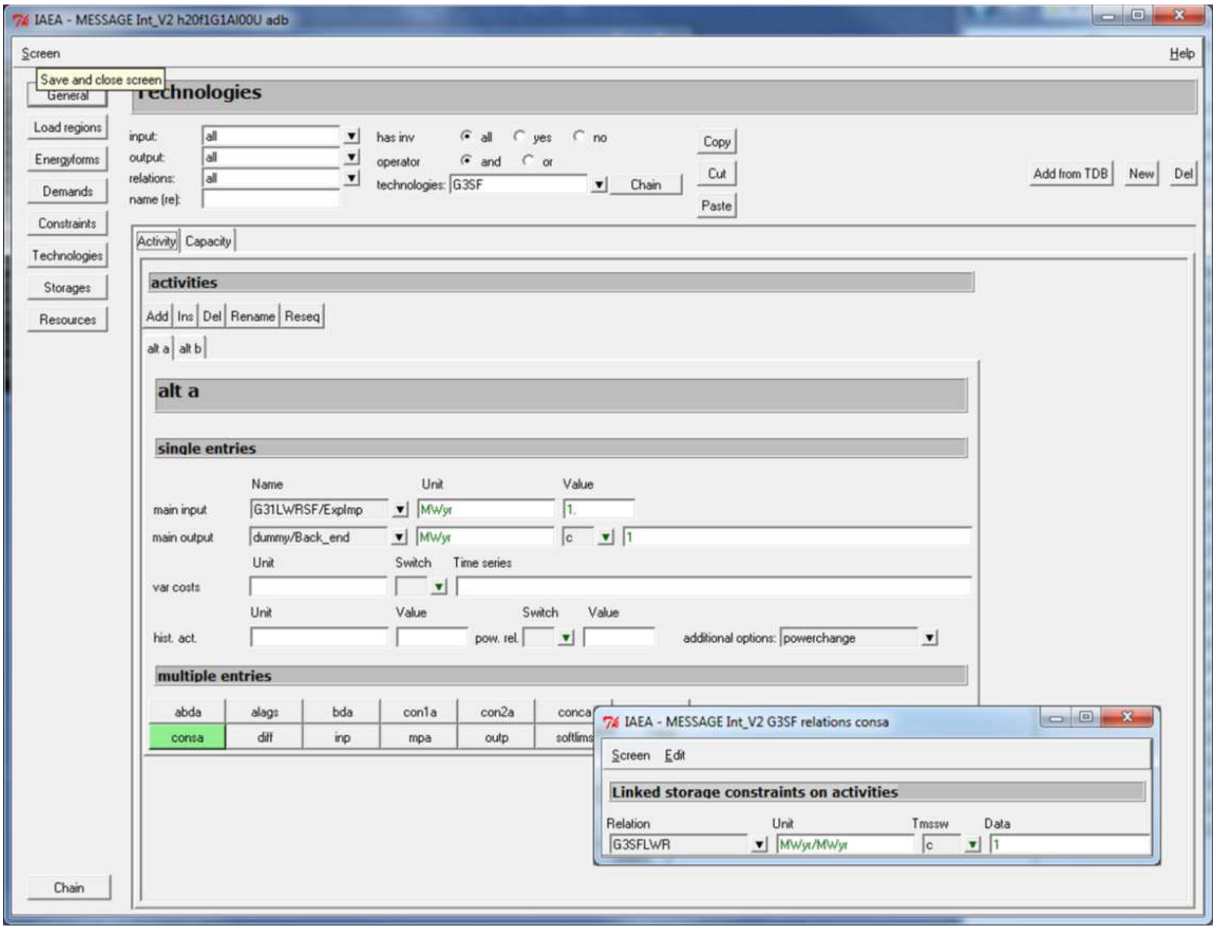


FIG. 164(b). Shipping spent fuel from NG3 to NG1.

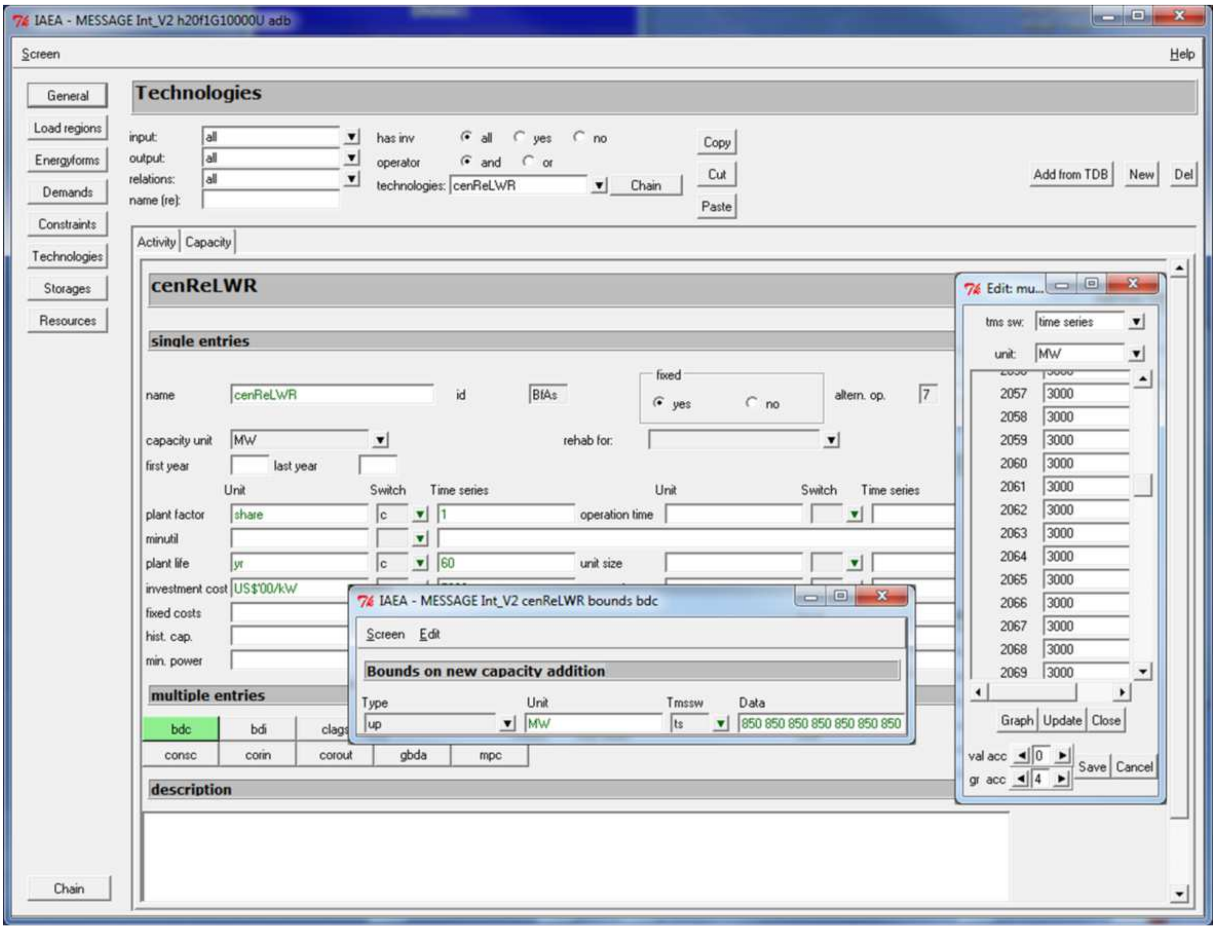


FIG. 165. Modelling of reprocessing facility.

3.1.5. Results and findings of the case study

The main output from the heterogeneous model of a global nuclear energy system calculated with MESSAGE includes key indicators, such as nuclear power production by reactor type, uranium cumulative demand, SWU, amount of spent fuel, Pu availability and others for non-synergistic and synergistic cases. Comparison of these indicators helps identifying and analyzing the benefits of cooperation among country groups and clarifying the issues which need to be solved in order to realize the associated benefits.

3.1.5.1. Non-synergistic case

Nuclear power production by reactor type

The indicator of nuclear power production shows the expected nuclear energy demand growth and the share of each reactor technology in the nuclear energy mix. Figure 166(a)–(d) shows the key indicator of power production for all three groups combined and the power production by reactor type for each group. NG1 and NG2 have twice the generation of NG3. NG1 shows the transition to FRs.

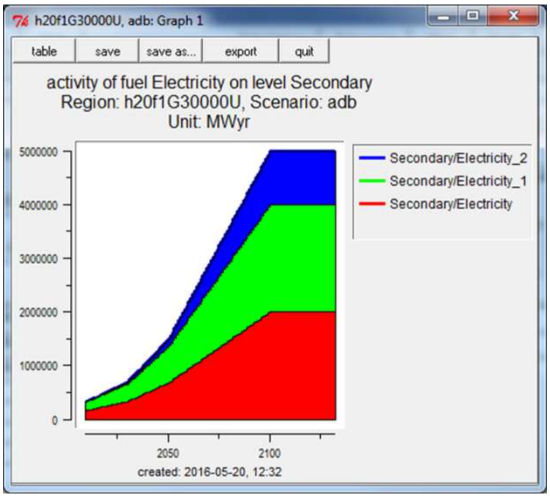


FIG. 166(a). Nuclear power production for all three groups (non-synergistic case).

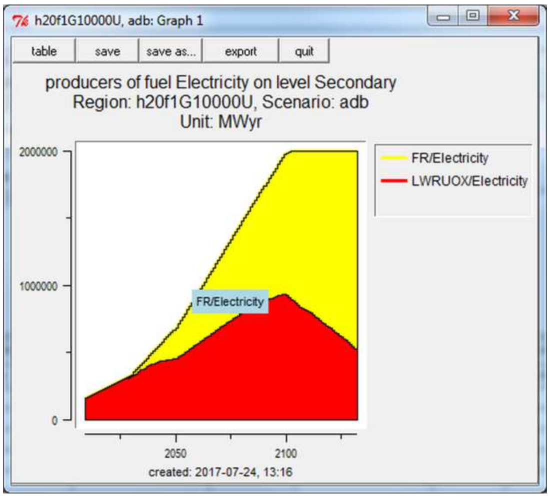


FIG. 166(b). Nuclear power production by reactor type for NG1 (non-synergistic case).

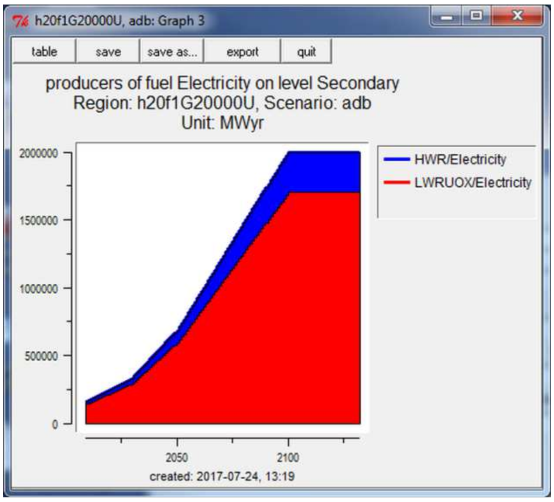


FIG. 166(c). Nuclear power production by reactor type for NG2 (non-synergistic case).

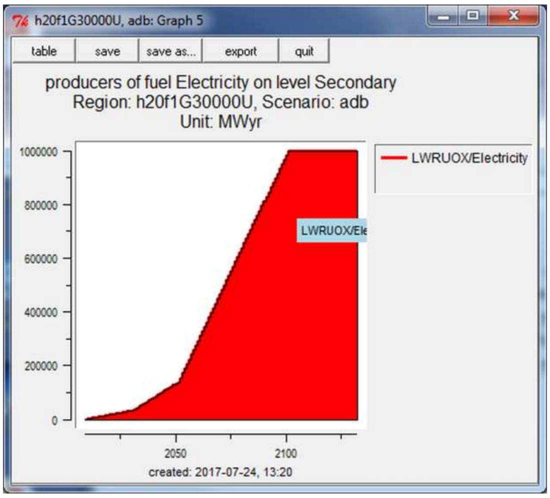


FIG. 166(d). Nuclear power production by reactor type for NG3 (non-synergistic case).

The FR share will be about 20% of total electricity generation in 2100. A further increase of the fast reactor share is restricted by the limited breeding performance of the break-even fast reactor and the share of electricity demand limited by 2000 GW(e)/year in 2100 for the NG1 group. NG2 reactor park comprises LWRs and HWRs. The share of HWRs is 6% of total electricity generation during the whole modelling period. NG3 shows the growth curve for the group of countries that begin to add nuclear power to their energy mix. This case was used as a reference one for a sensitivity study to investigate different growth rates for NG1, NG2 and NG3 groups by varying the fraction of world growth assigned to these groups.

NFC infrastructure of NG1

In the non-synergistic case, there is no movement of nuclear material between NGs. Each group has its own fuel cycle front end and back end requirements. Figure 167 shows the reprocessing load of LWR spent fuel. The reprocessing capacity of LWR spent fuel is assumed to be limited by a rate of 850 t/year in order to process available SNF until 2050, and by 3000 t/year after 2050.

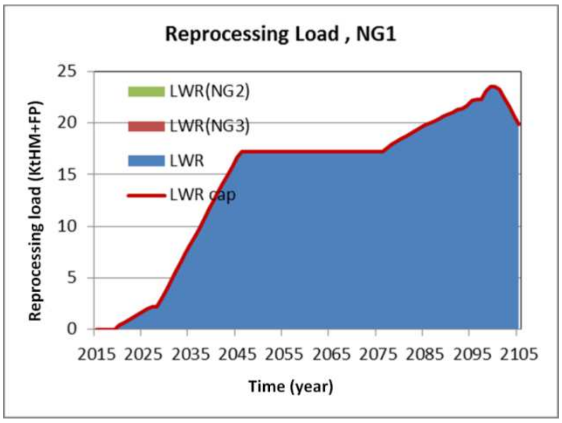


FIG. 167. Reprocessing load in NG1 (industrial adjusted reprocessing).

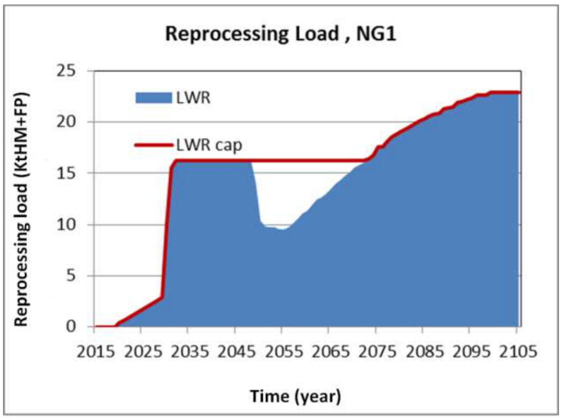


FIG. 168. Reprocessing load in NG1 (reprocessing by requirement).

The GAINS scenarios have been modelled by assuming there is no limitation on fuel cycle facility capacities. According to this assumption, for example, the reprocessing depends on Pu demand with no limitations except for the spent fuel availability. The GAINS objective was to provide just the correct amount of reprocessing capacity sufficient to support the specified FRs during the specified introduction period. However, as GAINS indicated, using the unlimited separation assumption results in high reprocessing requirements over a very short period when the stored inventory built up since 1970 is reprocessed, followed by a much lower reprocessing requirements based only on the current rate of discharge and cooling. Figure 168 shows the result for LWR reprocessing load. There are two issues attributed to reprocessing load. First, the introduction of considerable reprocessing capacities (up to 10 kt HM) in a few years (~1–3 years), second, reprocessing facilities do not operate at full capacity during their lifetime because a shortage of spent fuel occurs after some years of full-capacity operation. One of the possible ways to avoid this problem was suggested in GAINS; it is based on an industrial reprocessing approach. In the presented case, the reprocessing capacity was limited by the user. On the basis of this recommendation, a related modification of the new LWR reprocessing capacity introduction was modelled using the MESSAGE tool to develop a more practical and, potentially, more realistic introduction and operation of the reprocessing capacities. The result is shown in Fig. 167.

Accumulation of spent fuel

Figure 169(a) and (b) shows the stored LWR spent fuel in cooling and long term storage in NG1 and NG3 groups, respectively. Similarly, Fig 170(a) and (b) shows the accumulation of UOX spent fuel in long term storage in NG1 and NG3. Long term storages accumulate the spent fuel after cooling (6 years), at which stage it is ready for reprocessing. NG1 solves its issue of spent fuel accumulation by 2075. NG3 steadily increases spent fuel accumulation, achieving more than 500 kt HM by the end of century, while the spent fuel storage in NG1 archives its maximum capacity of 160 kt HM by 2035.

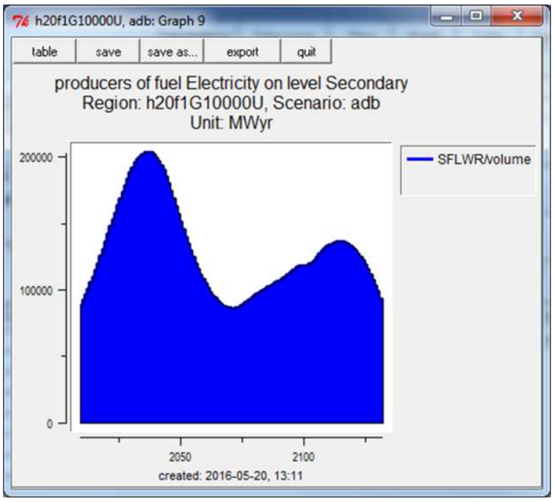


FIG. 169(a). LWR spent nuclear fuel in cooling and long term storage for NG1 (non-synergistic case).

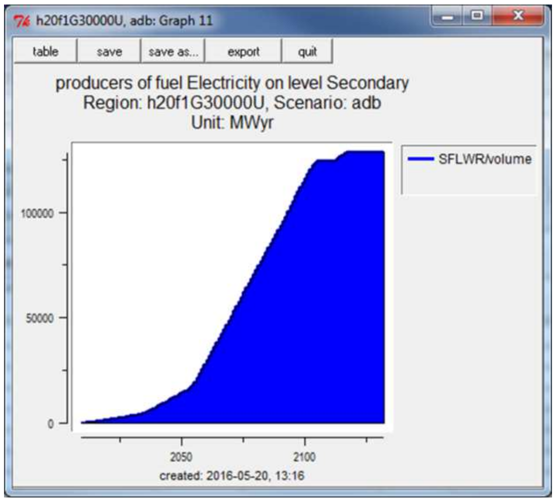


FIG. 169(b). LWR spent nuclear fuel in cooling and long term storage for NG3 (non-synergistic case).

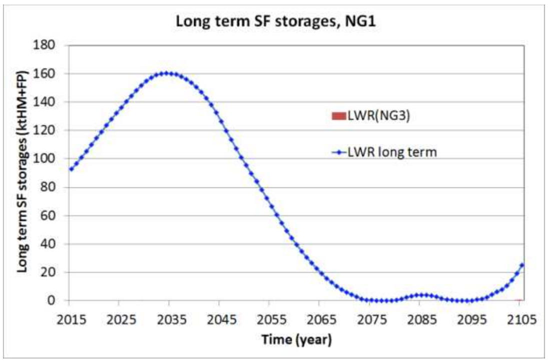


FIG. 170(a). LWR spent nuclear fuel in long term storage for NG1 (non-synergistic case).

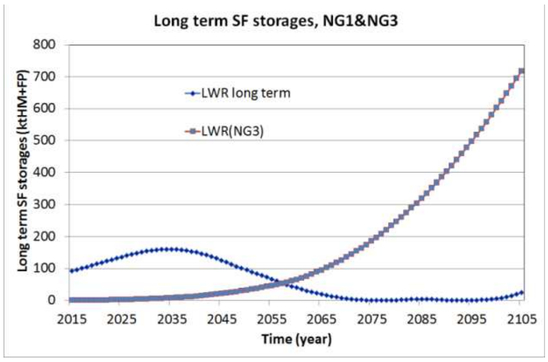


FIG. 170(b). LWR spent nuclear fuel in long term storage for NG1 and NG3 (non-synergistic case).

Annual and cumulative natural uranium demand

The demand for natural uranium is an important dimension of NE sustainability, which indicates the coherent effect of technical and institutional innovations. In the non-synergistic case, all NGs have equal access to natural uranium. Figure 171 shows annual and cumulative natural uranium consumption by all three regions. Conventional natural uranium resources (Table 47) of various cost categories that total 17.5 million tons are exhausted by 2074. The total uranium consumption by the end of the century will be about 37 million tons, which also includes additional uranium in phosphates.

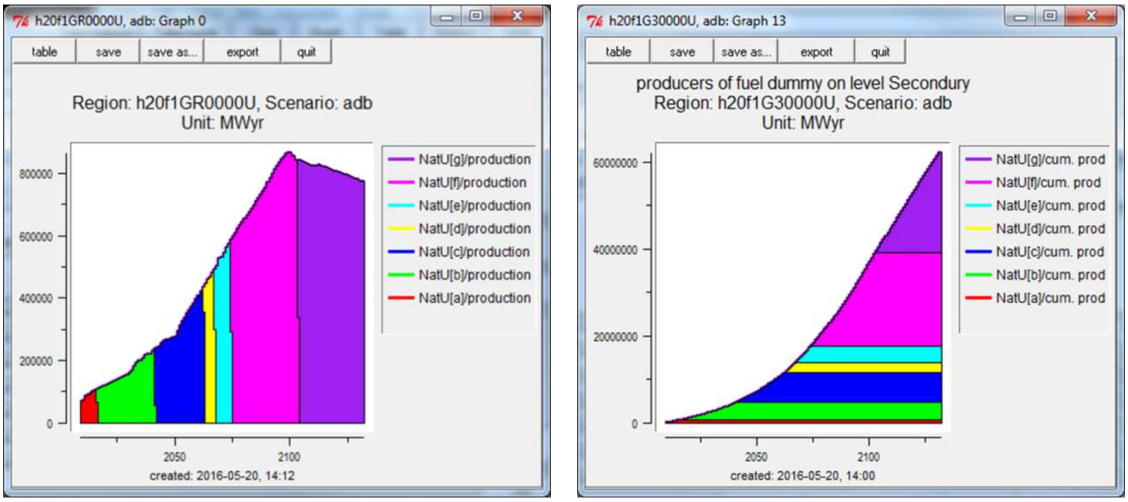


FIG. 171. Annual and cumulative natural uranium demand.

3.1.5.2. Synergistic case NG1–NG3

There is a movement of nuclear material between NGs in the synergistic case. This has an implication on power production by reactor types and on the infrastructure in NG1, where countries adopt the BAU–FR closed fuel cycle with reprocessing of plutonium from LWRs and FRs to use it for fabrication of MOX fuel for FRs.

The first variant of the synergistic case assumes that NG1 group provides fresh fuel for NG3 group and NG3 group returns spent fuel to NG1 group for reprocessing and reusing separated plutonium as feed of FRs in NG1. Figure 172(a) and (b) shows annual quantities of fresh fuel transported from NG1 to NG3 and spent fuel returned to NG1 from NG3. Since NG3 first introduces reactors after 2008, the flow of fuel is initially small but grows throughout the scenario. The amount of fresh fuel shipped differs (exceeds) the amount of returned spent fuel. This is due to the two factors, the fuel needed for new cores and the time delay between shipping fresh fuel and returning the cooled spent fuel. There is a step increase in fresh fuel shipments when the growth rate increases with the fuel for new cores being shipped at a higher rate.

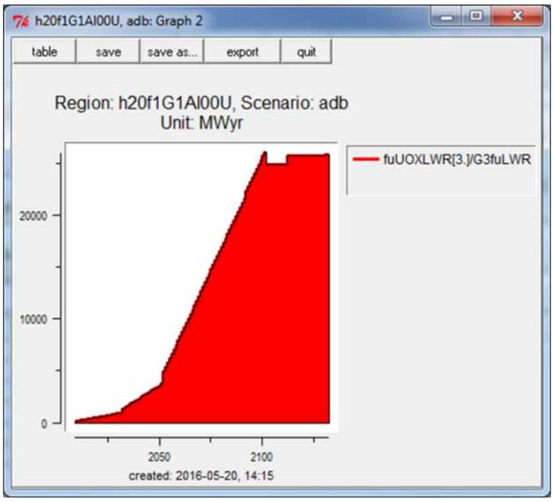


FIG. 172(a). Annual quantities of fresh fuel transported between groups (synergistic case).

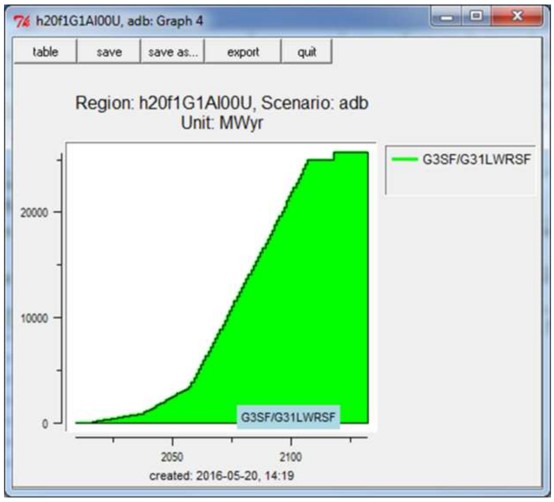


FIG. 172(b). Annual quantities of spent fuel transported between groups (synergistic case).

Cooperation between NG1 and NG3 impacts the structure of electricity generation growth in NG1, as more material would be available for FRs in NG1. Figure 173 shows power production in NG1 for this variant. The share of FRs in NG1 has increased in comparison to the non-synergistic case owing to additional Pu reprocessed from the NG3 spent fuel. Figure 174 shows the FR and LWR power production in NG1 for non-synergistic case. Visible differences for FR power production between synergistic and non-synergistic cases first appear in the medium term from 2050 and increase by about 25% by 2100.

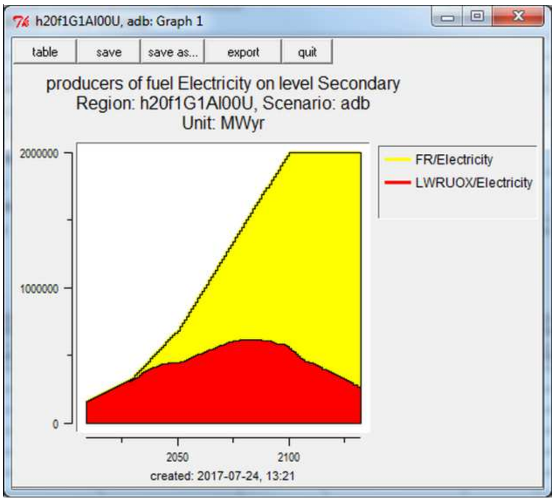


FIG. 173. Nuclear power production in NG1 for synergistic case.

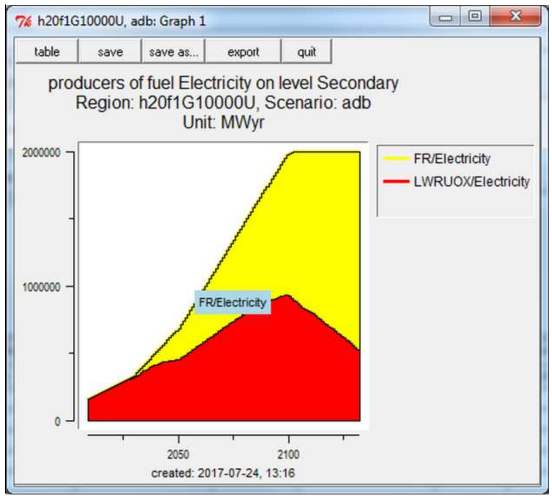


FIG. 174. Nuclear power production in NG1 for non-synergistic case.

The introduction of new LWR reprocessing capacity was assumed to be limited by 850 t HM/year spent fuel up to 2050 and by 3000 t HM/year spent fuel after 2050. The reprocessing facility should operate for its full lifetime, at full capacity. Figure 175 shows the reprocessing rates of spent LWR fuel for NG1 accounting for the additional spent fuel provided by NG3. For both non-synergistic (Fig. 176) and synergistic cases, the same reprocessing load is used during the modelling period up to 2050.

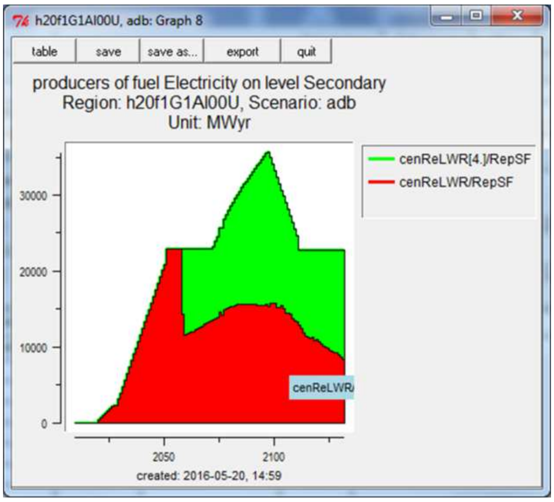


FIG. 175. LWR SNF reprocessing requirements in NG1 for synergistic case.

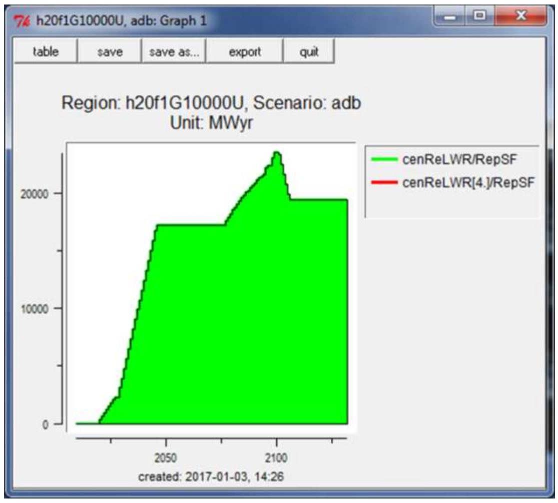


FIG. 176. LWR SNF reprocessing requirements in NG1 for non-synergistic case.

After 2050, new LWR reprocessing capacity increases in the synergistic case in comparison to the non-synergistic one as more fuel from NG3 goes to reprocessing in NG1 while the reprocessing rate is limited to 3000 t HM/year.

Figure 177 shows the stored LWR spent fuel in cooling and long term storage. There is some NG1 LWR spent fuel in the first part of the scenario until the excess stored fuel is reprocessed. After 2100, there is an increase in spent fuel shipped from NG3 owing to a levelling of electricity demand in NG1 and, hence, limited FR growth.

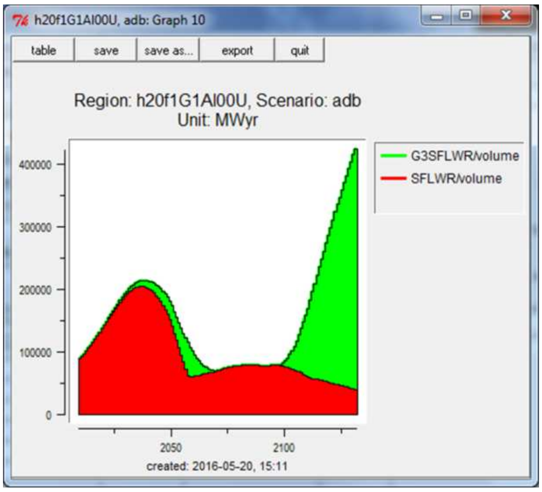


FIG. 177. LWR spent nuclear fuel in storage (cooling and long term) in NG1 for synergistic case.

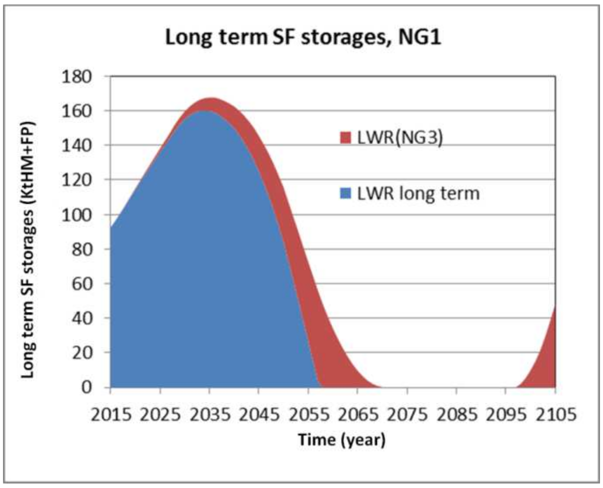


FIG. 178. LWR spent nuclear fuel in long term storage in NG1 for synergistic case.

The long term storage facility achieves its maximum capacity of 165 000 t HM by 2035, then the inventory decreases and fully depletes around 2070, as shown in Fig. 178. At that time, all LWR SNF available for reprocessing is reprocessed without the accumulation in long term storage. Practically identical storage capacities are needed to store NG1 SNF in the non-synergistic case and NG1 and NG3 SNF in the synergistic case. In the synergistic case, the only fuel stored in NG3 is the small amount cooling at the reactors prior to shipment to NG1.

NG3 benefits by not having to develop, site and construct nuclear fuel cycle facilities, including those related to the disposal of highly radioactive spent nuclear fuel. NG1 gains a source of additional used LWR fuel to support its strategy of transitioning to fast reactors.

3.1.5.3. Synergistic case NG1–NG3–NG2

Impact of NG3 and NG2 on NG1

In the previous case, no movement of fuel occurred between NG1 and NG2. The NG2 general strategy was either to directly dispose the used fuel or to reprocess the used fuel abroad. In this, the NG2 accumulates a very large amount of SNF. The synergistic approach for NG1 and NG2 could facilitate a solution to the global problem of accumulating SNF inventories and associated waste disposal. The second variant of cooperation assumed that the NG1 group provides fresh fuel for NG3 group and the shipping of all the NG2 and NG3 spent fuel to NG1 for reprocessing and recycling. Shipping of the NG2 spent fuel to NG1 has a significant impact on NG1 reactor mix share.

Figure 179 shows the power production growth and the reactor mix share in NG1. The power demand share is 40% of the total world demand in 2100. The FR's power reaches 100% of NG1 power production around 2095. The FR power production increases as compared to using SNF only from NG3 owing to the additional Pu reprocessed from the NG2 spent fuel.

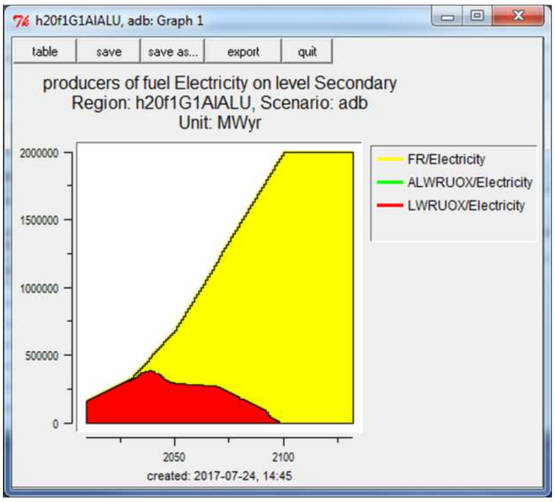


FIG. 179. Power production growth and reactor mix share in NG1.

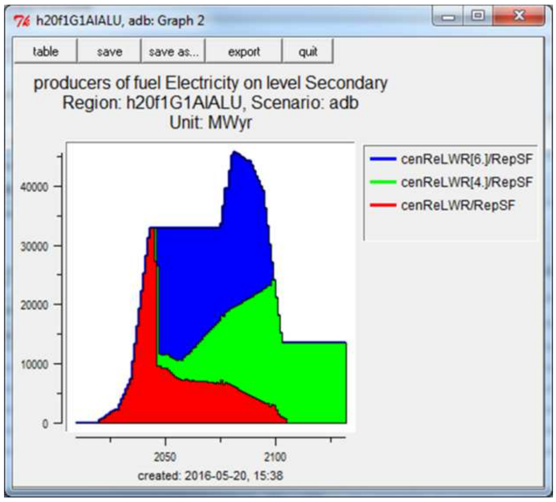


FIG. 180. LWR reprocessing load (NG3 and NG2 impact).

Figure 180 shows the reprocessing load when the NG3 and NG2 SNF is transported to NG1. If only the NG3 spent fuel was shipped to NG1, the reprocessing capacity was constrained by 850 t/year of SNF up to 2050 and by 3000 t/year of SNF after 2050. For this constraint, the use of NG2 spent fuel is limited. A constraint on the reprocessing capacity was increased up to 3000 t/year of SNF after 2035 for the case when NG2 transports its spent fuel to NG1. This allows to reprocess more spent fuel from NG2. The reprocessing requirement of NG1 sharply increases up to 33 t/year, then drops after 2045 and declines to zero by the end of the century. The reprocessing capacities are fully used during their lifetime and reprocess the NG2 and NG3 SNF in a complementary way.

Figure 181 shows the total stored spent fuel from LWRs, both in cooling and in long term storage. Figure 182 shows the LWR long term storage requirement in NG1. The NG2 SNF cannot be fully used. The NG2 SNF inventory decreases to 200 t by 2065 and then continuously increases owing to the excess of LWR spent fuel needed by NG1 to build the maximum number of FRs. A total demand of 2000 GW(e) in NG1 in 2100 limits the introduction of more FRs.

The NG1 power demand, as well as the reprocessing rate, are critical for the FR introduction rate and for the capability of NG1 to reprocess all spent fuel from other NGs. NG2 and NG3 should store and/or dispose part of their SNF in this scenario. An increase in the FR breeding ratio can only exacerbate the issue related to SNF accumulation. The introduction of FRs without an associated fuel cycle in NG2 and/or NG3 could help resolve this issue. Another approach would be to increase the NG1 share. It could be interesting to quantify the NG1 demand that may fully resolve the issue of worldwide SNF accumulation. For this purpose, the high growth NG1 scenario from 50% to 65% of the world demand (3250 GW(e) by 2100) was considered. In this scenario, SNF from all NGs is fully consumed by 2070. SNF, which is a waste to NG3 and NG2, serves as a resource to NG1 in this case allowing a transition to a large scale nuclear energy without accumulation of the large amount of SNF.

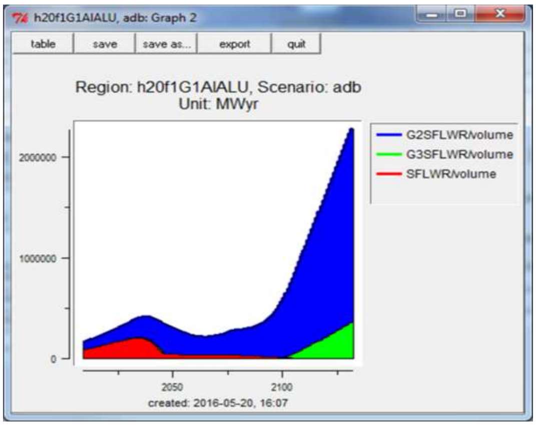


FIG. 181. LWR Spent nuclear fuel in cooling and long term storage in NG1 including NG3 and NG2 impact.

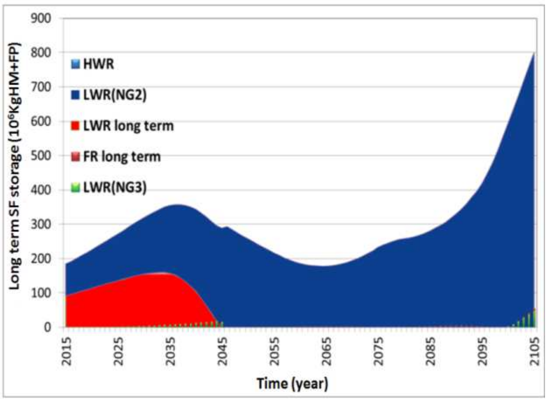


FIG. 182. LWR Spent nuclear fuel in long term storage in NG1 including NG3 and NG2 impact.

3.1.5.4. Sensitivity analysis of the shares of NG1–NG2–NG3 country groups in GAINS scenarios

Sensitivity analysis of world heterogeneous scenarios with different NG3 shares

Sensitivity analysis investigated different estimates of the NG3 market share by varying the fraction of the world growth assigned to NG3. NG1 share was always kept at a base case value (40% in 2100). NG2/NG3 share in 2100 was varied as 50/10, 40/20 (base case), 30/30, 20/40, and 10/50. The impact of the NG3 share on the NG1/NG3 fuel cycle including the front end and the back end requirements was evaluated.

Figure 183 shows power production growth in NG3 for different NG3 shares from 10% to 50%. In this analysis, the share of NG3 was varied and the NG1 share was maintained at a base case level (2500 GW(e)/year in 2100). The total demand corresponds to the GAINS high case (5000 GW(e)/year in 2100). This means that an increase in the NG3 share results in a decrease in the NG2 share.

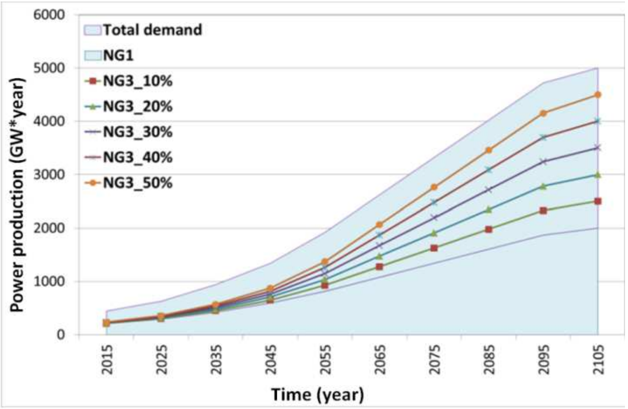


FIG. 183. *Power production growth.*

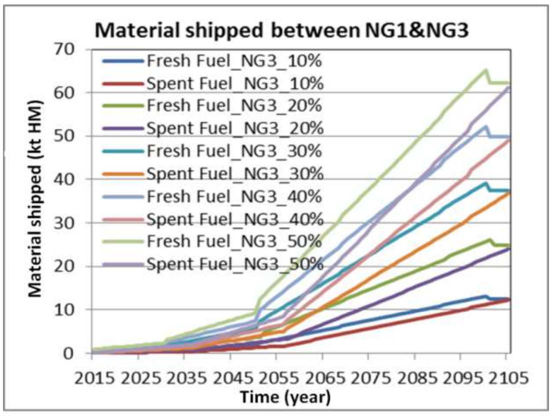


FIG. 184. Material shipped between NG1 and NG3.

In the synergistic case, NG1 was assumed to provide 100% of the fresh fuel to NG3 and take back 100% of its SNF. In this case, shipping of the fresh fuel and SNF would become an issue. The percentage of fresh fuel shipped to the total fresh fuel requirements of NG1 and NG3 is 5–20% in the short term, 14–45% in the medium term and 40–95% in the long term (Fig. 184).

More material would be available for FRs with an increase in the NG3 share in the synergistic case. Figures 185 and 186 compare the power production of LWRs and FRs. Visible differences begin in the medium term after 2050. FR power production increases with the NG3 share, achieving 1000–1900 GW/year for the NG3 share in the range 10–50% in the long term, by 2100 (see Fig. 185). LWR power production increases up to about 900 GW/year by 2100 for the non-synergistic case and declines towards zero for the NG3 share of 50% in the synergistic case (see Fig. 186). Other LWR power production curves are within this range.

In summary, there is a significant change of power production structure in NG1 caused by an increase in the NG3 share in the medium and long terms, with no impact in the short term. However, change of the NG1 power production by reactors has an impact on fuel cycle infrastructure in the region.

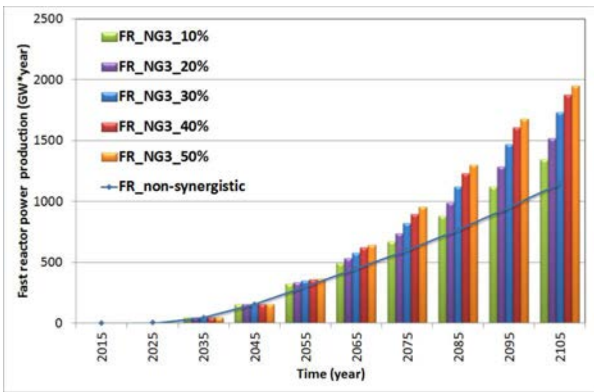


FIG. 185. FR power production growth.

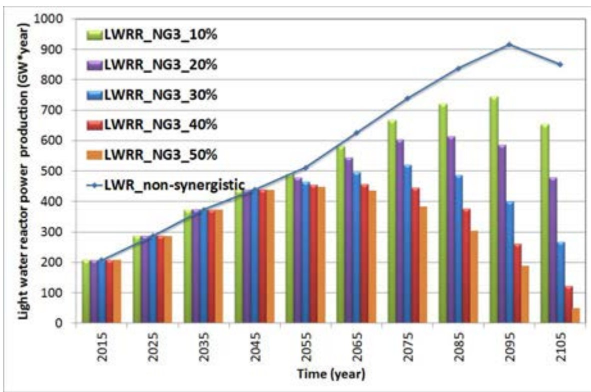


FIG. 186. LWR power production growth.

The introduction of new LWR reprocessing capacity was assumed to be limited by 850 t/year of SNF until 2050 and by 3000 t/year of SNF after 2050. All NG3 shares assume the same reprocessing load for the period up to 2050, as the reprocessing capacity of LWR spent fuel can only achieve a maximum rate of 850 t/year for all NG3 shares. Consequently, the same number of FRs are to be built based on the recovered plutonium and these will discharge the same amount of spent fuel for reprocessing (see Fig. 187). After 2050, new LWR reprocessing capacity increases as more fuel from NG3 goes to the reprocessing in NG1 and the possible reprocessing rate is now limited to 3000 t/year. In the medium term the LWR fuel reprocessing capacity achieves 20–32 kt/year for the NG3 shares in the range 10–50%.

Figure 188 shows the accumulation of SNF in NG1, including that from NG1 and NG3. The inventory of SNF is depleted around 2075 for NG3 with shares in the range 10–40%, and then all LWR SNF available for reprocessing is reprocessed without accumulation in the long term storage. Around 2100, SNF starts to accumulate again because the introduction of new FRs is constrained by flat total demand and the reactors commissioned after 2030 start to be decommissioned. Additional reprocessed plutonium from full core discharge at the retirement of those reactors can feed new FRs.

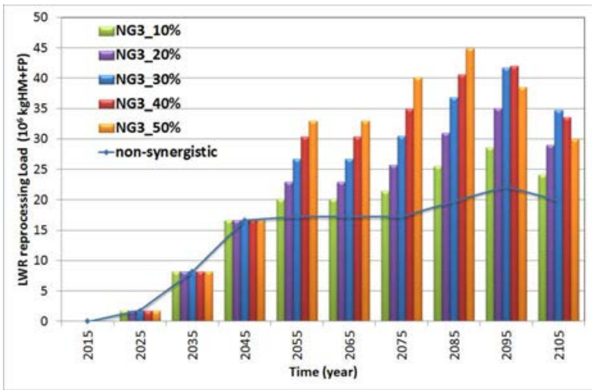


FIG. 187. LWR fuel reprocessing capacities in NG1.

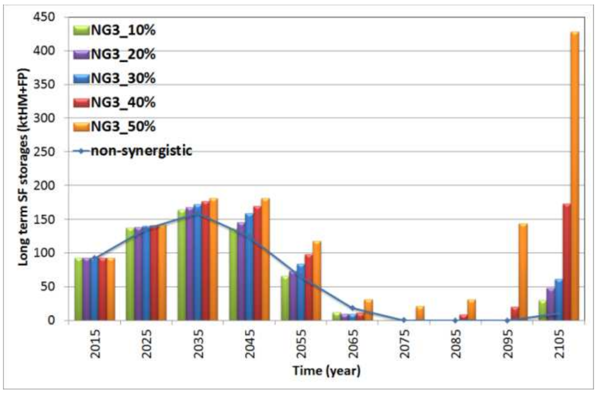


FIG. 188. LWR long term spent fuel storage accumulation in NG1.

For the 50% NG3 share, SNF available for reprocessing is not fully used. SNF accumulation declines to 20 t and then increases, owing to the restrictions on the introduction of FRs in NG1. Reprocessing capacity is sufficient to support the FRs, although the FR build rate is limited by the overall power demand growth in NG1, which flattens after 2100. Nevertheless, in this case the synergistic approach results in a significant reduction in the requirements for long term storage of SNF.

Sensitivity analysis of world heterogeneous scenarios with different NG1 to NG2 shares

The sensitivity analysis investigated the impact of NG1:NG2 shares and the role of collaboration with the NG3 group on the front end and back end NFC requirements, fixing the market share of NG3 at 20% by 2100. The change in the proportion of NG1:NG2 took into account the possible transition from one group to another.

In summary, there are significant savings of uranium resources and reductions of SNF volumes for options with a higher share of NG1 and a lower share of NG2 during a high growth scenario for nuclear energy. SNF from NG3 cannot be fully reprocessed in NG1 for scenarios with a low share of the NG1 nuclear power. The synergistic effects are rather small and begin to appear by the end of century for scenarios with large or nominal growth of the NG1 nuclear power.

Main conclusions and findings of the case studies

In the present century, global nuclear energy is likely to follow a heterogeneous world model, within which most of the countries will continue to use thermal reactors in a once-through nuclear fuel cycle.

The outputs of the performed studies indicate that the criteria for developing sustainable nuclear energy cannot be achieved without major innovations in reactor and nuclear fuel cycle technologies. Cooperation among countries could then amplify the positive effects of technology innovation in achieving sustainable nuclear energy for all interested users. Collaborative solutions in the nuclear fuel cycle and, specifically, in the fuel cycle back end are key to moving towards global sustainability of nuclear energy systems from the near term (2015–2030) through the medium term (2030–2050) towards the long term (2050–2100).

Countries that do not pursue fast reactor programmes could benefit from the synergistic cooperative approach as it results in reduced requirements for long term spent nuclear fuel storage and ultimate disposal of waste. However, there are a number of important legal and institutional impediments to cooperation among countries in the nuclear fuel cycle back end. Achieving synergistic NFC backend architectures requires industrial, public and political consensus. Responding to global challenges in a timely manner requires that building of the innovative architecture has to be started without delay.

3.1.6. Feedback from the case study on NES modelling with the MESSAGE tool

The MESSAGE tool was applied for the simulation of a heterogeneous world nuclear energy system assuming different countries pursue different policies regarding innovations in nuclear reactors and nuclear fuel cycles. The heterogeneous world model organizes countries into three groups according to their strategies for SNF management. The MESSAGE tool provides a good platform for creating a proper model of multiple groups operating separately or synergistically with interactions between the different groups. With MESSAGE it was possible to model the various possible options and variants of interregional cooperation among country groups, including some quite complex cases.

The major assumptions and boundary conditions for the NES considered could be introduced into the MESSAGE model adequately. In practice, the LWR reprocessing capacity was constrained to develop its more realistic introduction and operation. The fuel available for reprocessing for fast reactors is the NG1 and NG3 fuel modelled as alternatives. The constrained mode used for the reprocessing facility required the facility to operate at full capacity over its whole lifetime.

MESSAGE is quite flexible to model nuclear technologies with the necessary details, such as first loading and final unloading of fuel in reactors, cooling time for spent fuel discharged from reactor, lag and lead times for processes, and losses. Some nuclear processes can be taken into account, e.g., isotopic composition of spent fuel during the cooling time in storage during the nuclear power plant and reprocessing lag time because of radioactive decay of unstable isotopes. However, MESSAGE has some limitations regarding accounting for the decay of plutonium and minor actinides in long term stocks. Another issue relates to modelling of the cooling time in reactor storage facilities. There is no capability to move cooled spent fuel from a cooling storage to the long term one after a fixed cooling time. It would be very useful to extend the MESSAGE capability to simulate this operation.

Different fuel cycle steps, such as uranium conversion and enrichment, fresh fuel fabrication and reprocessing of spent fuel need to be modelled as facilities. For example, in a non-synergistic case each group has its own fuel cycle facilities to mine, convert, enrich and fabricate fresh fuel and to store and/or dispose of spent fuel. NG1 has a separation facility to reprocess spent fuel from fast and thermal reactors. In a synergistic case, the NG3 group follows a strategy to obtain fuel cycle services from NG1 and NG2, including the front end services such as mining, conversion, uranium enrichment and fresh LWR fuel fabrication, and the back end services of taking back the used LWR fuel after it has cooled. Both variants can be modelled with MESSAGE by using the activity and capacity pages for associated technology.

Sensitivity studies can be easily performed by varying the demand in country groups. The MESSAGE model updates the nuclear material flows and the nuclear infrastructure accordingly. Comparison of the results from sensitivity studies appears to be quite simple and practical with MESSAGE.

3.2. INPRO GLOBAL AND REGIONAL SCENARIOS WITH INTRODUCTION OF THORIUM

3.2.1. Introduction (general information)

Thorium is being seen as an attractive addition to the available nuclear material resources. There is a growing global interest in the use of a thorium based fuel cycle for supporting future large scale nuclear energy system deployment. The role of thorium fuel cycle in enhancing global nuclear energy sustainability has been studied by INPRO [3–5, 66–68]. These studies potentially focused on the prospective role of the thorium based fuel cycle in supporting the uranium–plutonium based fuel cycle for meeting future energy demands. Thorium has been studied as an important alternative nuclear fuel, particularly in thermal and fast reactors. Particular benefits of using thorium fuel include its natural abundance, reduced enrichment requirements in the fuel cycle, high conversion yield to fissile material (^{233}U) in the thermal neutron spectrum and improved thermal and neutron properties that may be potentially useful for nuclear energy systems of current as well as future generations.

3.2.2. Objectives and task description

This section summarizes the INPRO studies related to the potential role of thorium fuel cycles for enhancing nuclear power sustainability in the 21st century. The following specific areas were considered in INPRO studies on the thorium fuel cycle:

— Reduction in natural uranium requirements and the opportunity to reduce enrichment requirements of uranium;
— Increase in available fissile material resources of the world by ^{233}U breeding from thorium;
— Minimized production of plutonium and minor actinides by use of thorium fuel leading towards reduced waste inventories and radiotoxicity;
— Requirements of the front end and back end modifications in the existing fuel cycle facilities for commercial exploitation of thorium fuel.

The INPRO scenario studies presented in this section considered modelling the three variants of thorium utilization in the nuclear fuel cycle using MESSAGE: (i) once-through fuel cycle using thorium in thermal reactors without spent fuel reprocessing, (ii) closed fuel cycle using thorium and/or ^{233}U in thermal reactors only with spent fuel reprocessing and recycling of the fissile Pu and ^{233}U and (iii) closed fuel cycle using thorium and/or ^{233}U in thermal and fast reactors with spent fuel reprocessing and recycling of the fissile plutonium and ^{233}U.

3.2.3. Description of the model, input data, NES options, assumptions and metrics (indicators) for scenario analysis

The methods, major assumptions and boundary conditions for NESs, as well as data for thermal and fast spectrum nuclear power plants for U/Pu fuel cycles used in the studies were based on the analytical framework for assessing transition scenarios to future sustainable NESs developed in the GAINS and thorium collaborative projects [3, 5].

Global nuclear power demand growth: Non-geographical group model

According to the GAINS project, two nuclear energy demand scenarios were selected for assessment. In the high scenario, global nuclear power demand reaches 1500 GW(e) in the middle of the century and 5000 GW(e) by 2100. The moderate case assumes 1000 GW(e) in the middle of the century and 2500 GW(e) in 2100.

Natural uranium and thorium resources

The data on uranium resources were divided in five grades: a, b, c, d and e. Grades a, b and c refer to identified and undiscovered resources in the US $40/kgU, US $80/kgU, and US $130/kgU cost categories that total 16 million tons of natural uranium. Grade d is associated with uranium in phosphates and has a resource of 22 000 000 tons of uranium with a recovery cost of >350 US $/kgU. Resources of grade e are associated with uranium in sea water with the cost of recovery higher than US $450/kgU. Thorium resources were estimated at about 6.08 million tons, including undiscovered resources with the cost of recovery less than US $80/kgTh.

Reactor system and data

The reactor data for the U/Pu fuel cycle that are necessary for NES modelling and comparison of the variants were taken from the data bank of the GAINS project [3]. Data of the reactors utilizing Th/^{233}U fuel were provided by Member States participating in the thorium project. The reactors utilizing the U/Pu and Th/^{233}U fuel cycle that have been chosen for scenario simulation are listed in the Table 51(a).

TABLE 51(A). REACTOR TYPES BASED ON UOX/MOX AND ON THORIUM FUEL

Reactor types based on UOX/MOX fuel						
Reactor	HWR	LWR	ALWR	LWRM	FR (BR~1)	FR12 (BR~1.2)
Fuel type	NatU	UOX	UOX	MOX	MOX, depU	MOX, depU
Reactor types based on thorium fuel						
Reactor	LWR0	LWR1	LWR2	HWR1	HWR2	FRTh
Fuel type	UO_2, Th	Pu, Th	Pu, ^{233}U, depU	Pu, Th	Pu, ^{233}U, Th	Pu, depU, Th in blankets

The thorium project performed an estimation of economic parameters for LWRs, HWRs and FBRs. The task of estimating economic competitiveness of the innovative reactors is complicated because of the necessity to assess possible trends in the cost of constituents. The data on thorium based reactors published in open sources were insufficient or less reliable. It was assumed that the difference between U/Pu and ^{233}U/Th fuelled reactors of the same type in capital cost and costs of operation and maintenance is low enough to be negligible. The capital cost of an HWR was assumed to be 10% higher than for an LWR. The capital cost of an FBR was assumed to be 25% higher than the capital cost of LWR.

The thorium project compiled input data on the cost of various fuel cycle options based on the various sources. The parameters of the U/Pu fuel cycle front end are relatively more transparent while the reprocessing, MOX, and waste management related data are much less reliable. The reference economic parameters of the considered reactors and fuel cycles are given in Table 51(b). Taking into account the large uncertainty in data available on the fuel cycle, the thorium project recognized that these costs are subject to change in the future and should be updated when new reference information is collected and evaluated.

TABLE 51(B). ECONOMIC PARAMETERS OF REACTOR TYPES BASED ON UOX/MOX AND ON THORIUM FUEL

	Unit	Type	Reference value
Reactor costs			
Overnight cost	US $/kW(e)	LWR/Th	2000
		HWR/Th	2200
		FBR MOX/Th	2500
Fixed O&M cost	US $/kW·year	LWR/Th	55
		HWR/Th	60
		FBR MOX/Th	60
Variable O&M cost	mill/kW·h	LWR/Th	0.5
		HWR/Th	0.5
		FBR MOX/Th	0.5
Fuel cycle costs			
Conversion	US $/kg U	LWR, HWR	8
Enrichment	US $/kg SWU	LWR UOX	110
Fuel fabrication	US $/kg HM	LWR UOX	275
		HWR UOX	85
		FR MOX	350
		HWR UOX	85
		LWR1	325
		LWR2	1500
		HWR1	100
		HWR2	500
		FR Bl U/Th	350
Reprocessing	US $/kg HM	UOX	800
		MOX	800
		FR MOX	1000
		FR Bl U	800
		Th HEU and Th Pu	2000
		Th Pu ^{233}U	2000
		FR Bl Th	1200

Fuel cycle options with thorium utilization

The schemes and characteristics of the fuel cycles available for simulation, as well as the result of this simulation, depend strongly on the reactor data and material flow parameters compiled. Three variants of thorium fuel introduction were considered in the scenario study:

(i) Once-through fuel cycle based on thermal reactors utilizing thorium without spent fuel reprocessing;

(ii) Closed fuel cycle based on thermal reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and ^{233}U (as well as Pu) recycling;
(iii) Closed fuel cycle based on thermal and fast reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and recycling of ^{233}U and Pu.

The once-through fuel cycle based on thermal reactors using uranium fuel (BAU case in GAINS) and thermal reactors of LWR types with Th/(^{235}U+^{238}U) fuel is presented in Fig. 189. The drawn system includes the existing and advanced LWR-type reactors using UOX fuels, the existing HWRs using UOX fuel and the advanced LWRs using Th/(^{235}U+^{238}U) fuel. The back end consists of spent fuel intermediate storage.

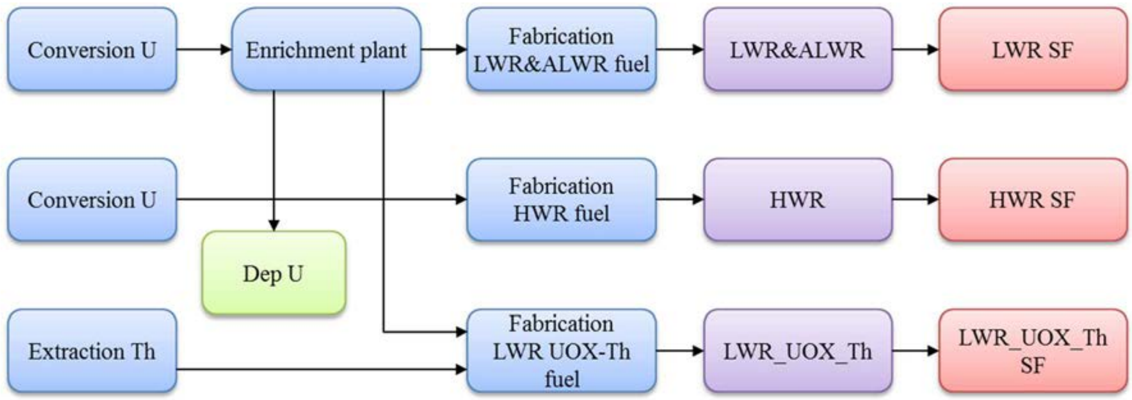


FIG. 189. Once-through fuel cycle that includes light water thermal reactors utilizing thorium without spent fuel reprocessing.

The variant of the closed nuclear fuel cycle using the uranium and thorium spent fuel reprocessing includes the existing and advanced LWR-type reactors using UOX fuel, the existing HWRs with UOX fuel, the advanced LWRs utilizing Pu/Th/^{233}U fuel and the HWRs also utilizing Pu/Th/^{233}U fuel. In Fig. 190, plutonium from the reprocessed spent fuel is being used for fresh fuel fabrication for advanced thermal reactors and ^{233}U is being recycled for Pu/Th/^{233}U fuel production.

Placement of thorium in blankets of a fast reactor fuel is a very common consideration and is associated with the use of ^{233}U in fast reactor's core. If ^{233}U is not utilized, the core becomes unsustainable as the plutonium consumption surpasses the plutonium production and requires external feed, unless such reactor is intended as a Th-^{233}U breeder for producing ^{233}U fuel for LWRs and HWRs.

Figure 191 gives a scheme for the closed fuel cycle based on thermal and fast reactors with thorium in radial blankets and multi-recycling of plutonium and ^{233}U in thermal (both Pu and ^{233}U) and fast (only Pu) reactors.

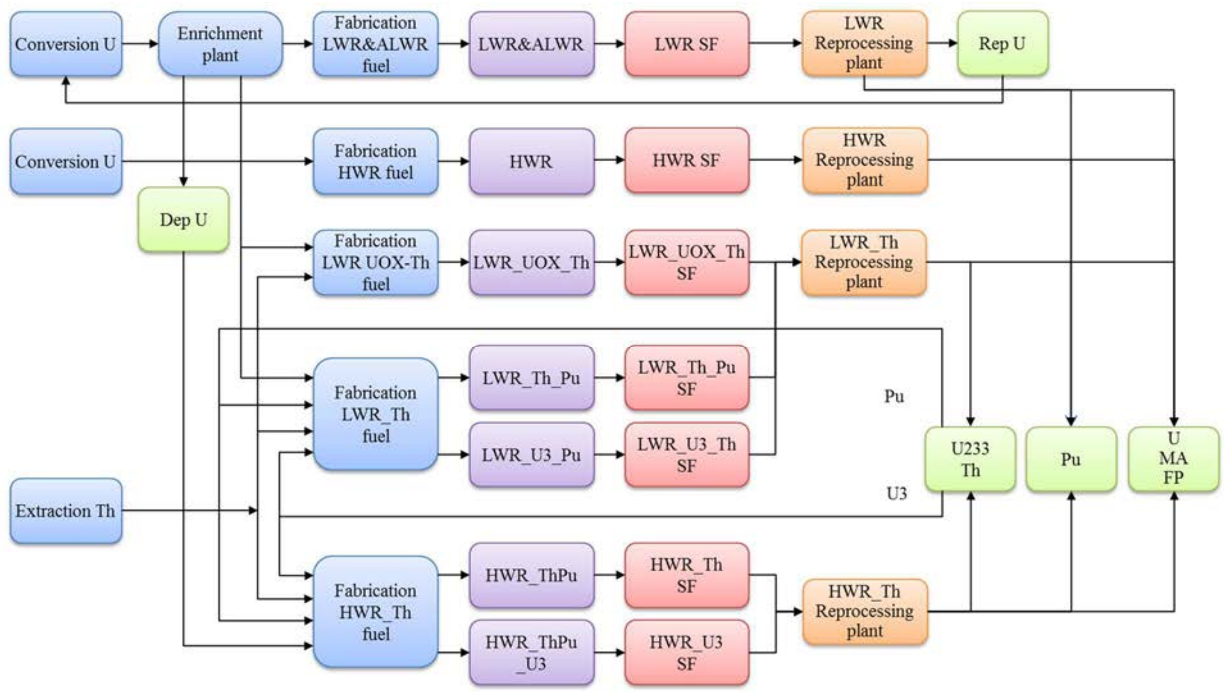


FIG. 190. Closed fuel cycle scheme based on thermal reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and recycling of Pu and ^{233}U.

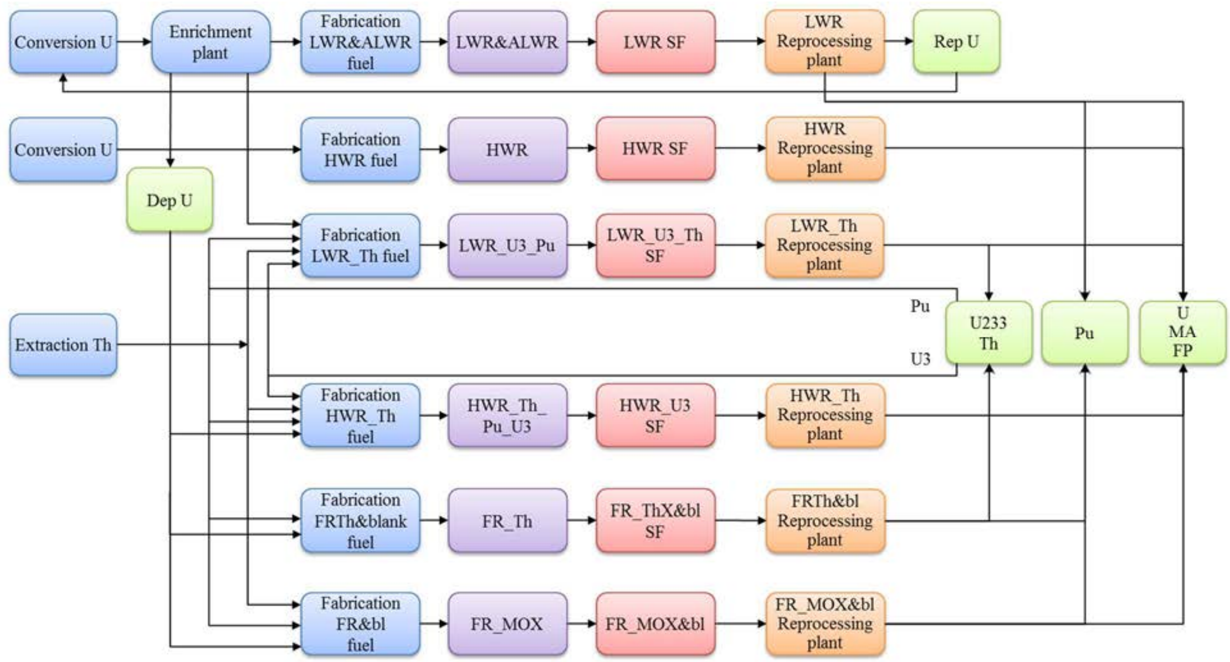


FIG. 191. Closed fuel cycle scheme based on thermal and fast reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and recycling of ^{233}U and Pu.

The following MESSAGE output parameters have been selected as the indicators to compare fuel cycle options:

— The distribution of total nuclear generation capacity among reactor types constituting the system as the result of the material balance consideration and economic optimization process;

— Cumulative consumption of natural uranium in the system;

— Necessary services of uranium enrichment, fuel fabrication and spent fuel reprocessing;

— Spent fuel and minor actinides accumulated in the system;

— Annual discharge and consumption of plutonium, ^{233}U and minor actinides.

3.2.4. Modelling of selected NES elements with MESSAGE

The once-through thorium fuel cycle based on thermal reactors without spent fuel reprocessing

Once-through thorium fuel cycle modelled in this scenario study includes existing and advanced LWRs using UOX fuel, existing HWRs using natural uranium fuel and advanced LWRs using thorium and UOX fuels (LWR0). After irradiation, spent fuels are put into temporary storage in an interim storage facility.

Thermal reactors consume uranium fuel and their fuel chain comprises conversion, enrichment and fuel fabrication which are modelled in the same manner as in the case of the once-through fuel cycle in the DEMO CASE NFC1 [2]. This section represents only modelling specifics of the thorium based reactor (LWR0) and fabrication of its fuel.

The LWR0 uses two fuel types: 0.76 of thorium fuel and 0.24 of enriched UOX fuel. Figure 192 presents the modelling of fresh fuel fabrication for LWR0. The thorium resource and its costs should be added to the uranium resources at the resource level. Both fuels are considered as applicable in this model. To produce one unit of fresh fuel, fabrication technology uses 0.76 of uranium fuel as the main input and 0.24 of UOX fuel as a secondary input (see Fig. 192).

The model simulates the LWR0 unit which is assumed to have 900 MW(e) of installed capacity with a capacity factor of 80%. The LWR0 activity and capacity details are given in Figs 193 and 194. LWR0 consumes annually 21.36 t HM of fresh fuel (5.12 t HM of UOX fuel, 16.24 t HM of ThO_2) to produce 720 MW/year of electricity. It discharges the same amount, i.e. 21.36 t HM of UOX and ThO_2 spent fuel to storage. The relative fractions of fresh fuels consumed by the reactor per unit of electricity output should be 0.029 67 (=21.36/720) for fresh fuel, including ThO_2 and UOX (Fig. 193). The same fraction is discharged to the cooling pool.

The initial core loading and final core discharge data need to be given as the fraction of reactor installed capacity (Fig. 194). The LWR0 installed capacity is 900 MW(e), the initial core loading is 16 t HM for UOX fuel, 51 t HM of ThO_2, a total of 67 t HM. The corresponding relative number in 'corin' is 0.005 07 (=(67-21.36)/900) for fresh fuel. The final core unloading (including fission products) is the same.

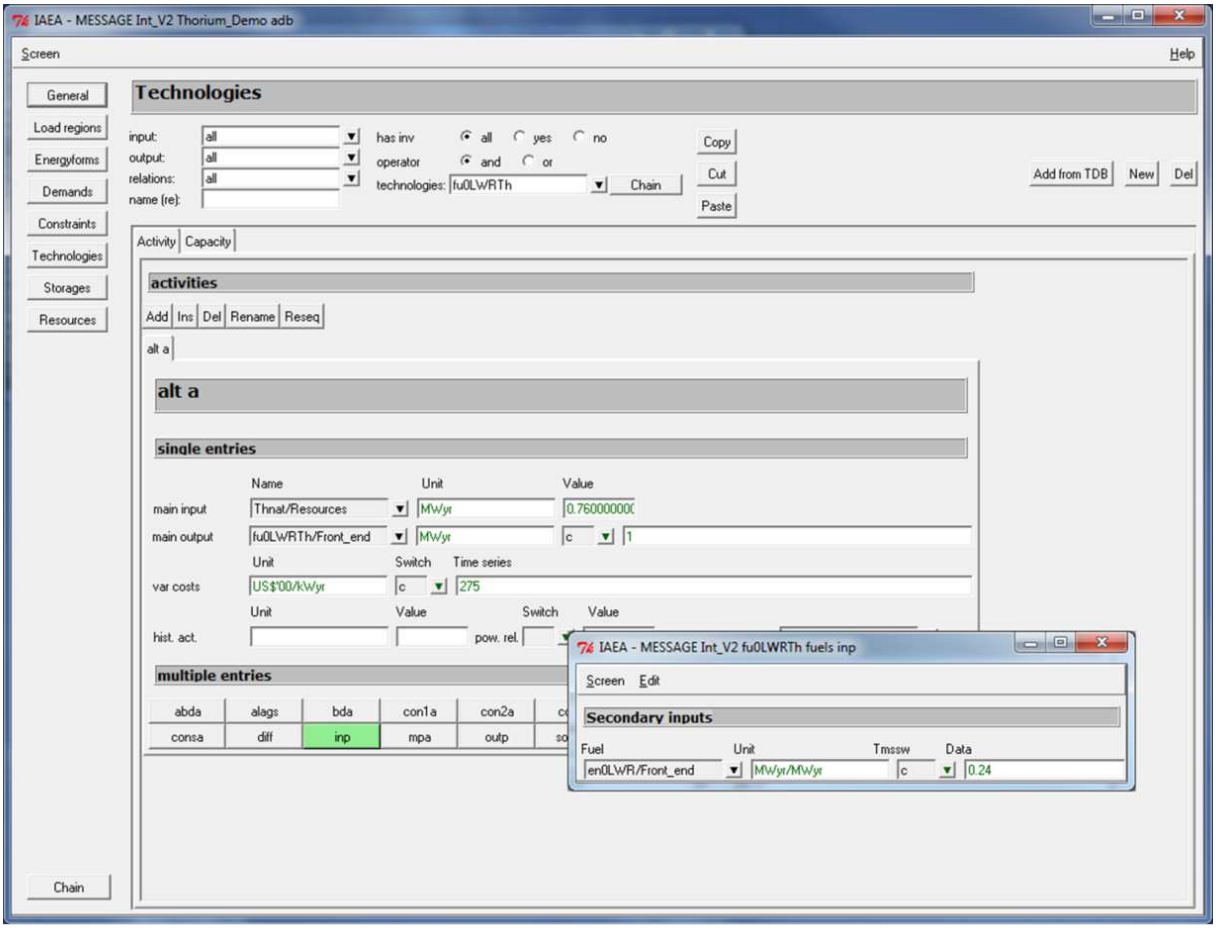


FIG. 192. Modelling of fresh fuel fabrication for reactor technology LWR0.

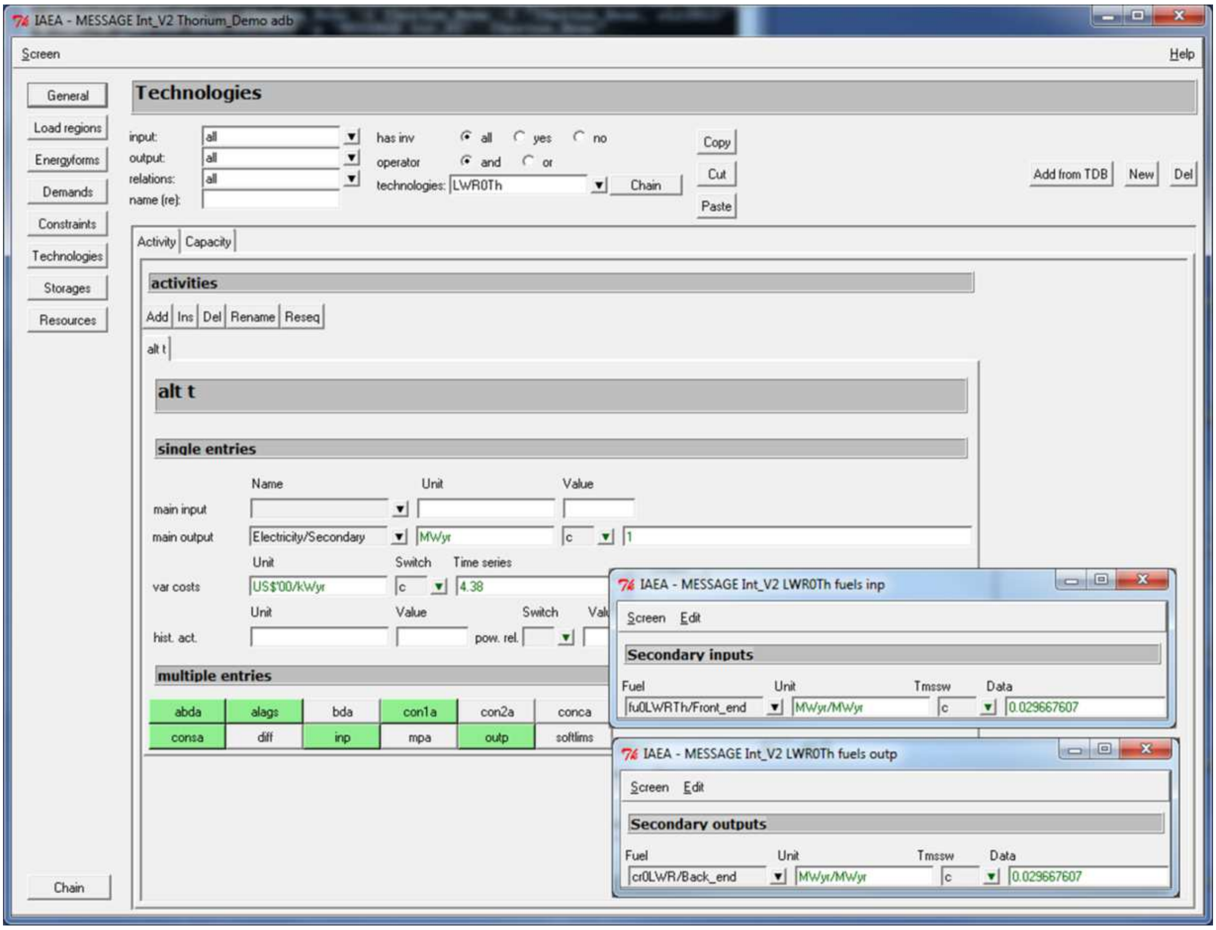


FIG. 193. LWR0Th activity page.

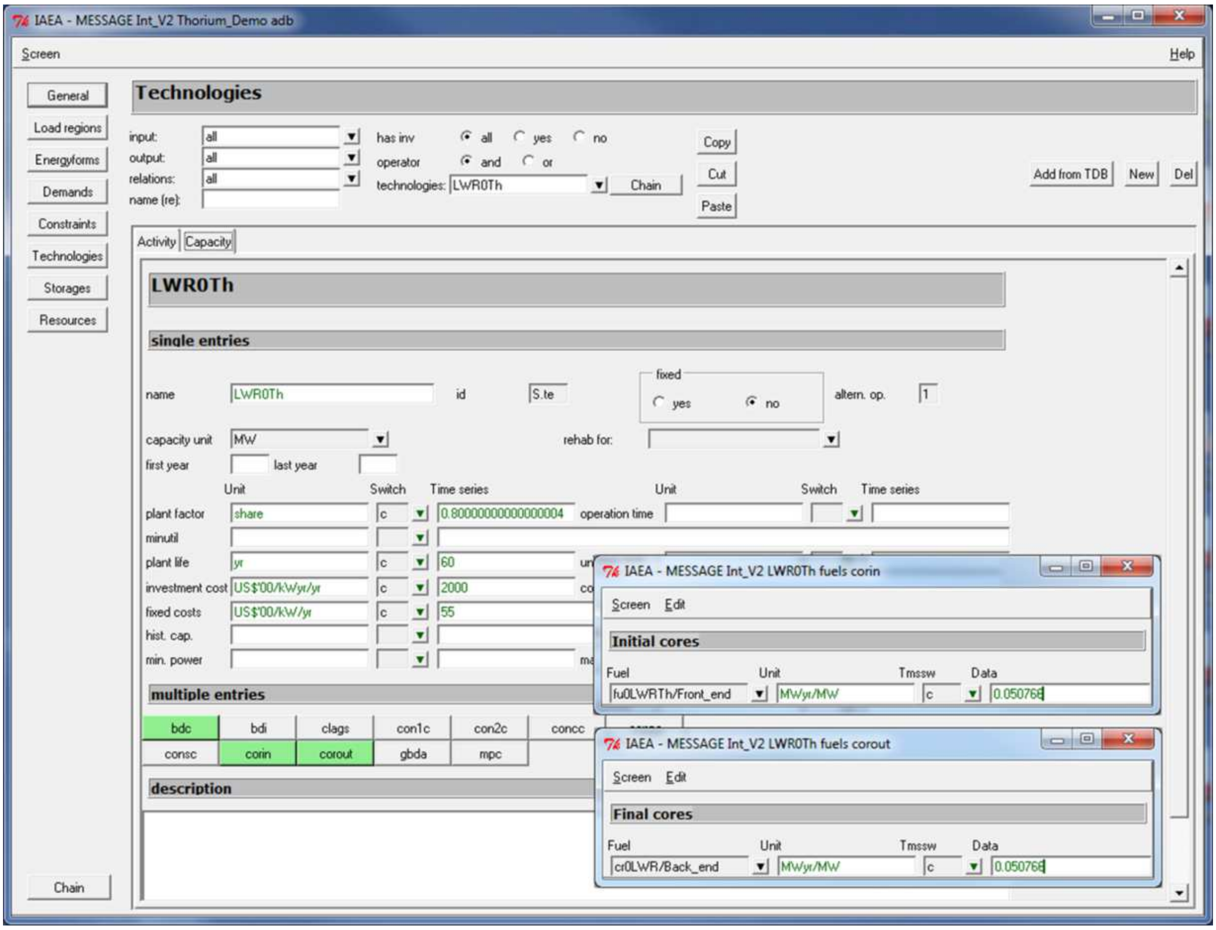


FIG. 194. LWR0Th capacity page.

Closed thorium fuel cycle based on thermal reactors with spent fuel reprocessing and Pu/^{233}U recycling

A closed thorium fuel cycle based on thermal reactors includes the existing HWRs, the existing and advanced LWRs (LWR1 and LWR2) and the advanced LWRs and HWRs (HWR1 and HWR2) utilizing thorium, plutonium and ^{233}U. This scenario study envisaged thorium utilization in HWR1 type reactors using Pu/Th fuel, and consequent ^{233}U utilization in HWR2 reactors using Pu/^{233}U/Th fuel, as well as the corresponding LWR1 utilizing Pu/Th fuel and LWR2 based on Pu/^{233}U/depleted U. Figures 195–200 illustrate modelling of the HWR1 and HWR2 tandem utilizing reprocessed plutonium as a driver in fresh fuel for HWR1 and also the ^{233}U recycled for Pu/Th/^{233}U fuel fabrication.

Figure 195 presents the modelling of fresh fuel fabrication for HWR1 consisting of 0.0376 reprocessed plutonium and 0.9624 thorium.

Figure 196 shows the HWR1 activity page. HWR1 has an annual consumption of 30 t HM of fresh fuel (Pu/Th) to produce 635 MW(e)/year of electricity (=668 × 0.95). It discharges in total 30 t HM of spent fuel to related storage. The relative fractions of fresh fuel consumed by the reactor to the unit of electricity output should be 0.047 28 (=30/635) for fresh fuel. The same amount is discharged to the cooling pool.

Reprocessing technology is constructed as a facility, as shown in Fig. 197. It includes several alternatives for reprocessing of different spent fuel types. Figure 197 shows an alternative for reprocessing of spent fuel from HWR1. It takes one unit of spent fuel and puts into storage 0.949 24 of thorium, 0.018 991 1 of plutonium, 0.001 953 of minor actinides, 0.008 599 7 of ^{233}U, and 0.020 569 9 of FP. The main output has an auxiliary role and puts one unit of SNF to the dummy level.

Uranium-233 is recycled for HWR2 fuel production. Figure 198 shows modelling of fresh fuel for HWR2. Fabrication of one fresh fuel unit needs 0.010 86 of plutonium, 0.014 446 22 of ^{233}U and 0.947 693 of thorium.

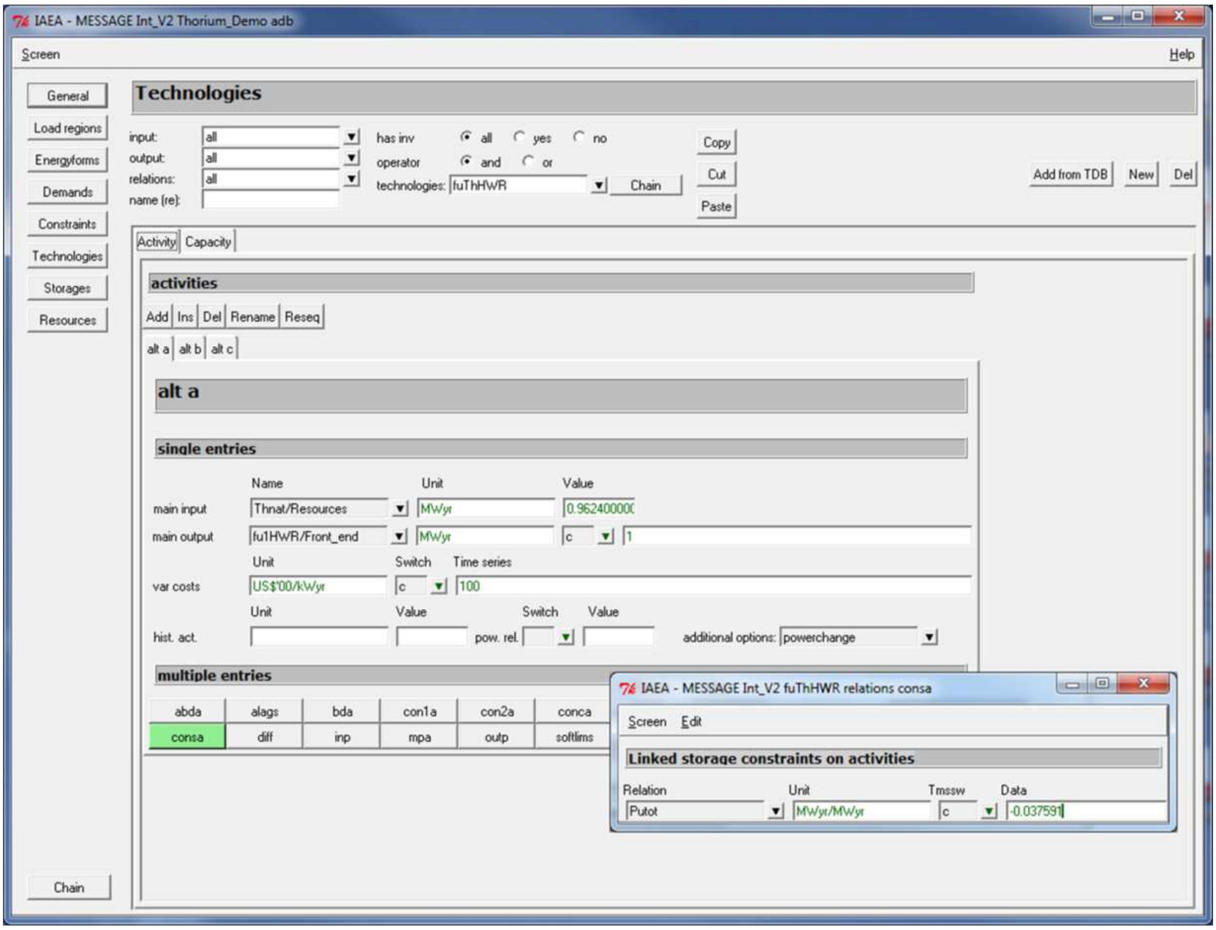


FIG. 195. Fuel for HWR1 (Pu–Th).

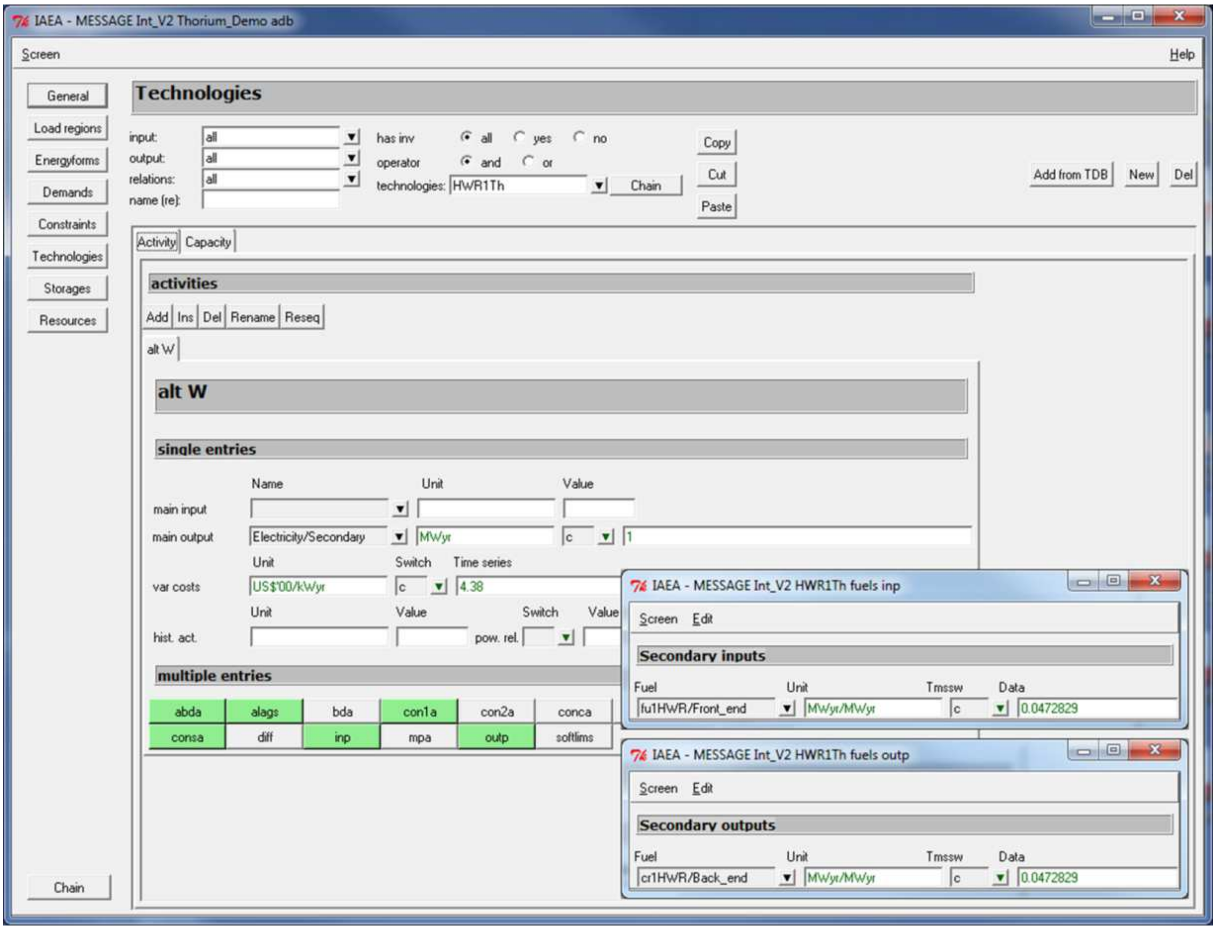


FIG. 196. HWR1 activity page.

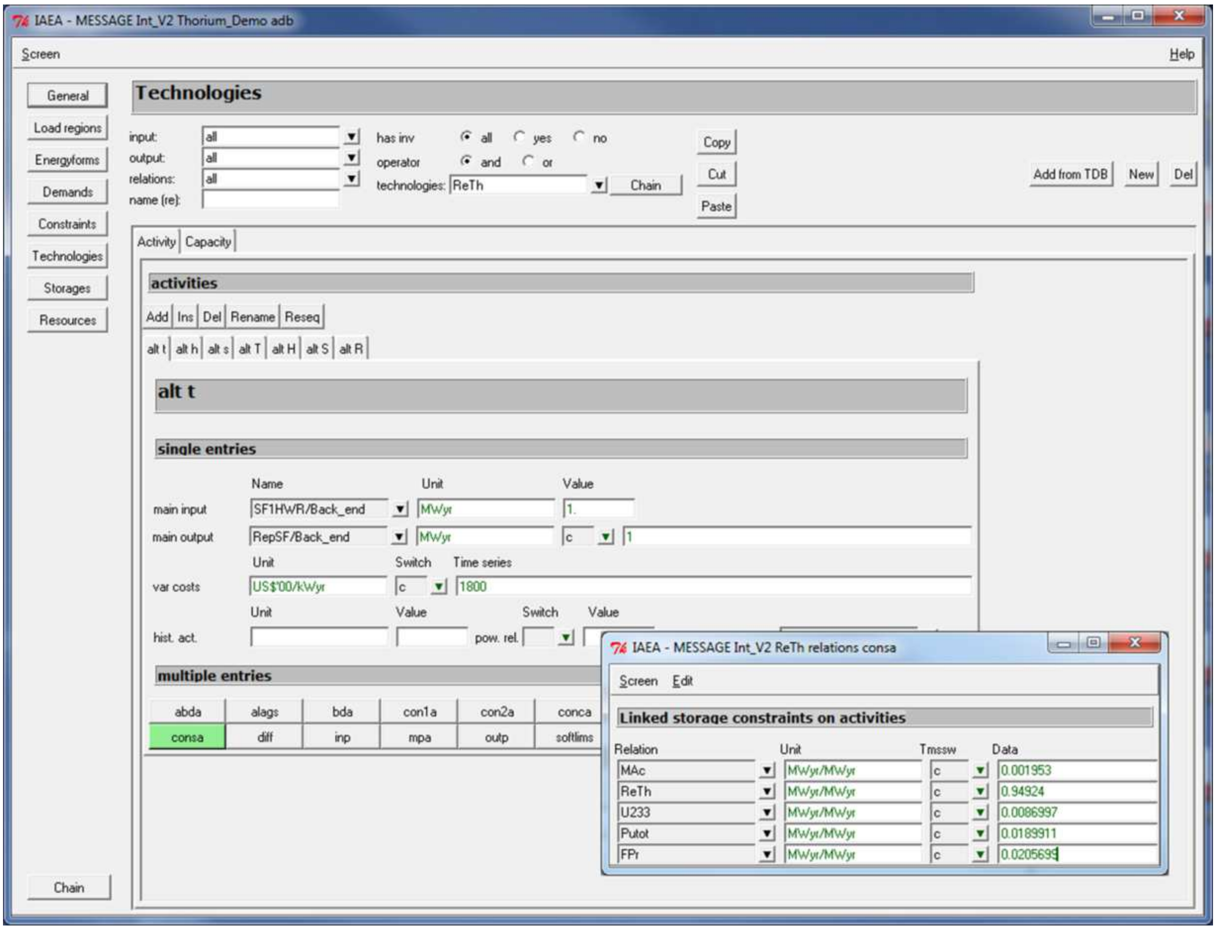


FIG. 197. Reprocessing of HWR1 SNF fuel.

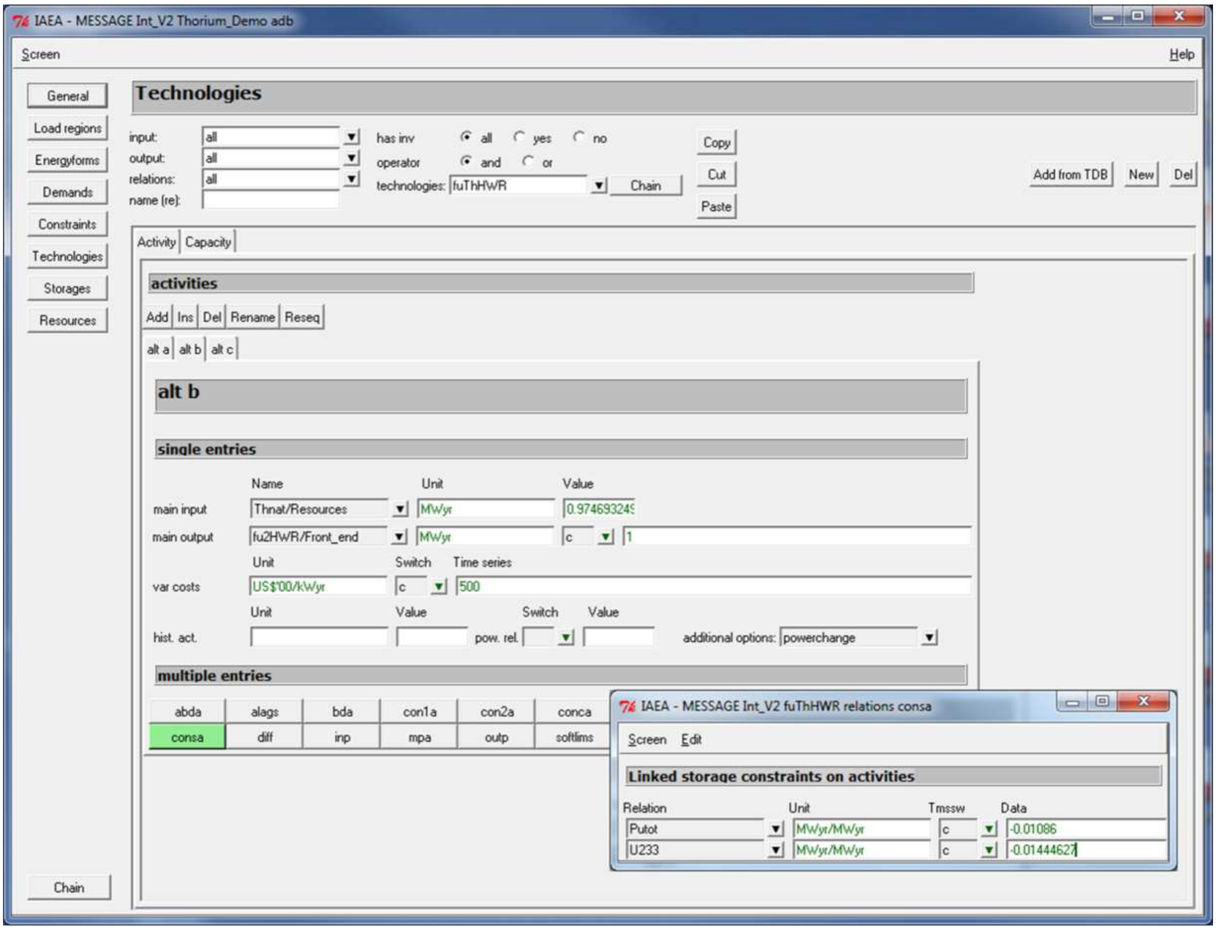


FIG. 198. *Fuel for HWR2 (Pu Th ^{233}U).*

The HWR2 activity page is shown in Fig. 199. HWR2 requires an annual consumption of 30.6 t HM of fresh fuel (Pu/Th/^{233}U) to produce 635 MW(e)/year of electricity (=668 × 0.95). It discharges in total 30 t HM of spent fuel to related storage. The relative fractions of fresh fuel consumed by the reactor per unit of electricity output should be 0.048 15 (=30.6/635) for fresh fuel. The same amount is discharged to the cooling pool.

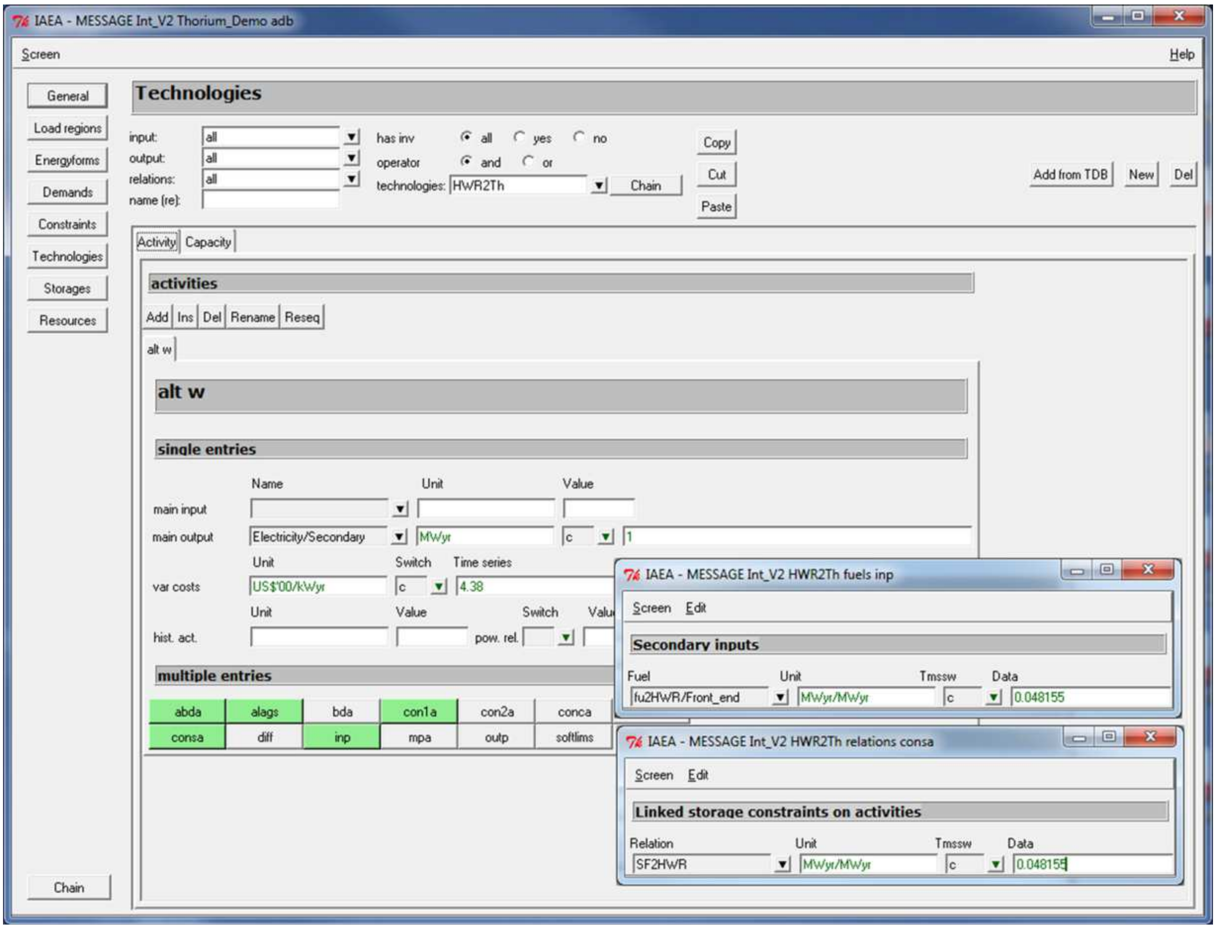


FIG. 199. HWR2 activity page.

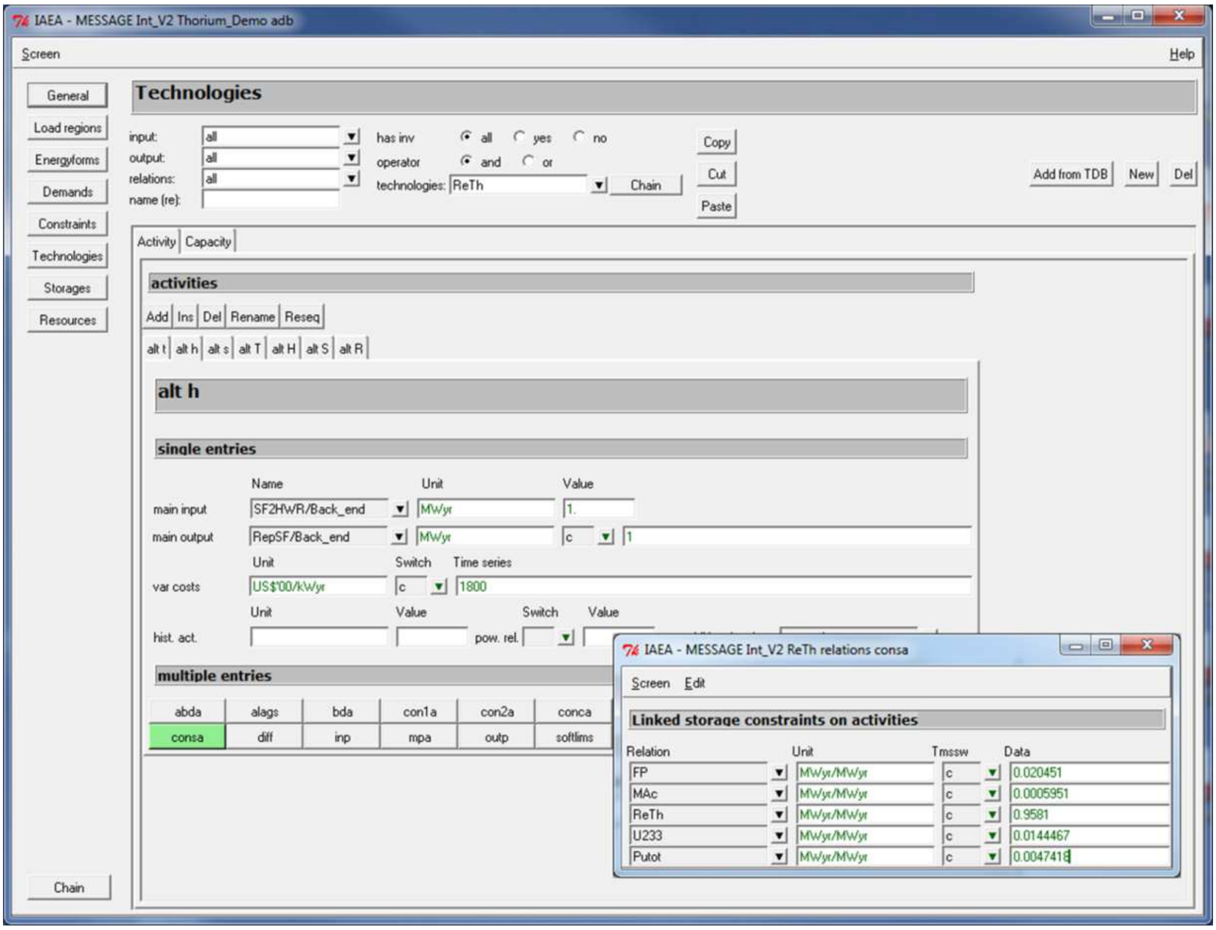


FIG. 200. Reprocessing of HWR2 SNF fuel.

Figure 200 shows an alternative option for reprocessing of spent fuel from HWR2. One unit of spent fuel is divided into 0.9581 of thorium, 0.004 741 8 of plutonium, 0.000 595 1 of MA, 0.014 446 7 of ^{233}U, and 0.020 451 of FP.

Thorium fuel cycle based on thermal and fast reactors with spent fuel reprocessing and Pu/^{233}U recycling

The model of the thorium fuel cycle based on thermal and fast reactors includes thermal reactors and fast reactors (FR0Th) with thorium in radial blankets and with multi-recycling of plutonium and ^{233}U in thermal reactors and only plutonium multi-recycling in fast reactors. Radial FR blankets are loaded with depleted U, which is obtained from the enrichment process.

Figure 201 shows modelling of the fast reactors (FR0Th) with thorium in radial blankets and MOX fuel for the core. FR0Th requires annual consumption of 8.3 t HM of MOX fuel and 22 t HM of Th for the blanket to produce 748 MW(e)/year of electricity. The relative fractions of fresh fuels consumed by the reactor per unit of electricity output are 0.011 (=8.3/748) for MOX fuel and 0.03 (=22/748) for blanket fuel.

Figure 202 shows an alternative option for reprocessing of spent fuel from thorium blankets. One unit of spent fuel is divided into 0.9895 of thorium and 0.0105 of ^{233}U.

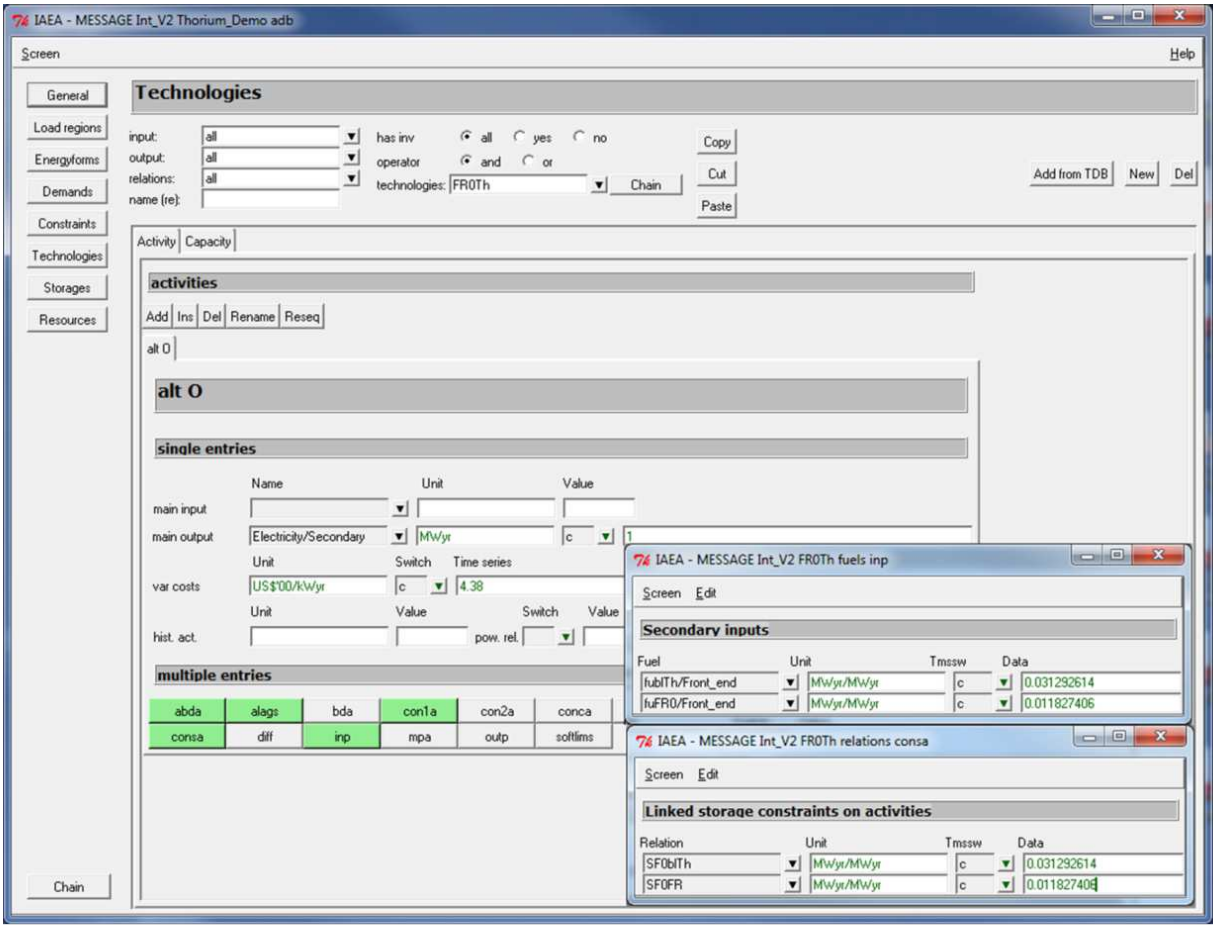


FIG. 201. FR0Th activity page.

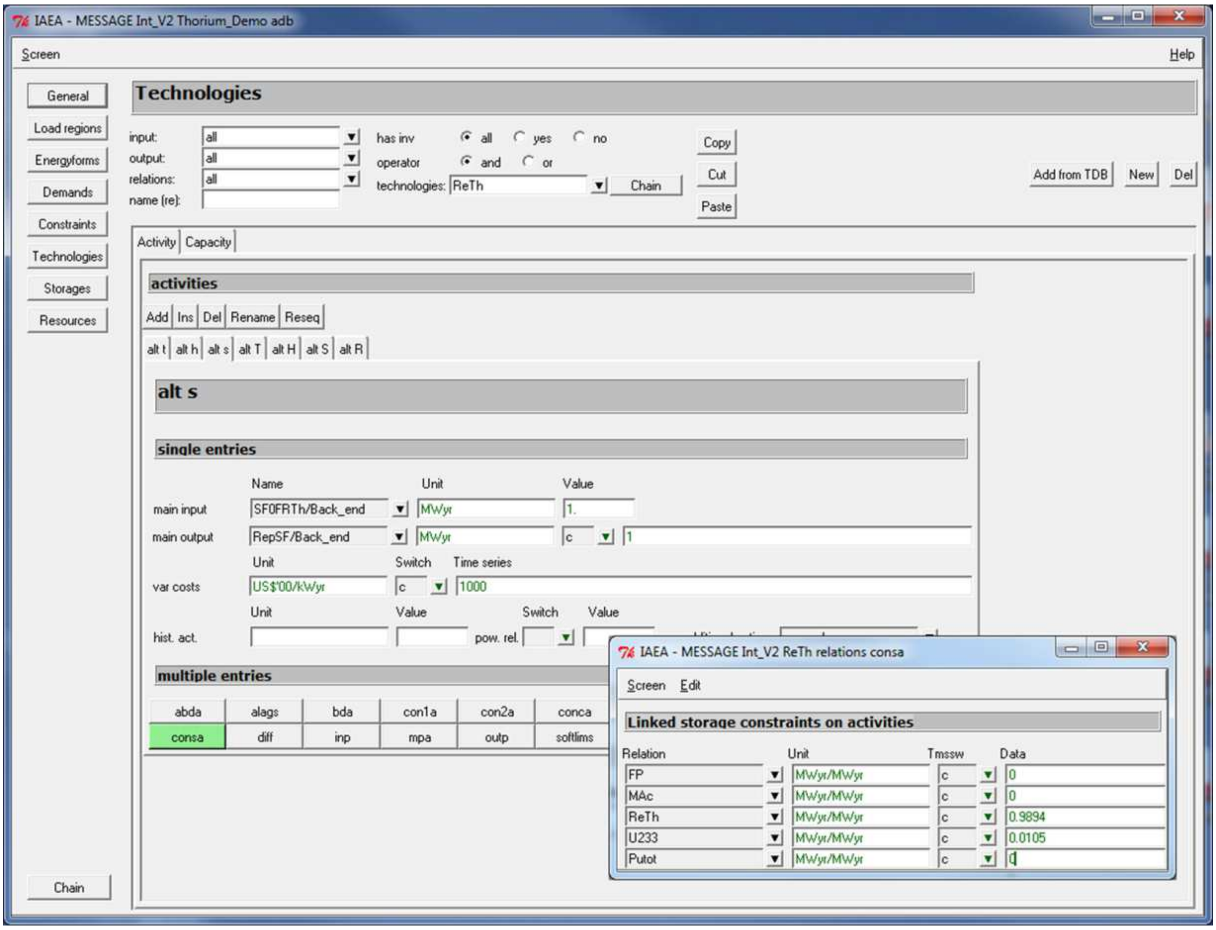


FIG. 202. Reprocessing of FR0Th blanket SNF.

3.2.5. Main results and findings of the case study

Once-through thorium fuel cycle based on thermal reactors without spent fuel reprocessing

Figures 203 and 204 show thorium introduction in the ‘G3’ GAINS group of countries (countries without FRs in the 21st century) in the case of the high demand scenario. The two options were compared (BAU and LWR0). The thorium based reactor under consideration was LWR0, using enriched UOX, and thorium fuel. Both options were based on a once-through fuel cycle without reprocessing of spent fuel.

The maximum introduction of the Th option was considered, assuming the share of the HWR is kept at 6% of the total nuclear power. By 2100, the share of thorium based NPPs will be ~94% of total nuclear generation.

By 2100, the findings for the case of once-through thorium fuel cycle in thermal reactors without using spent fuel reprocessing facilities are:

- — Thorium based NPPs dominate electricity generation and meet 90% of electricity demand.
- — Introduction of LWR0 reduces annual plutonium and MA discharges by a factor of ~1.9 in comparison to the BAU scenario.

— Spent nuclear fuel accumulates up to ~826 kt in the BAU scenario and up to ~1142 kt in the LWR0 scenario.

— The LWR0 introduction increases cumulative natural uranium consumption by ~40% compared to the BAU scenario.

— The introduction of the LWR0 scenario also increases the enrichment requirements by a factor of ~1.9 compared to the BAU scenario.

— Thorium fuel cycle fuel fabrication requirements are ~76% of the total fuel fabrication requirements.

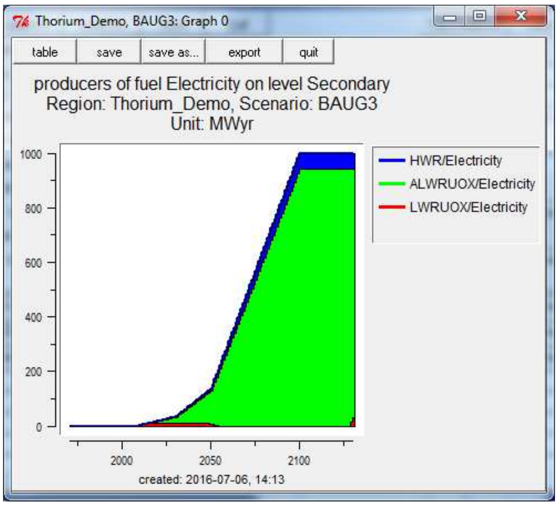


FIG. 203. Nuclear power structure, BAU, NG3.

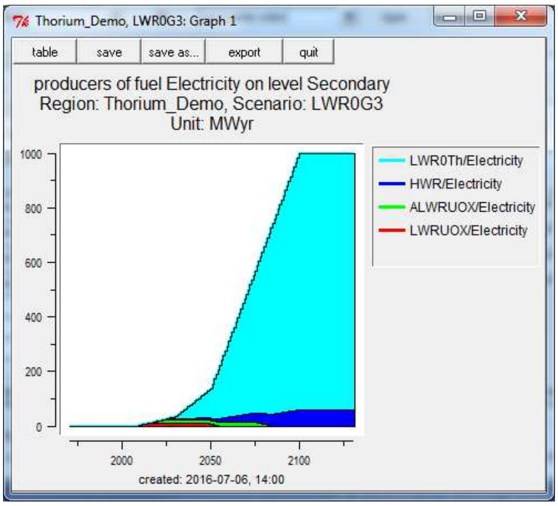


FIG. 204. Nuclear power structure, LWR0, NG3.

Closed thorium fuel cycle based on thermal reactors with spent fuel reprocessing and Pu/^{233}U recycling

Comparison of options: BAU and LWR12&HWR12

Figures 205 and 206 give the results for thorium introduction in the BAU case, i.e., when only LWRs and HWRs are available. The BAU option serves as the reference fuel cycle. The Th option 'LWR12&HWR12' is based on LWR1 using Pu–Th fuel, LWR2 using Pu–^{233}U–DepU fuel, HWR1 using Pu–Th fuel and HWR2 using Pu–^{233}U–Th fuel. In this case, the transition to thorium could be done through the incineration of civilian grade plutonium and achieving a reduction in existing SNF stockpiles. NES structure was based on material balance consideration without economic optimization.

Figure 205 shows the power demand trend for each reactor type for the BAU option. The advanced light water reactor (ALWR) was introduced in 2015 and replaces the LWR. HWR keeps its power share around 6% of total nuclear power. By 2100, the share of thorium based NPPs reaches only ~23% of the total nuclear generation.

The projections for the LWR12&HWR12 scenario show that by the year 2100:

— Thorium based NPPs will account for ~23% of electricity demand.

— The cumulative consumption of natural uranium is reduced by ~20% compared with the BAU scenario.

— The load on enrichment facilities is reduced by ~24% compared with the BAU scenario.

— Reprocessed Pu does not accumulate and is discharged and consumed at the rate of ~1.5 kt/year.

— The rate of discharge/consumption of ^{233}U is ~0.45 kt/year.

— Accumulation of SNF is reduced from ~5800 kt to ~520 kt.

— The thorium fuel cycle (FC) fabrication accounts for ~36% of total fuel fabrication requirements.

— Reprocessing requirements for the thorium fuel cycle are ~34% of the total reprocessing requirements.

— There is an increase in annual MA discharge from ~0.12 to ~0.15 kt/year.

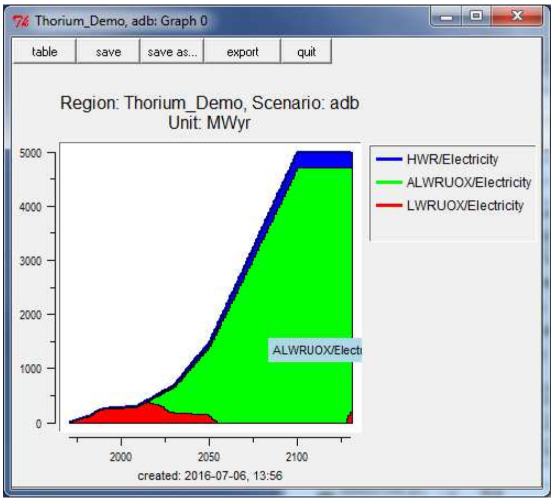


FIG. 205. Nuclear power demand structure, BAU.

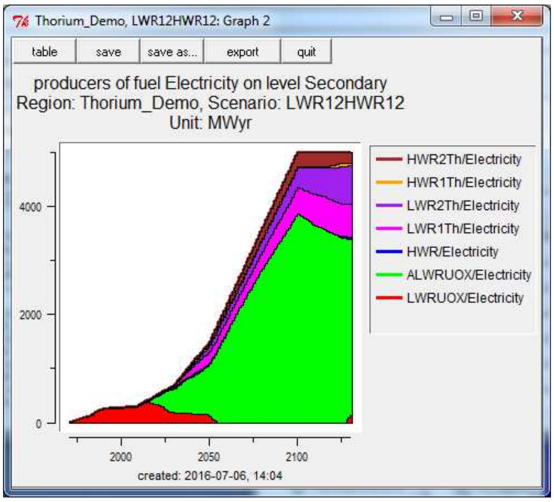


FIG. 206. Nuclear power demand structure, LWR12/HWR1.2.

Thorium fuel cycle based on thermal and fast reactors with spent fuel reprocessing and Pu/^{233}U recycling

Comparison of options: BAU, FR and FRTh&LWR12&HWR12

Figures 207 and 208 represent thorium introduction in the case of implementing FRs in the high demand scenario. The three options were compared: BAU, FR and FRTh&LWR12&HWR12. The Th option FRTh&LWR12&HWR12 was based on FR with a Th blanket and the thermal reactors LWR1, LWR2, HWR1 and HWR2. The transition to a closed fuel cycle involves incineration of civilian grade plutonium in fast and thermal thorium reactors.

Figure 205 shows the power demand trend of each reactor type for the BAU option. HWRs keep around a 6% share of the total nuclear power produced by thermal reactors. The share of thorium based NPPs is ~27% of the total nuclear generation by 2100. In turn, this share is divided approximately 50:50 between fast and thermal reactors.

Figure 207 shows the power demand structure for FR options. The FR share is ~47% by 2100. According to the GAINS reprocessing conditions, HWR spent fuel is not reprocessed for the case involving FRs.

By the year 2100:

— There is no accumulation of reprocessed plutonium; reduction by factor of ~1.5 is observed in annual Pu discharge/consumption compared to FR introduction.

— Annual rate of discharge/consumption of ^{233}U is ~0.4 kt/year.

— Accumulation of SNF is further reduced for FR_Th compared to FR introduction.

— There is a significant reduction in cumulative natural uranium consumption, which drops to ~40 million tons for the global BAU scenario and to ~27 million tons for the FR and FR_Th introduction scenarios.

– Significant decrease by a factor of ~2 is also observed in requirements for enrichment of the FR and FR_Th introduction compared to the BAU scenario.

– MA discharge remains approximately similar in all considered scenarios.

– The fuel fabrication load for thorium FC is ~40% of total fuel fabrication requirements.

– Approximately 39% of total reprocessing requirement is attributed to the reprocessing of thorium FC.

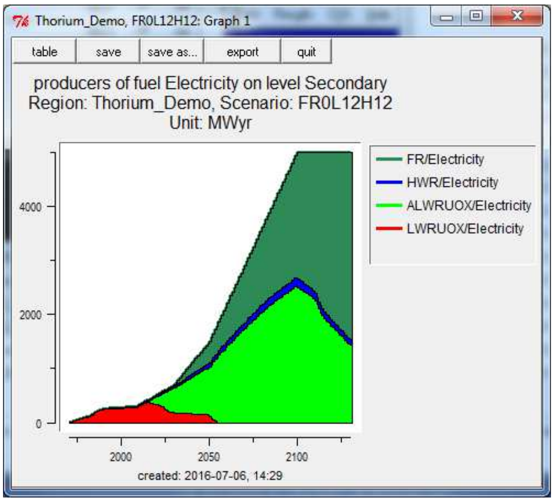


FIG. 207. Nuclear power demand structure, SFR.

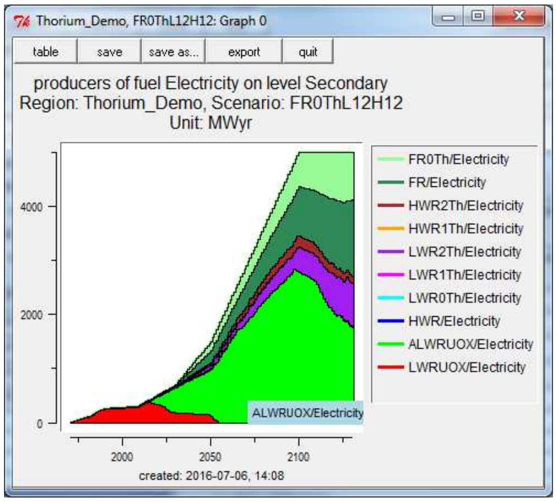


FIG. 208. Nuclear power demand structure, FRTh/LWR12/HWR12.

Remarks on NES structure based on material balance considerations and economical optimization

For the purpose of the thorium project considered above, the NES structure was based only on plutonium and ^{233}U availability without economic optimization. Material flow analysis was performed for the maximum possible introduction of thorium based reactors (Figs 205–208). The optimized structure of nuclear generation systems achieved by minimization of the total system cost was obtained on the basis of the input data for resources and for the reactors and the fuel cycle provided in Tables 51(a) and (b) to generate economically reasonable options for comparison. The results of LWR12&HWR12 and FRTh/LWR12/HWR12 options for optimization are shown in Figs 209 and 210.

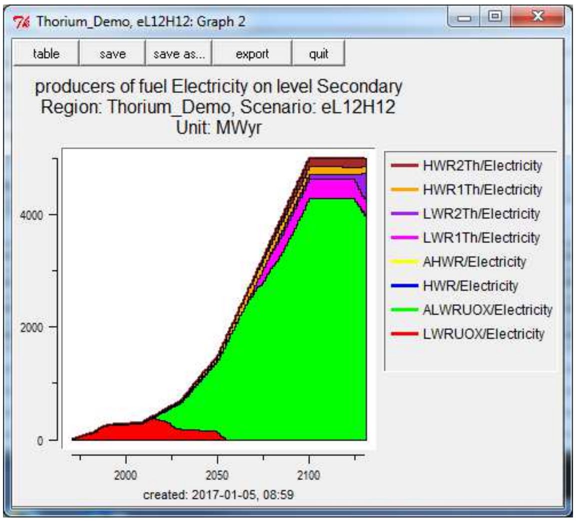


FIG. 209. Nuclear power demand structure, LWR12/HWR12, based on material balance consideration and economic optimization.

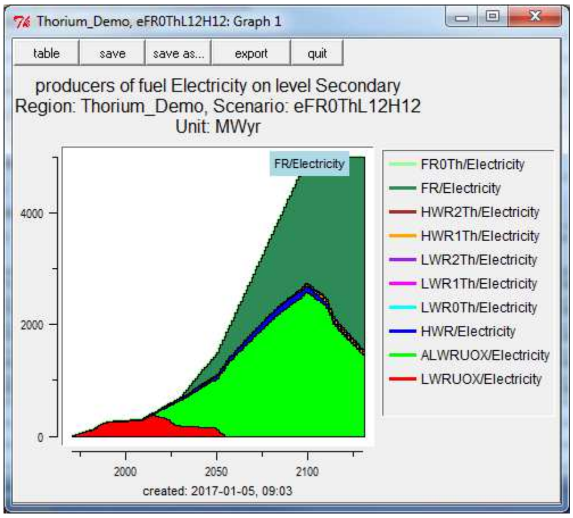


FIG. 210. Nuclear power demand structure, FRTh/LWR12/HWR12, based on material balance consideration and economic optimization.

The economically optimized LWR12/HWR12 option shows that by 2100 the share of NPPs utilizing Th/^{233}U could attain 15% of total nuclear generation in comparison to 23% for the NES structure based on material balance only. Thorium based HWRs are cheaper than LWRs with thorium. The cheapest thorium reactor, HWR1, is to be commissioned in 2025 and becomes competitive with an ALWR when cheap uranium (US $40/kg) is exhausted (2030). LWR1 reactors could be commissioned in 2065 when uranium of grade ‘c’ (US $130/kg) is exhausted (2072).

Nuclear power demand structure, FRTh/LWR12/HWR12, based on the material balance considerations and economic optimization is shown in Fig. 209. Thorium based reactors would not be competitive compared to ALWR’s and fast reactor’s electricity cost, and the thorium option would be completely removed from the LWR and fast reactor market domain.

Conclusions

Following conclusions were drawn from thestudy of thorium introduction in the global and regional models:

(i) Reducing long-lived radioactive waste inventories by diminishing the production of plutonium and minor actinides could be achieved in once through ThFC based on

$^{235}U/Th/^{233}U$ fuel. However, the natural uranium and ^{235}U enrichment requirements are increased;

(ii) A reduction in natural uranium and ^{235}U enrichment requirements as well as the incineration of civilian grade plutonium could be achieved in a closed ThFC based on $Pu/Th/^{233}U$ fuel. However, the production of MA is not decreased and even, in some cases, it is increased;

(iii) There are no advantages in reduction of natural uranium requirements for the various ThFC options in comparison with FR options;

(iv) Fabrication and reprocessing related infrastructure for thorium fuel needs to be developed for commercial utilization of the thorium fuel and fuel cycles.

3.2.6. Feedback on NES modelling with the MESSAGE tool

Material flow calculations were performed with the MESSAGE tool which is the IAEA's model for large scale dynamic system engineering and economic optimization that is used for the development of medium and long term energy scenarios and policy analysis.

The MESSAGE tool is commonly used to formulate and evaluate alternative energy supply strategies for user-defined constraints on, for example, new investment limits, market penetration rates for new technologies, fuel availability and trade. The tool is flexible enough and can also be used for the analysis of NES, including thorium utilization. It allows balancing the two fissile material flows: Pu and ^{233}U.

The nuclear power specific processes such as changes of the isotopic composition of spent fuel during the cooling period in NPP storage and the reprocessing time lag owing to radioactive decay of unstable isotopes can be taken into account.

Comparison of the results of NES modelling with the various tools including MESSAGE was carried out in the framework of the 'Global scenarios' activities of the INPRO project [3] and good convergence of the results was confirmed.

3.3. MINOR ACTINIDE TRANSMUTATION IN INPRO CASE STUDIES ON GLOBAL SCENARIOS

3.3.1. Introduction (general information)

Treatment of long-lived radioactive waste is one of the most pressing issues in the nuclear industry. Many experts seek to ensure its solution through the use and improvement of radioactive waste storage and disposal technologies. However, such solution moves the problem of ultimate waste management to future generations. The MA accumulation is increasing owing to the absence of partitioning and transmutation systems.

A more sustainable solution could be achieved based on innovative technologies utilizing Pu and MA. Implementation of such technologies could help minimizing the amount of radioactive waste destined for final disposal. Advanced technologies could enhance the proliferation resistance of the nuclear fuel cycle, improve the use of natural resources and potentially increase the economic competitiveness of nuclear power plants.

3.3.2. Objectives and task description

This study considered the implementation of MA utilization based on innovative technologies including fast reactors, accelerator driven systems (ADS) and MSR. The objective of this study was to define incentives and milestones for introduction of those technologies into the global NES, as the burners of MA, and identify a possible niche for the technology where it would be competitive and compatible with other prospective nuclear technologies aimed to enhance sustainability of the NES.

In particular, the study determined the potential role of the ADS driven subcritical reactors in MA based modelling of various scenarios for nuclear energy. Another technology of interest is the MSR, specialized in the recycling of MAs (neptunium, curium and americium). Introduction of the MSR into the scenario of global nuclear energy was to determine the potential role of the MSR in the structure of the future of nuclear power scenario and to identify its ability to provide a reduction in MA accumulation by 2100.

3.3.3. Description of the model, input data, NES options, assumptions and metrics (indicators) for scenario analysis

Four NESs with combinations of thermal reactors, fast reactors, ADS and MSR with closed fuel cycles were considered in the study. The global nuclear power demand growth, the data for thermal and fast reactor power plants, ADS and MSR and the major assumptions were based on the analytical framework for assessing transition scenarios to future sustainable NESs developed in the GAINS collaborative project [3].

In the scenario considered, global nuclear power demand growth reaches 1500 GW/year by the middle of the century and 5000 GW/year by 2100. According to the GAINS high nuclear power demand case that is a medium expectation of the IPCC/SRES (International Panel on Climate Change/Special Report on Emissions Scenarios).

The data on the existing and innovative technologies utilizing MAs that have been chosen for scenario simulation are given in the Tables 52–54.

The AFR is an advanced fast reactor with a medium BR (BR ~1.2) and a high burnup (~54 GW·d/t). Design work assumes an advanced cladding material ODS (oxide dispersion strengthened) steel is being developed to achieve high irradiation resistance. The composition data for refuelling are shown in Tables 53 and 54. The fresh fuel contains around 1% MA, because MA recycling in FRs is one of the design conditions for the commercial FR.

TABLE 52. GENERAL CHARACTERISTICS

Parameter	Unit	ALWR	FR	AFR	ADS	MSR
Electric output	MW(e)	1 500	870	1 500	160	1 000
Thermal output	MW	4 410	2 100	3 570	400	2 860
Thermal efficiency	%	34	41.4	42.017	40	
Load factor	%	85	85	85	95	85
Life time	year	60	60	60	60	60
Average fuel residence time of whole core	EFPD	1 760	435.771	2 160	1 800	
Average specific power	MW/t	34.091	86.461 5	24.780	56.69	80

density of whole core						
Average burup of whole core	MW·d/kg	60	37.677	53.526	107.447	1 044.615
Initial core inventory	t HM	129.360	24.288	144.07	6.701	35.250
Equilibrium loading	t HM/year	22.803	17.292	20.693	1.291	0.895

TABLE 53. NUCLIDE GROUP COMPOSITION OF SPENT FUEL

	U tot	Pu tot	MA	FP
ALWR	0.923 5	0.012 466 1	0.001 821 5	0.062 241 8
FR	0.84	0.118 85	0.002 35	0.038 41
AFR	0.857	0.082 781	0.003 892 98	0.056 1
ADS		0.464 9	0.535 1	
MSR				1

TABLE 54. NUCLIDE GROUP COMPOSITION OF FRESH FUEL

	U tot	Pu tot	MA	FP
ALWR				
FR	0.882	0.118 0		
AFR	0.921 8	0.074 3	0.999 6	
ADS	0.001 39	0.443 32	0.445 7	0.109 54
MSR		0.534 217	0.389 09	

The ADS is represented by a conceptual design called EFIT (lead cooled European Facility for Industrial Transmutation), developed within the EURATOM Sixth Framework Programme with the aim of demonstrating the technical feasibility of transmutation in an ADS. The EFIT is an industrial scale transmutation facility; it has a subcritical core of 400 MW thermal power with a k_{eff} (effective neutron multiplication factor) of 0.97. The sub-criticality level is chosen to make certain that the core always remains subcritical under all plant conditions. The fission reactions are driven by an accelerator which delivers a proton beam of 800 MeV and 20 mA (16 MW) into a lead target where spallation reactions occur that release neutrons. The Pu comprises about 46.5% of the fuel, the remainder being MA. Fresh Pu is required for the initial core only, and for subsequent cycles merely fresh MA are added.

The MSR is represented by the High Flux Molten Salt Reactor design having a fast spectrum in the core and a thermal spectrum in the reflector (fast-thermal spectrum). In a molten salt reactor (MSR), the fuel is dissolved in a fluoride salt coolant. This reactor has a homogeneous liquid fuel continuously circulating through the core. This MSR is loaded with Pu and MAs (Np, Am and Cm) from LWR, ALWR and FR spent fuels. The fuel is continuously fed and discharged (reprocessed). Fission products can be removed online and substituted by MAs.

The reactor introduction rates considered for analyzing the different scenario conditions using the GAINS framework were selected as follows:

(a) ADS is introduced after 2075 till 2100 at a consistent rate with the plutonium availability and the balance amount of MA required for ADS operation during the plant's lifetime;

(b) MSR is introduced after 2075 at a consistent rate with Pu availability and the balance amount of MA required for MSR operation during the plant's lifetime.

(c) For MSR, reprocessing of the SNF takes place on the site.

Two MESSAGE output parameters have been selected as the indicators used to analyze fuel cycle options: structure of the nuclear energy demand and the reprocessed minor actinide accumulation.

Fuel cycle options with MA utilization

The fuel cycle options considered in the scenario study are shown in Figs 211–214:

– BAU+FR;

– BAU+AFR;

– BAU+FR break-even and ADS;

– BAU+FR break-even and MSR.

Schemes for the drawn systems include the existing and advanced LWR-type reactors using UOX fuels and the existing HWRs using UOX fuel; they are designated as a BAU+ scenario. The front end includes uranium mining, conversion, enrichment and fresh fuel fabrication. Depleted uranium storage is also considered in the fuel cycle. The back end consists of spent fuel intermediate storage, reprocessing and storage of the reprocessed products.

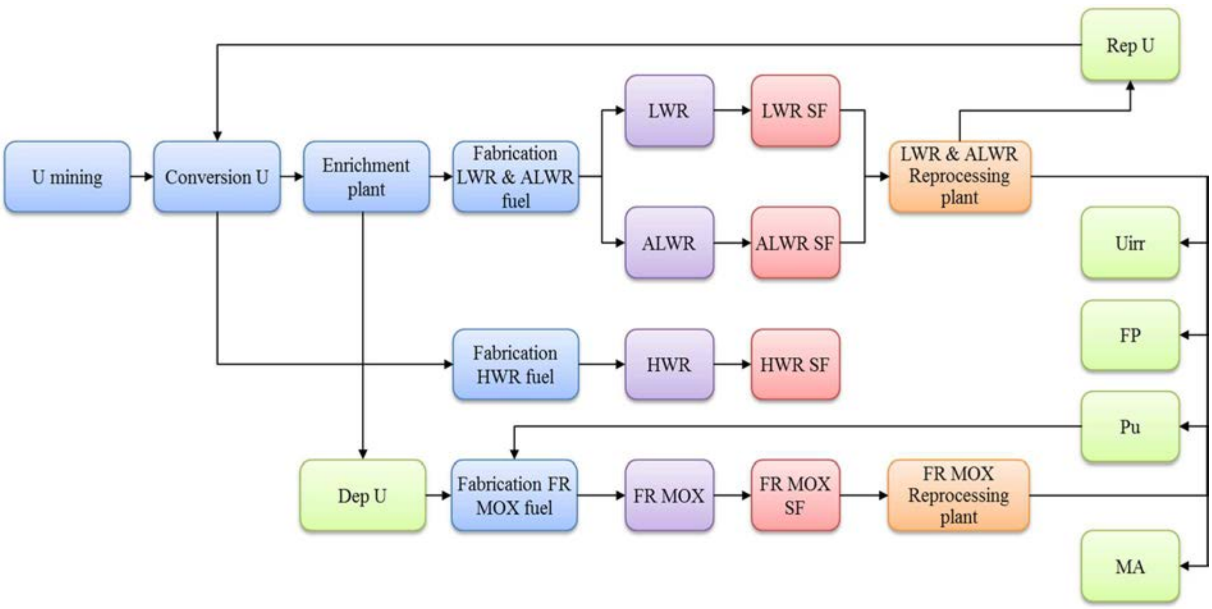


FIG. 211. Fuel cycle system of BAU+FR break-even scenario.

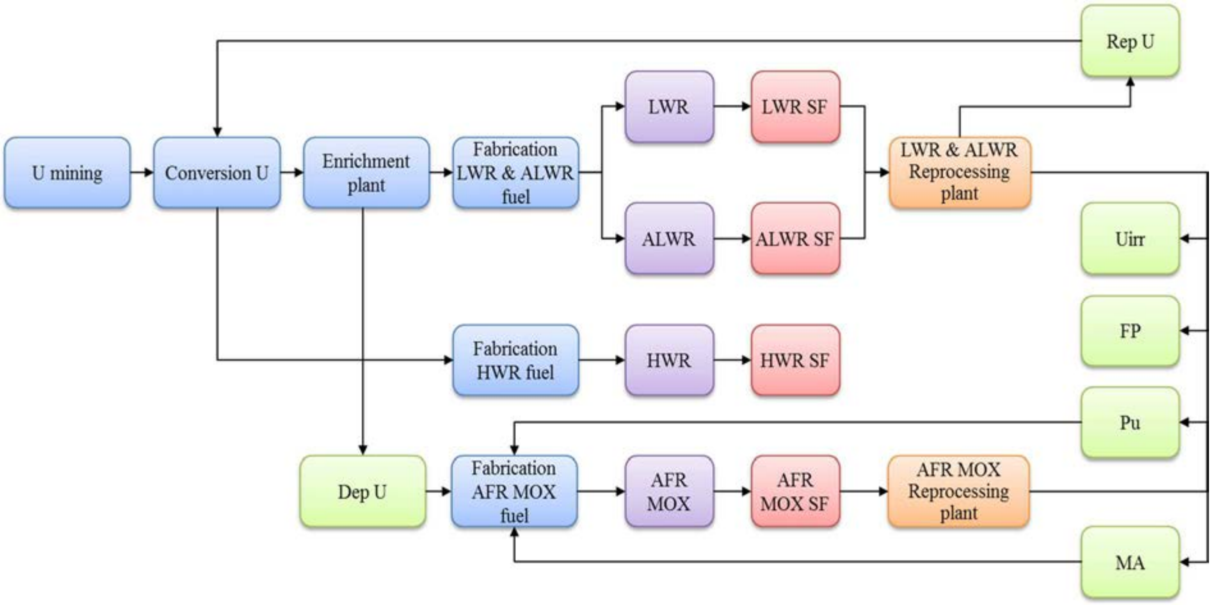


FIG. 212. Fuel cycle system of BAU+AFR scenario.

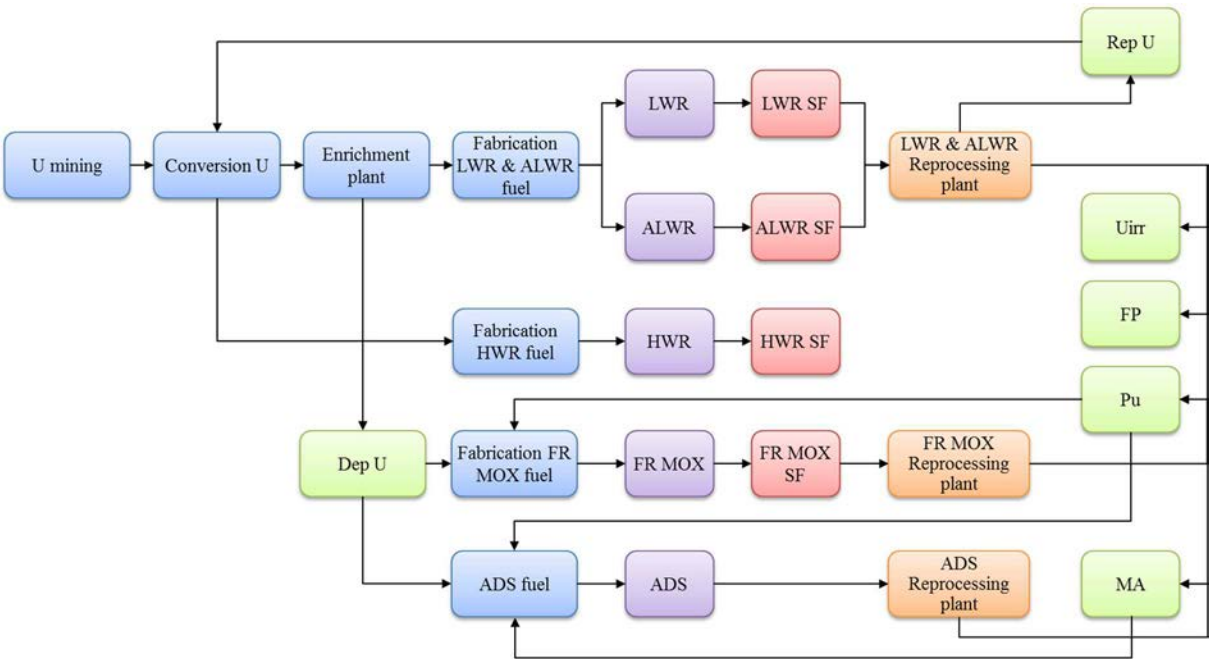


FIG. 213. Fuel cycle system of BAU+FR break-even and ADS scenario.

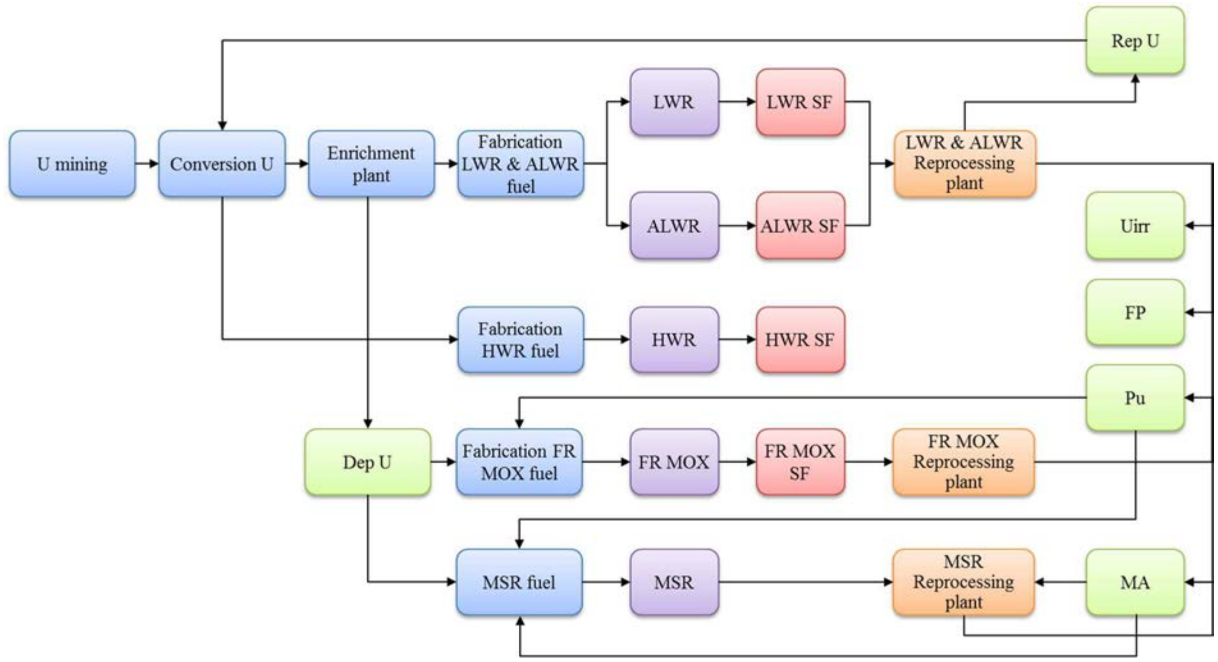


FIG. 214. Fuel cycle system of BAU+FR break-even and MSR scenario.

3.3.4. Modelling of selected NES elements with MESSAGE

This section represents modelling specifics of the technologies for MA utilization, including fuel fabrication, reactors and reprocessing. As mentioned above, the reactor parameters of FRs, AFRs, ADS and MSRs were homogenized to a one region core, as with LWRs or HWRs.

Fuel cycle system of BAU+FR break-even scenario

The mode of fuel cycle system based on the BAU+FR break-even scenario includes thermal and fast reactors with plutonium multi-recycling in a closed nuclear fuel cycle. The FR break-even uses MOX fuel for the core and depleted uranium for the blankets. A one-region model of the reactor assumes average annual consumption for the whole reactor, including the core and the blankets. One unit of fresh fuel for FR technology uses 0.118 of plutonium and 0.882 of depleted uranium (see Fig. 215).

The FR activity and capacity pages are shown in Figs 216 and 217. The model simulates the FR unit which is assumed to have 870 MW(e) of installed capacity with capacity factor of 85%. The FR annually consumes 17.292 t HM of fresh fuel to produce 739.5 MW(e)/year of electricity and discharges 17.292 t HM of spent fuel to temporary storage. The relative fractions of fresh fuel consumed by the reactor to the unit of electricity output should be 0.023 38 (=17.292/739.5) for fresh fuel, including the averaged core and blanket fuel (Fig. 216). The same fraction is discharged to the cooling pool.

The initial core loading and the final core discharge data should be given at the fraction of unit amount of the reactor installed capacity (Fig. 217). The FR installed capacity is 870 MW(e); the initial total loading is 24.2882 t HM. The corresponding relative number in 'corin' is 0.008 04 (=(24.2882-17.292)/870) for fresh fuel. The final core unloading (including fission products) is the same.

Reprocessing technology includes several alternatives for reprocessing of different spent fuel types. Figure 218 shows an alternative for reprocessing spent of fuel from a break-even FR. It takes one unit of spent fuel and puts into storage 0.84 of irradiated uranium, 0.018 851 of plutonium, 0.002 34 of MA and 0.038 41 of FP. The main output has an auxiliary role and puts one unit of SNF to the dummy level.

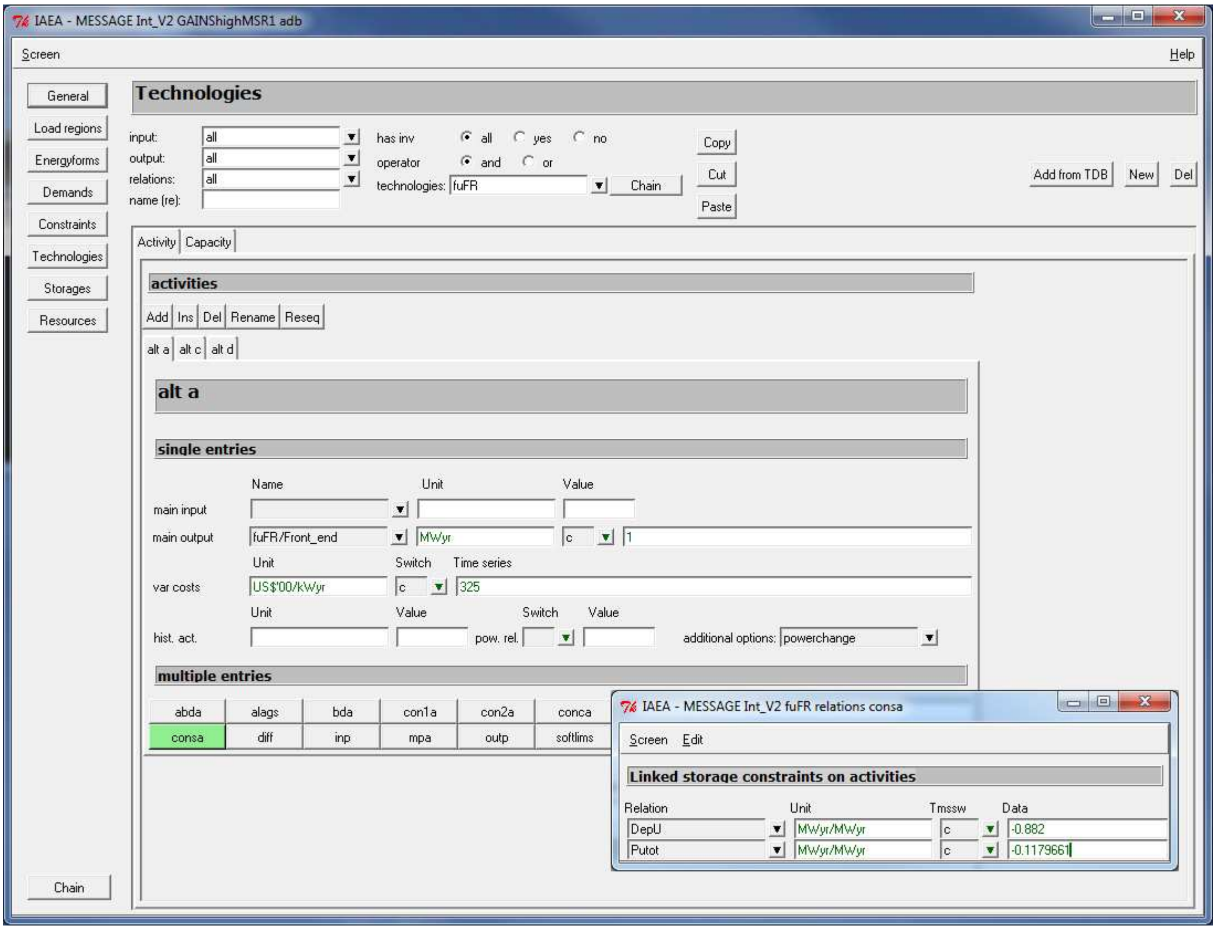


FIG. 215. Modelling of fuel fabrication for reactor technology FR.

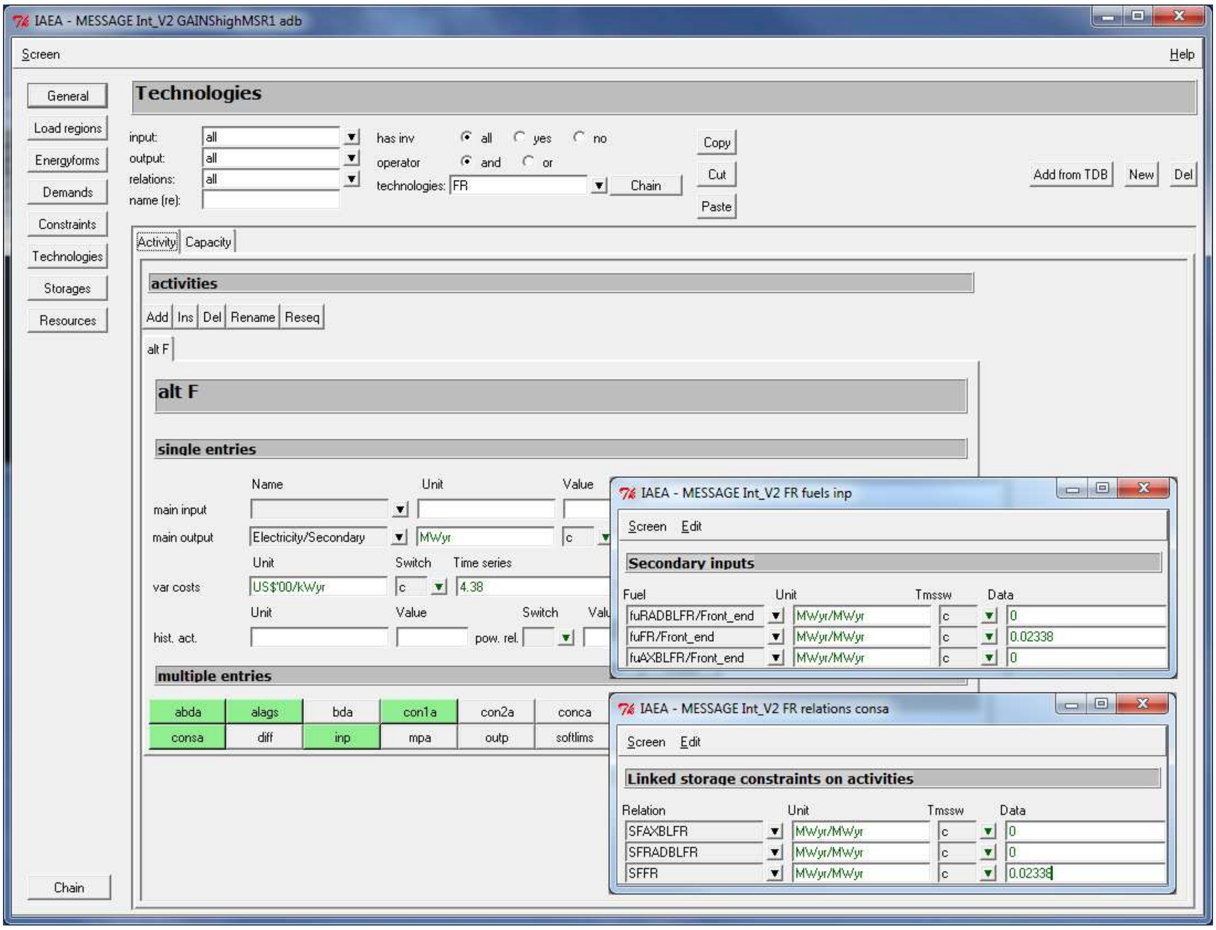


FIG. 216. FR activity page.

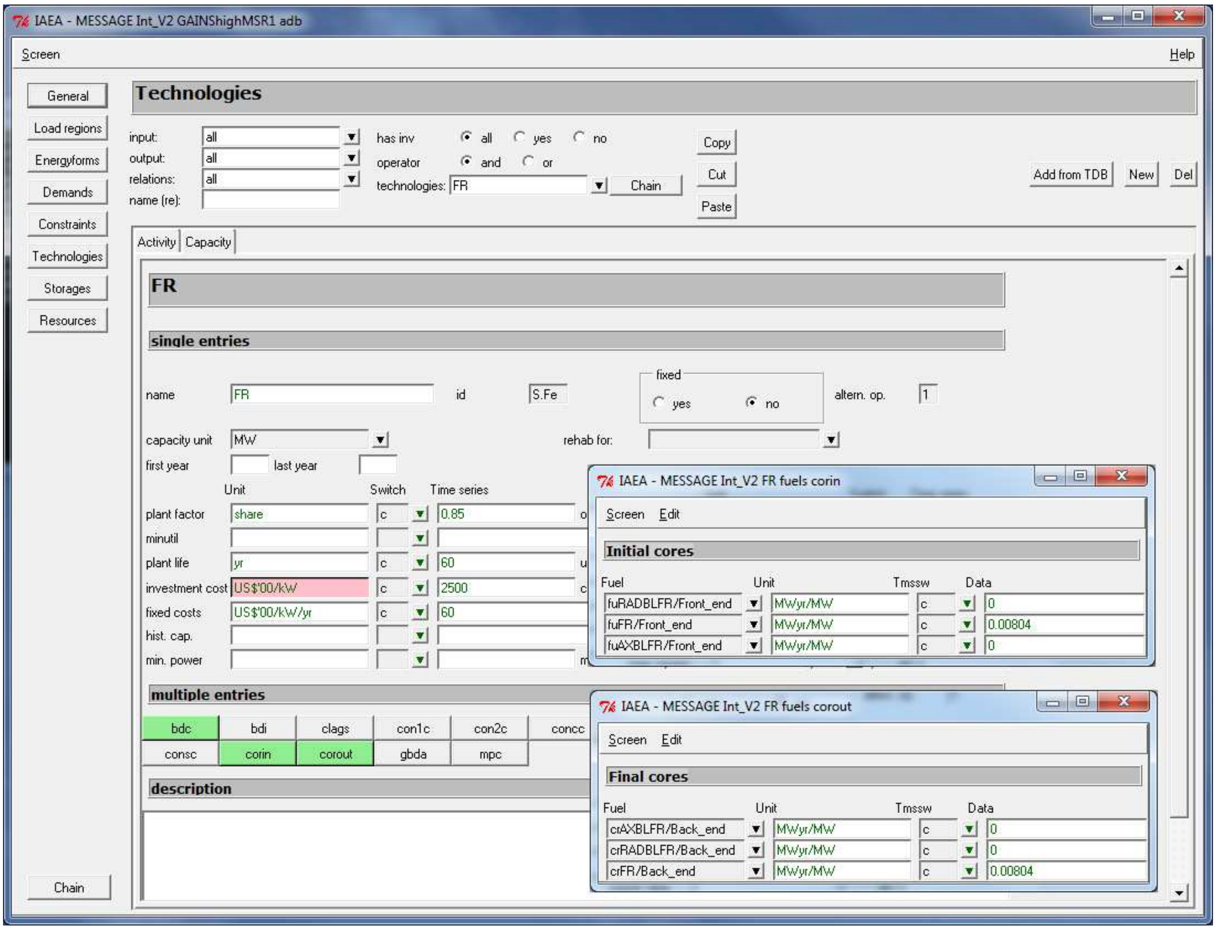


FIG. 217. FR capacity page.

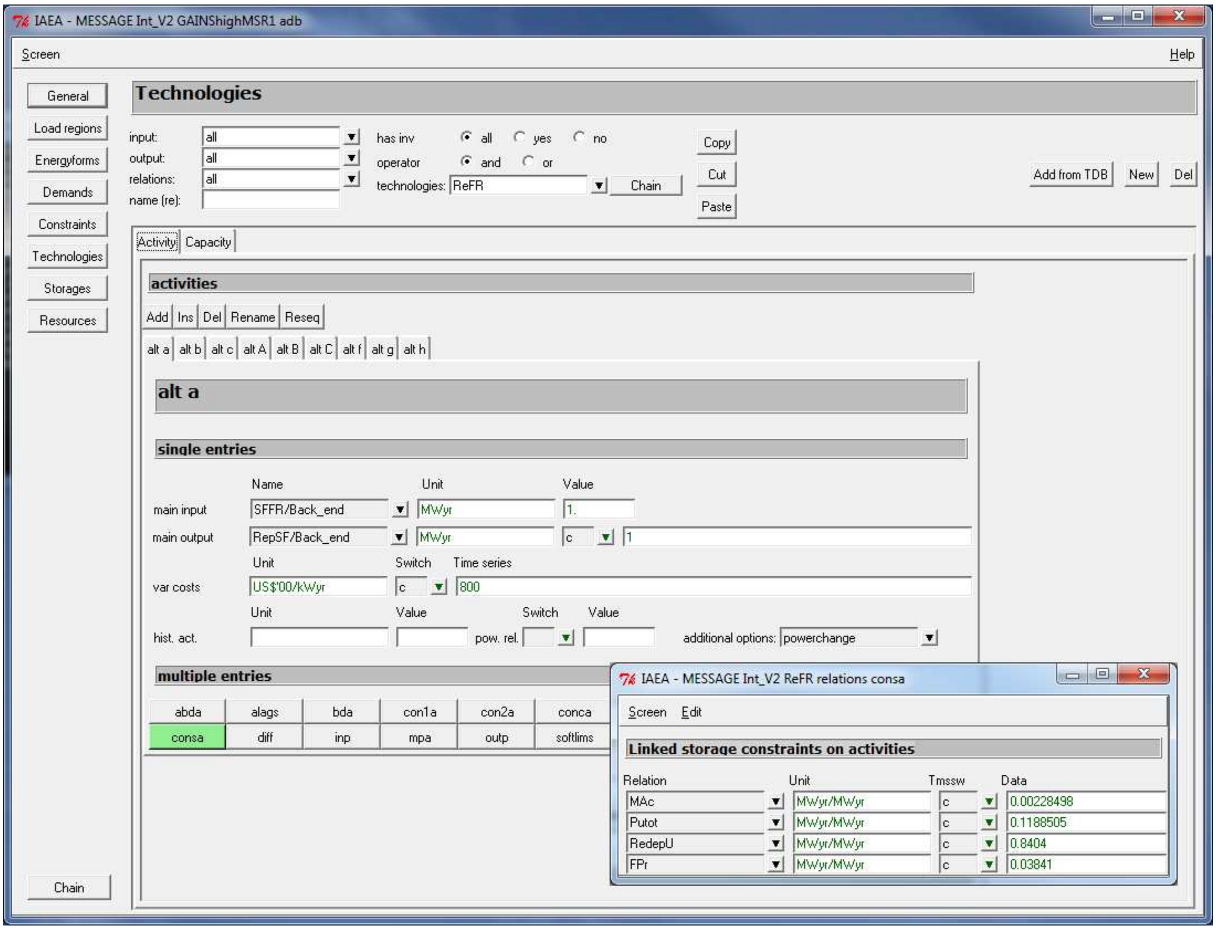


FIG. 218. Reprocessing of FR SNF fuel.

Fuel cycle system of scenario BAU+AFR

The AFR uses MOX fresh fuel which contains around 1% MA for core and depleted uranium for blankets. In the one-region model a unit of fresh fuel for AFR technology uses 0.0743 of plutonium, 0.0035 of MA and 0.9218 of depleted uranium as shown in Fig. 219.

The AFR activity and capacity pages are given in Fig. 220 and 221. The model simulates the AFR unit which is assumed to have 1500 MW(e) of installed capacity with a capacity factor of 85%. The AFR annually consumes 20.693 t HM of fresh fuel to produce 1275 MW(e)/year of electricity and discharges 20.693 t HM of spent fuel to temporary storage. The relative fractions of fresh fuel consumed by the reactor per unit of electricity output should be 0.0162 (=20.693/1275) for fresh fuel, including the averaged core and blanket fuels (Fig. 220). The same fraction is discharged to the cooling pool.

The initial core loading and the final core discharge data should be given to the fraction of unit amount of the reactor installed capacity (Fig. 221). The AFR installed capacity is 1500 MW(e); the initial total loading is 144.065 t HM. The corresponding relative number in ‘corin’ is 0.082 25 (=(144.065-20.693)/1500) for fresh fuel. The final core unloading (including fission products) is the same.

Figure 222 shows an alternative option for reprocessing spent fuel from the AFR. It takes one unit of spent fuel and puts to storage 0.857 of irradiated uranium, 0.082 78 of plutonium, 0.003 74 of MA and 0.0561 of FP. The main output has an auxiliary role and puts one unit of SNF to the dummy level.

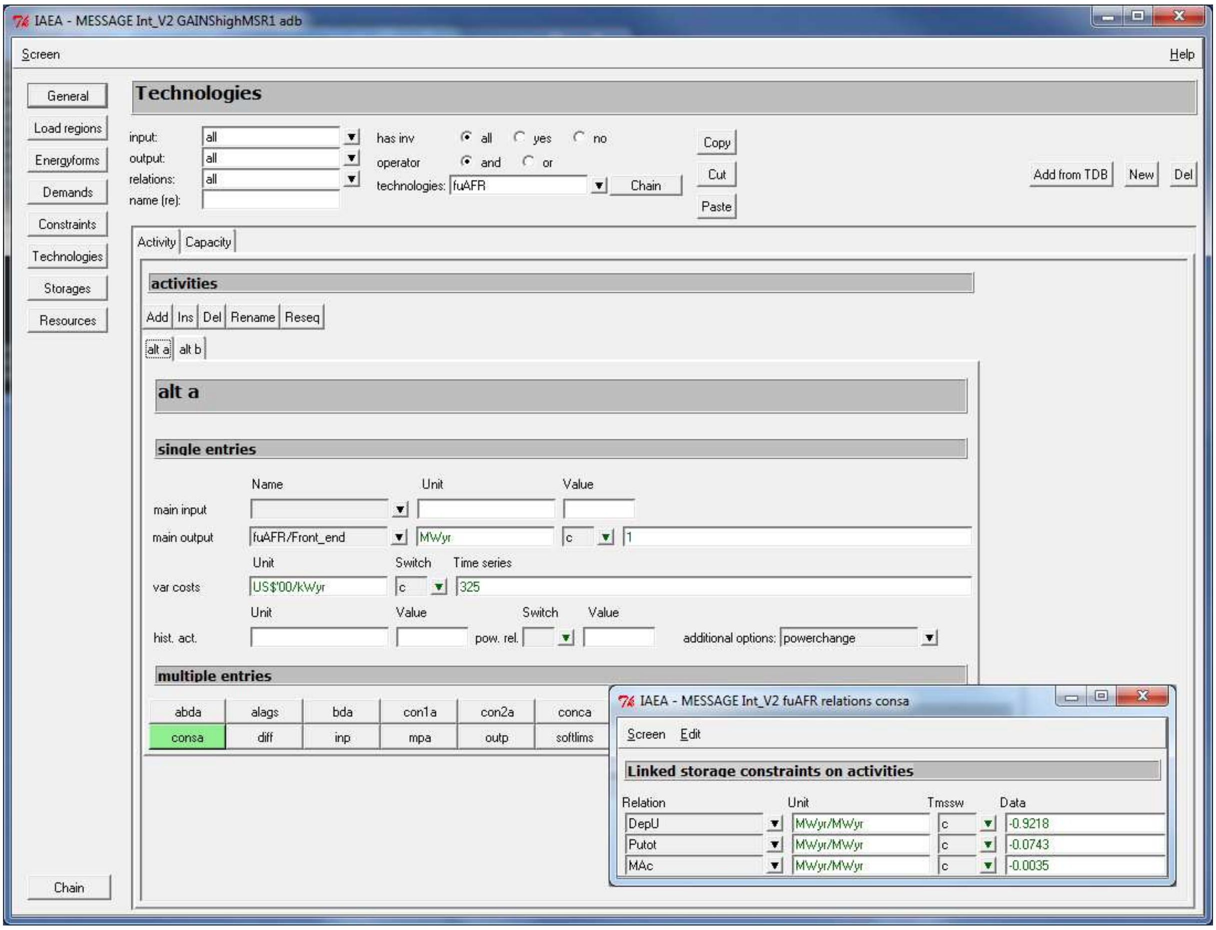


FIG. 219. Modelling of fuel fabrication for reactor technology AFR.

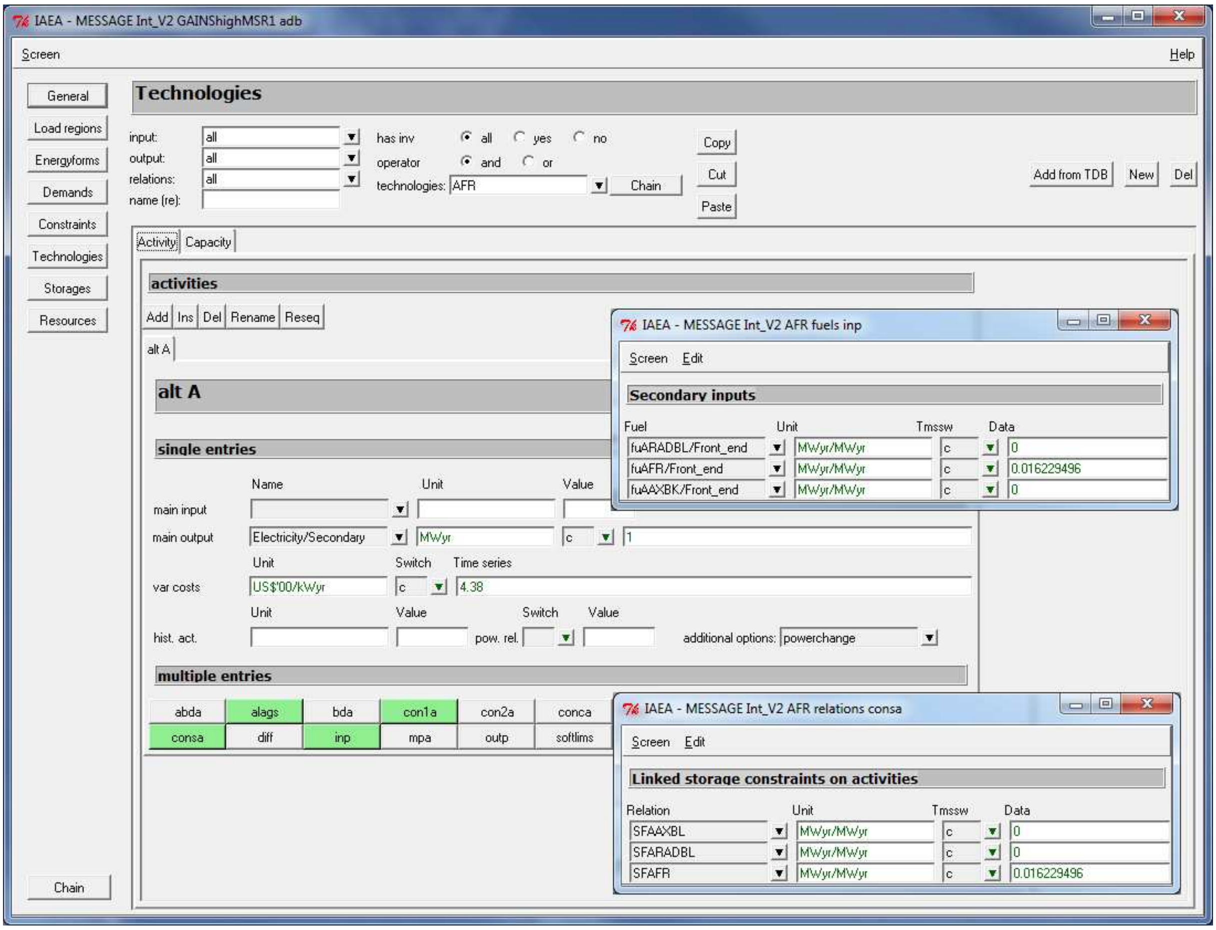


FIG. 220. AFR activity page.

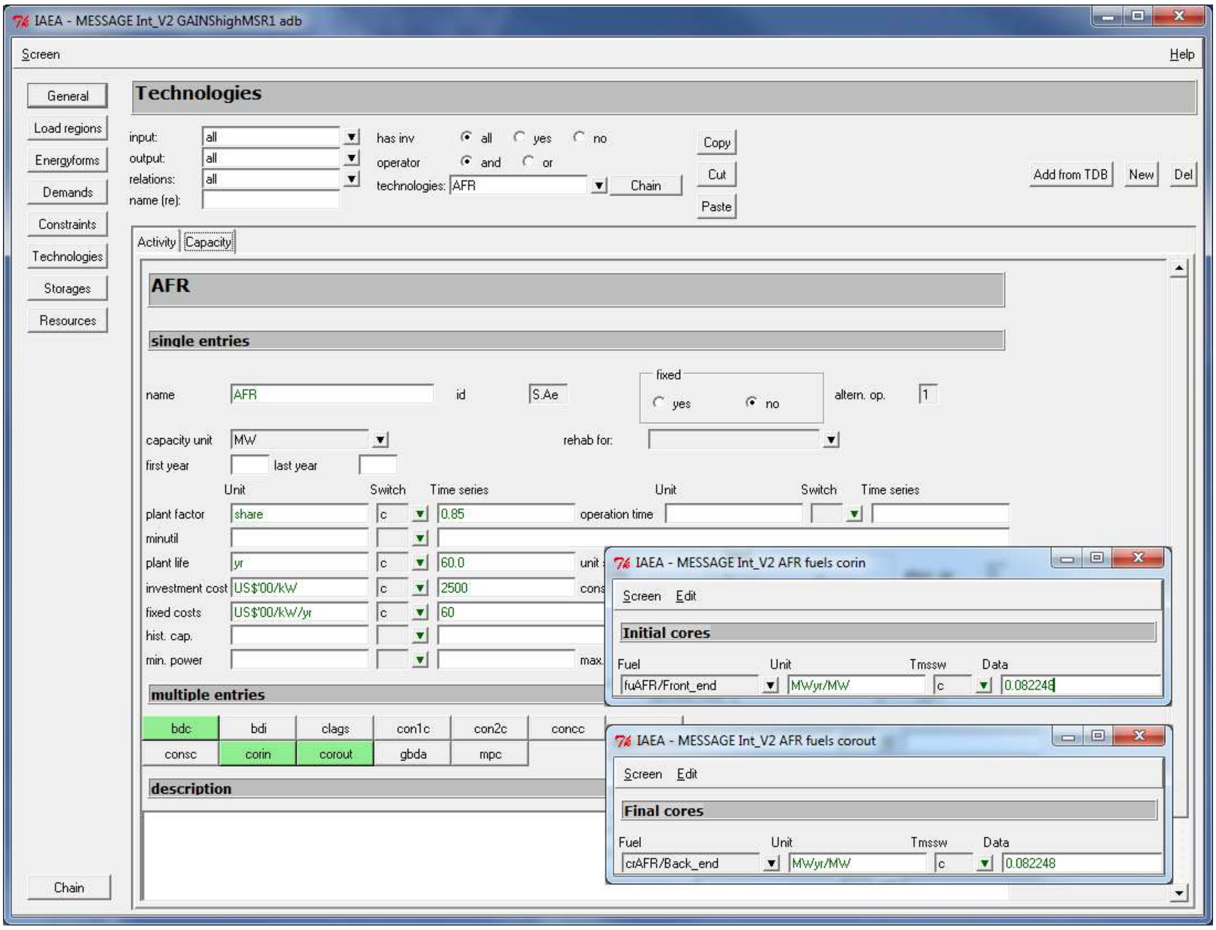


FIG. 221. AFR capacity page.

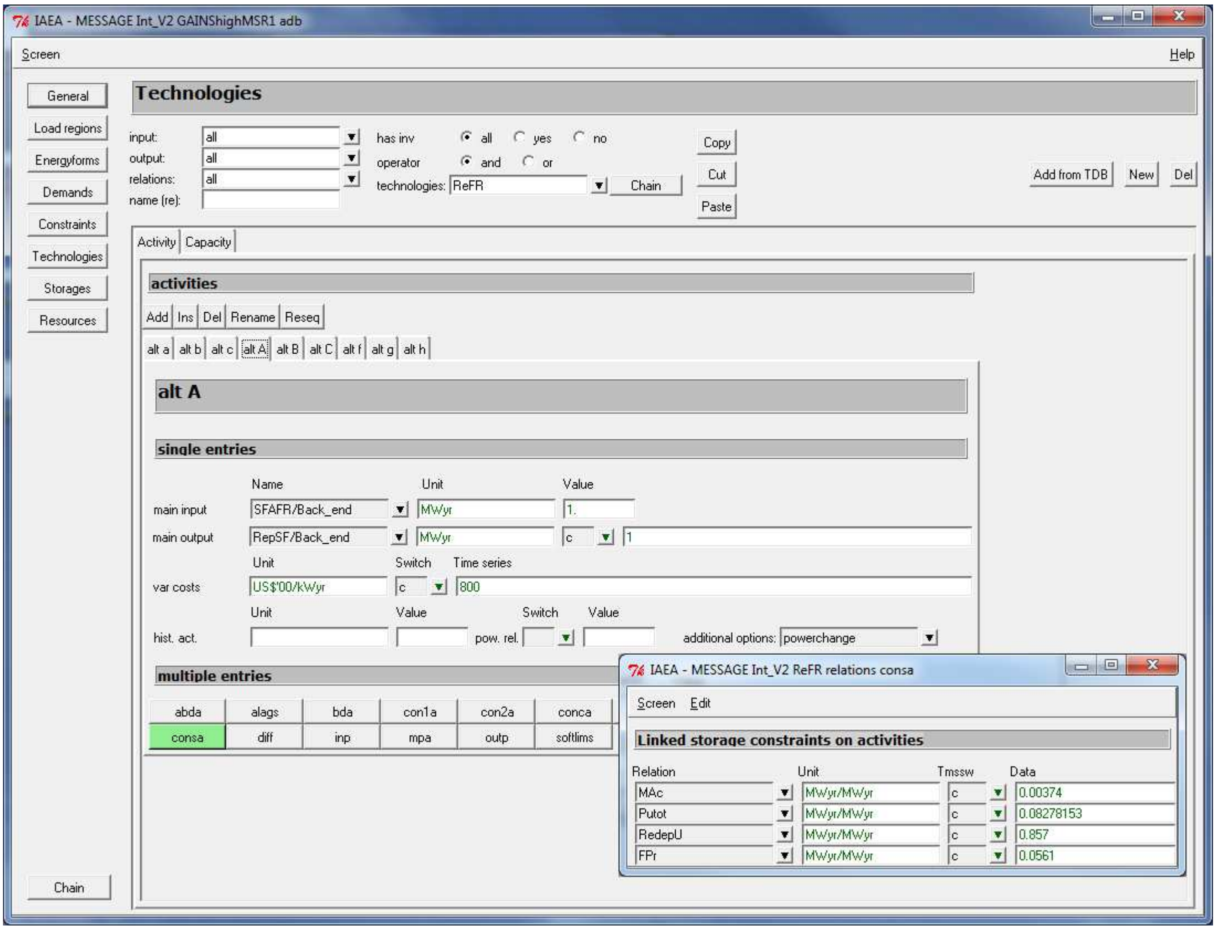


FIG. 222. Reprocessing of AFR SNF fuel.

Fuel cycle system of the BAU+FR break-even and ADS scenario

The model of fuel cycle system based on the BAU+FR break-even and ADS scenario includes thermal, break-even fast reactors and ADS with plutonium and MA multi-recycling in a closed fuel cycle. A one-region model was applied for all reactors.

Formally, the ADS is modelled in the same way as the AFR. Figure 223 shows modelling of fuel fabrication for the ADS. The fuel consists of 0. 4649 of plutonium and 0.5351 of MA.

The ADS activity and capacity pages are given in Figs 224 and 225. The model simulates the AFR unit which is assumed to have 160 MW(e) of installed capacity with a capacity factor of 95%. The AFR annually consumes 1.291 t HM of fresh fuel to produce 152 MW(e)/year of electricity and discharges 1.291 t HM of spent fuel to temporary storage. The relative fractions of fresh fuel consumed by reactor per unit of electricity output should be 0.008 492 59 (=1.291/152) for fresh fuel, including the averaged core and blanket fuels (Fig. 224). The same fraction is discharged from the technology.

The initial core loading and final core discharge data should be given to the fraction of unit amount of the reactor installed capacity (Fig. 225). The AFR installed capacity is 160 MW(e); the initial total loading is 6.701 t HM. The corresponding relative number in 'corin' is 0.033 813 (=(6.701-1.291)/160) for fresh fuel. The final core unloading (including fission products) is the same.

Figure 226 shows an alternative option for reprocessing spent fuel from the ADS. It takes one unit of spent fuel and puts to storage 0.4425 of plutonium, 0.4454 of MA and 0.109 54 of FP.

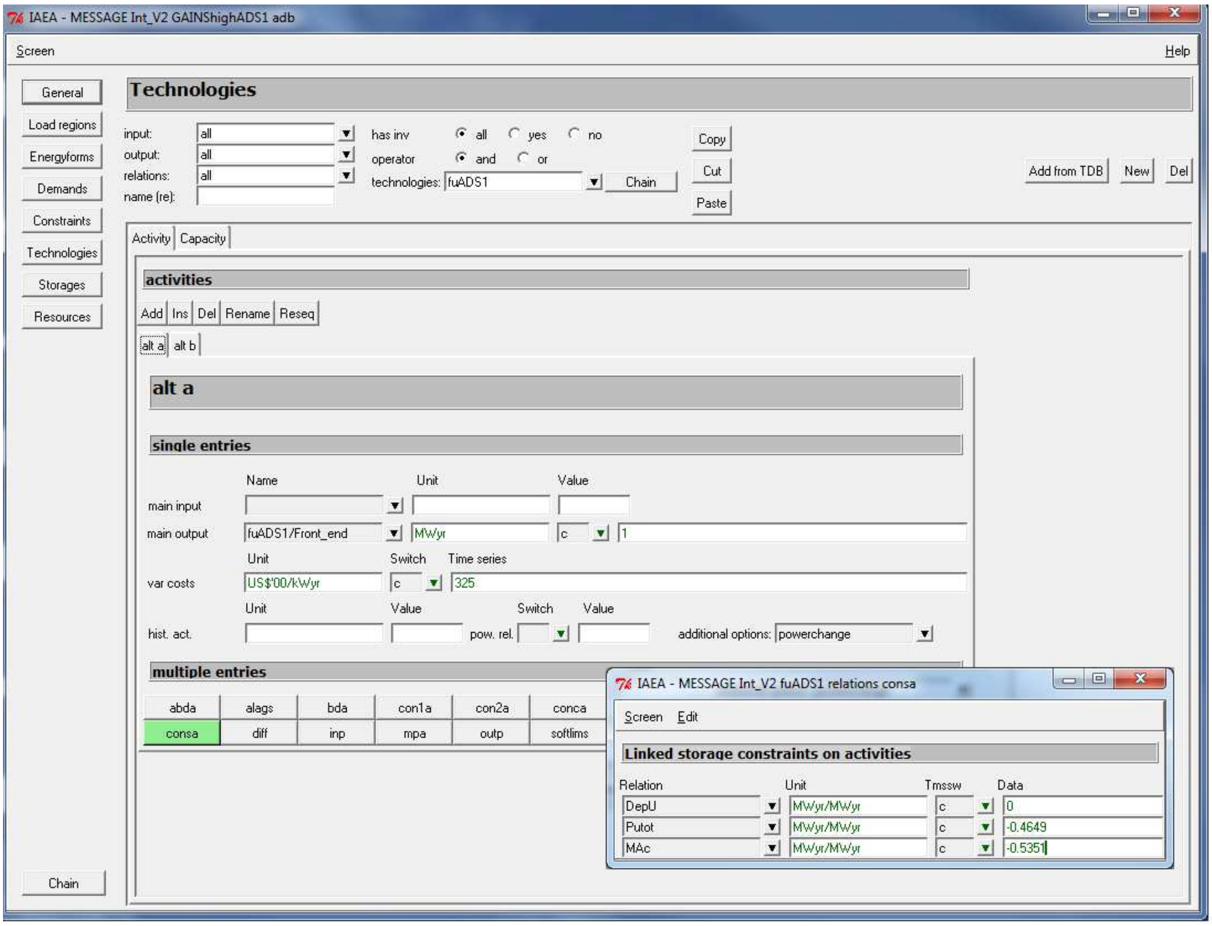


FIG. 223. Modelling of fuel fabrication for ADS.

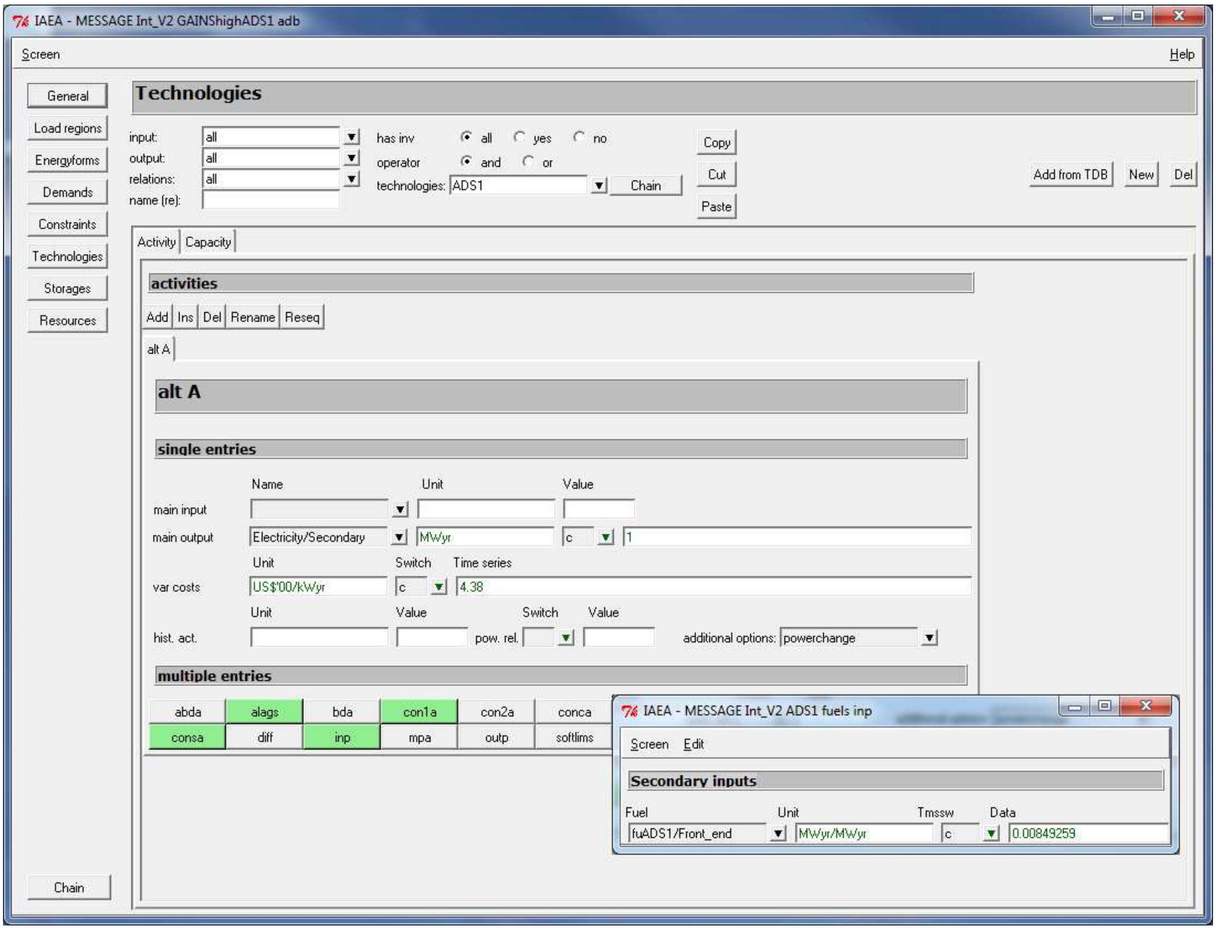


FIG. 224. ADS activity page.

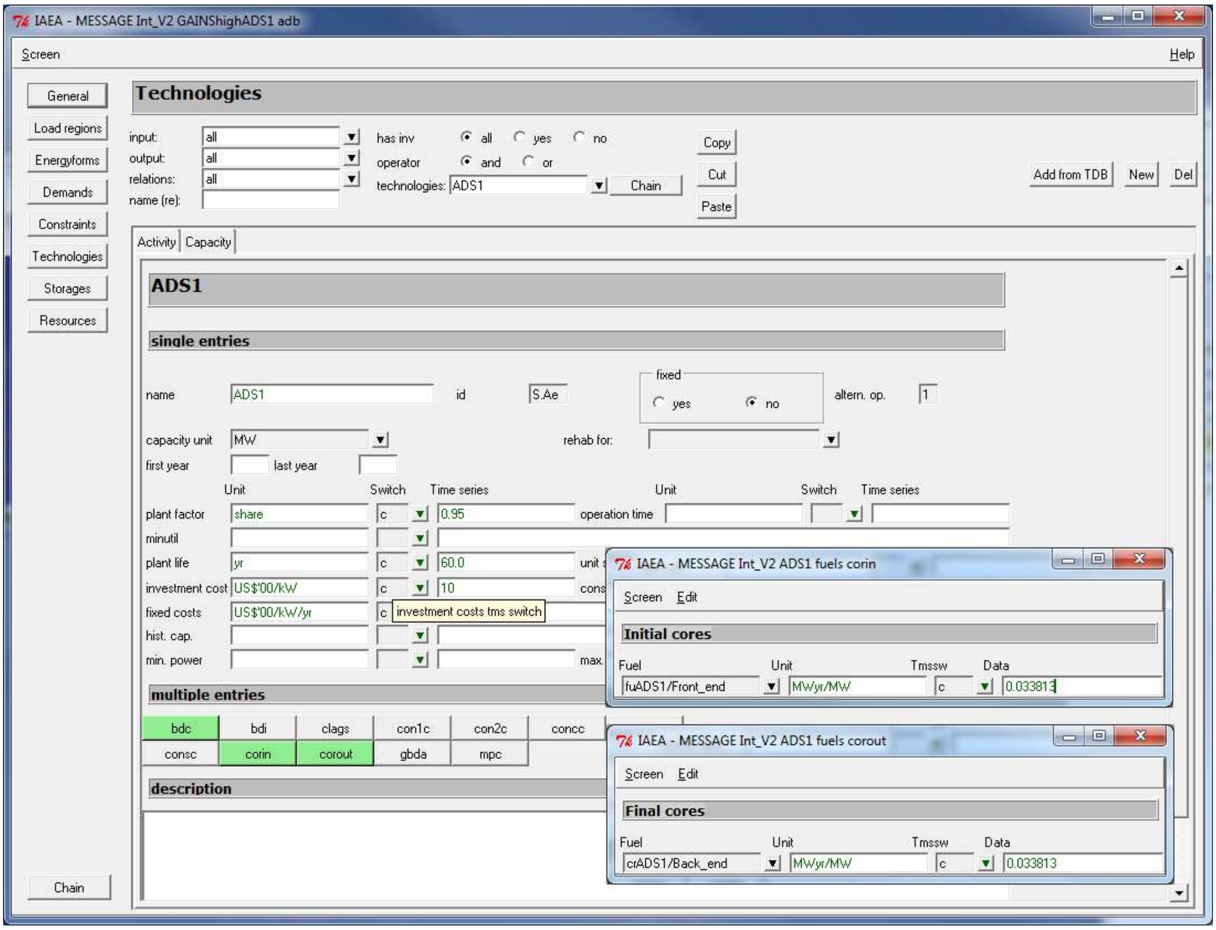


FIG. 225. ADS capacity page.

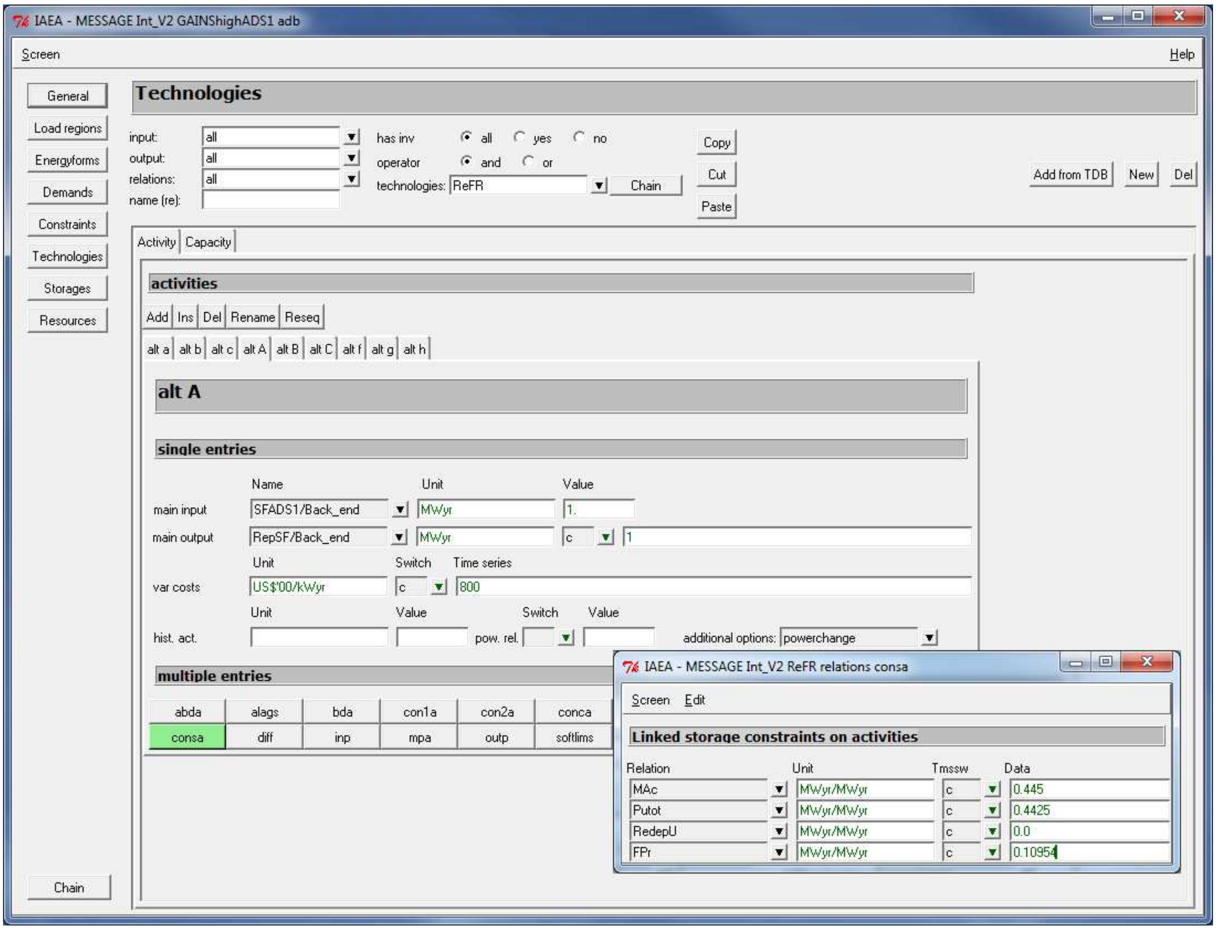


FIG. 226. Reprocessing of ADS SNF fuel.

Fuel cycle system of the BAU+FR break-even and MSR scenario

The model simulates the MSR unit which is assumed to have 1000 MW(e) of installed capacity with a capacity factor of 95% and produce 950 MW(e)/year of electricity. The MSR uses 35.250 t HM of fresh fuel for the first loading and discharges 35.250 t HM of spent fuel to temporary spent fuel storage. The corresponding relative number in 'corin' is 0.035 25 (=(35.250)/1000) for fresh fuel, as shown in Fig. 227.

Fresh fuel fabrication for the initial loading is shown in Fig. 228. The fuel consists of 0.534 21 of plutonium and 0.389 09 of MA. Uranium in the 0.076 68 fraction was not taken into account in this model.

The MSR annually replaces around 0.999 t of FP with the same amount of MA via continued reprocessing. The relative fraction of discharged FP is 0.001 05 (=0.999//720) and this is the same as the fraction for the consumed MA, as shown in Fig. 229. Reprocessing of the MSR fuel assumes that one unit of discharged FP is replaced by one unit of the consumed MA (see Fig. 230).

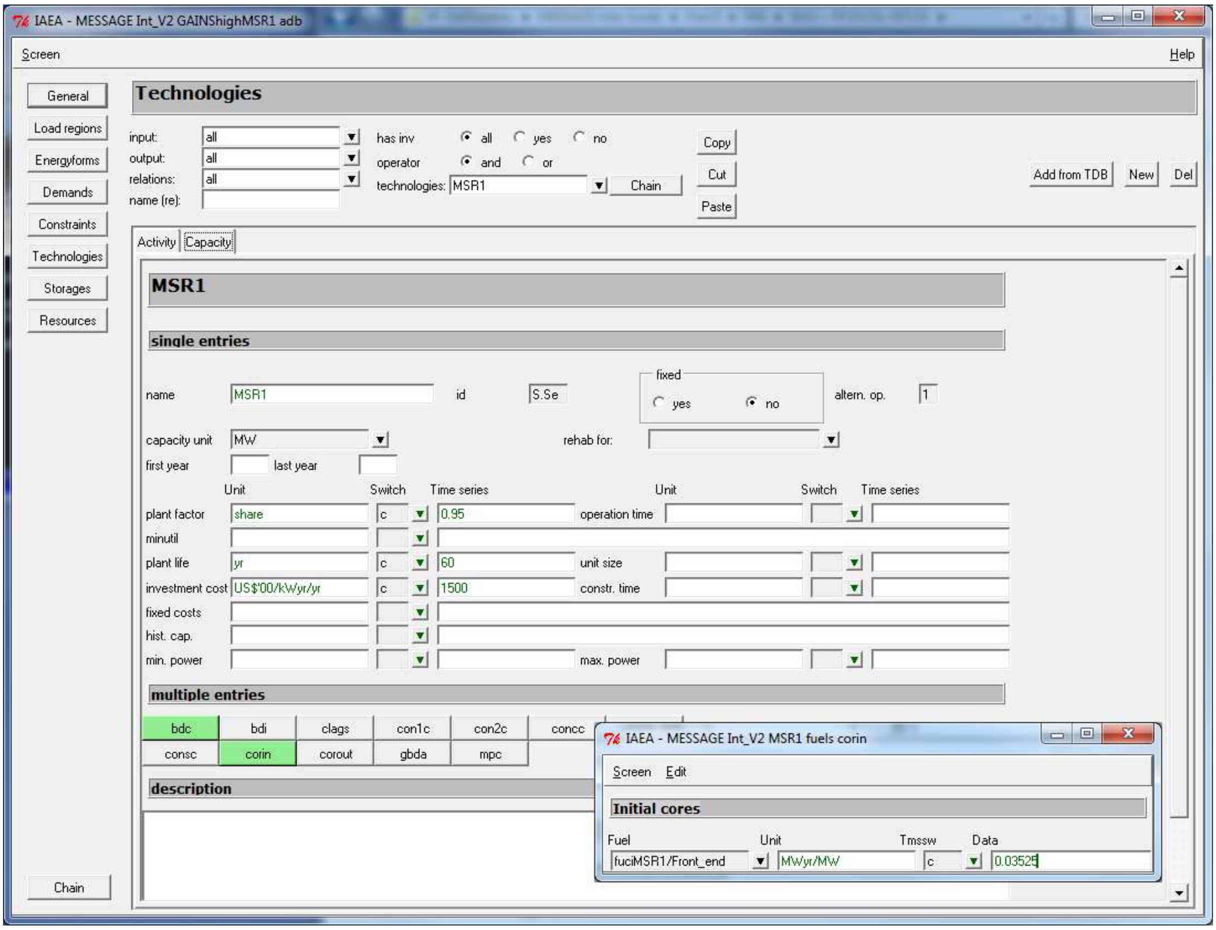


FIG. 227. MSR capacity page.

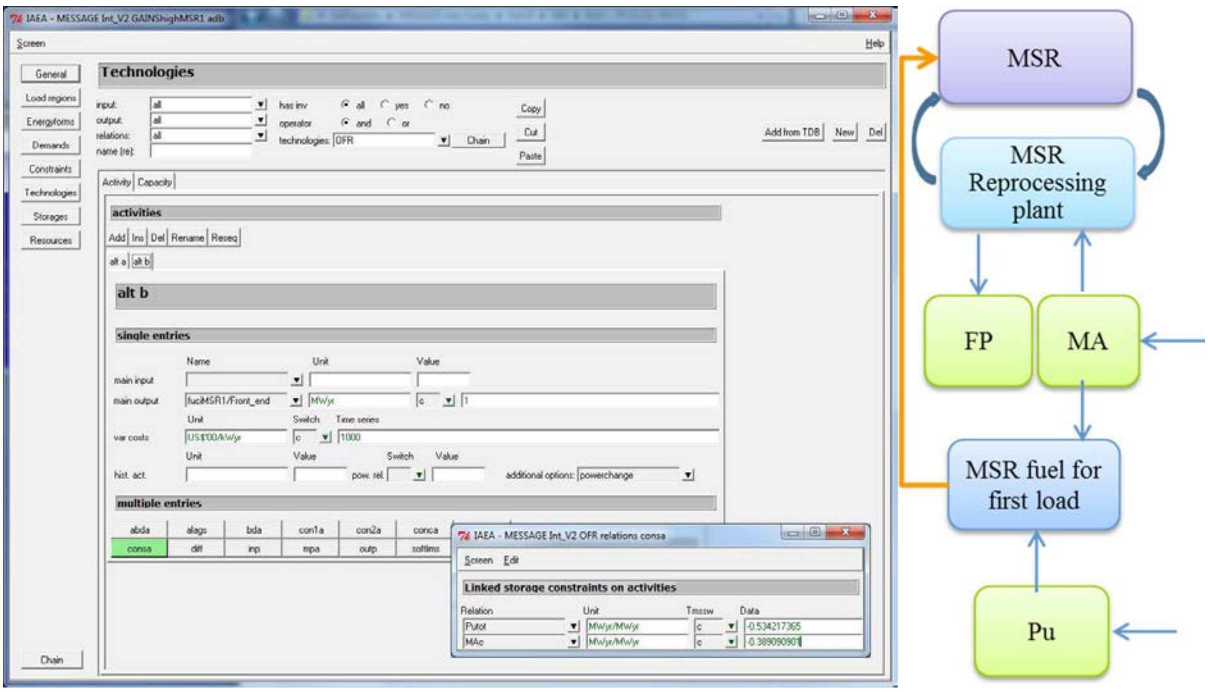


FIG. 228. Fabrication of fuel for MSR first loading.

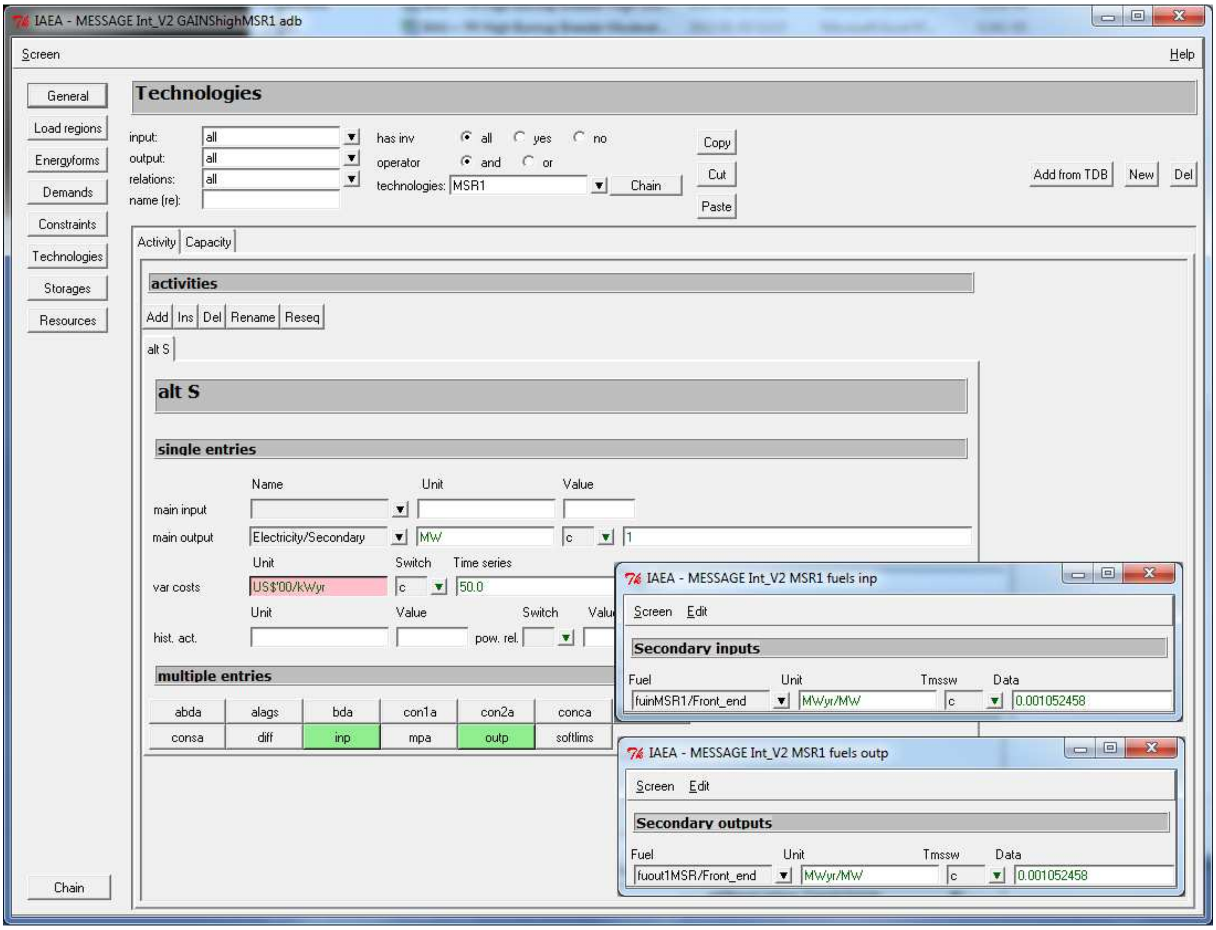


FIG. 229. MSR activity page.

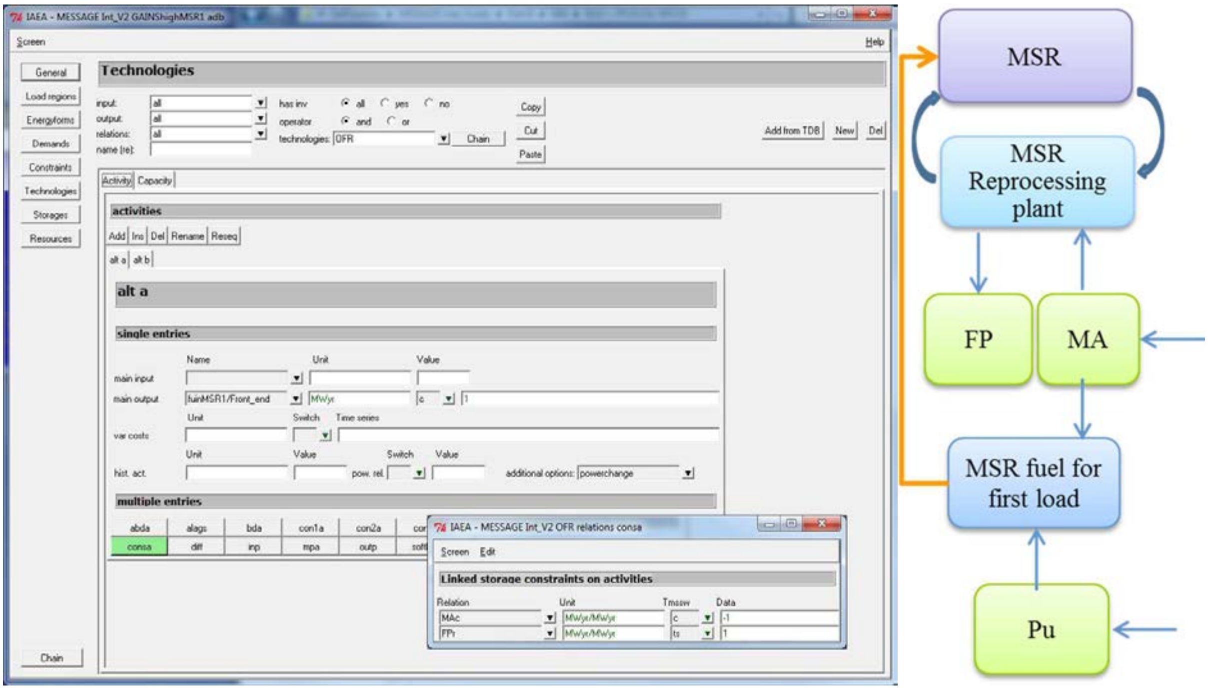


FIG. 230. Reprocessing of MSR SNF fuel.

3.3.5. Main results and findings of the case study

Introduction of BAU+ scenario with FR break-even and the effect of FR and MA introduction into BAU+ scenario

The nuclear power demand structure for the BAU+ scenario with a fast reactor when the fast reactor is of the 'fast reactor break-even' (BR ~1.0) type is shown in Fig. 231. The estimated MA accumulation (assuming no specific plan for MA transmutation) for the scenario is shown in Fig. 232. The nuclear power demand structure for the scenario and the estimated MA accumulation for the AFR 'high burnup fast reactor breeder' is shown in Figs 233 and 234. The fuel for the high burnup fast reactor breeder contains MA and, hence, this reactor contributes to MA burning.

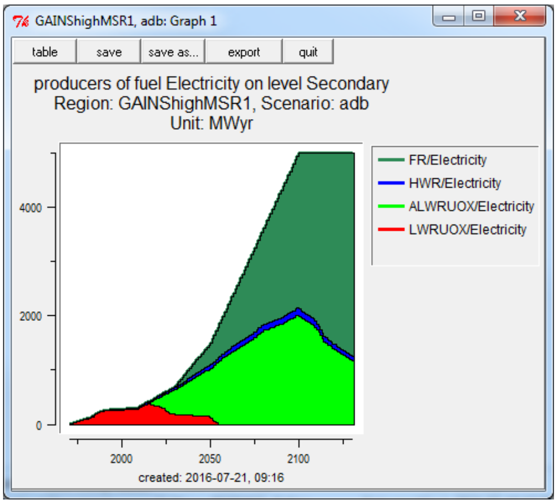


FIG. 231. *Nuclear power demand structure for scenario with FR introduction.*

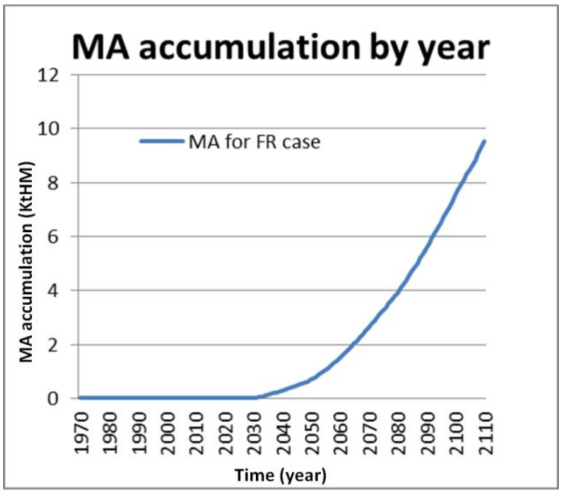


FIG. 232. *MA accumulation for scenario with FR introduction.*

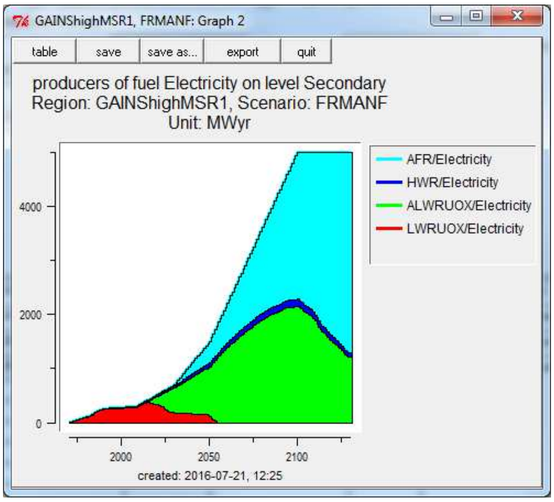


FIG. 233. *Nuclear power demand structure for scenario with AFR introduction.*

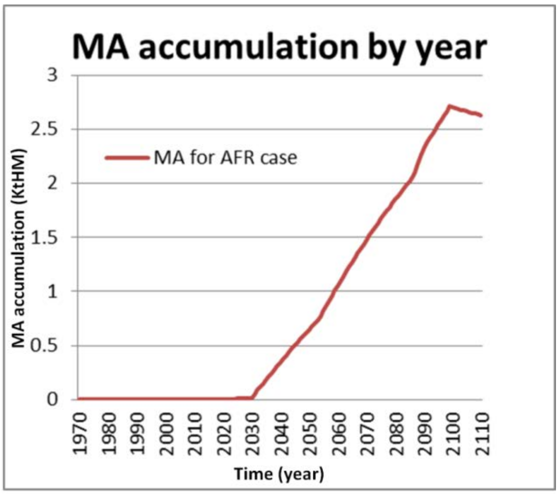


FIG. 234. *MA accumulation for scenario with AFR introduction.*

Effect of introduction of ADS into the BAU+ scenario with FR break-even

Introduction of an ADS in the NFC improves the situation with respect to MA accumulation problem. Analysis of this issue is presented in the framework of the GAINS homogeneous world model with the introduction of ADS into the BAU+ high scenario with FR break-even. In order to reduce the amount of MA in the above-mentioned scenarios, there is a need to introduce around 150 GW of the ADS installed capacities. This accounts for about 2–3% of the total installed capacities. Figure 235 illustrates the structure of NES for the high cases of the BAU+ scenario with FR break-even and ADS.

The introduction of an ADS in the BAU+ scenario with FR break-even leads to a large decrease in MA accumulation, which is illustrated in the Fig. 236. Without ADS introduction, the amount of MA after reprocessing by 2100 will be around 7000 t HM. The ADS deployment decreases this figure to about 1000 t HM.

The drastic decrease in MA accumulation up to the end of century is a consequence of commissioning a new ADS that consumes a large amount of MA for the initial loading. After 2110, the MA accumulation stops decreasing owing to the fact that the ADS burns MA only in equilibrium loading.

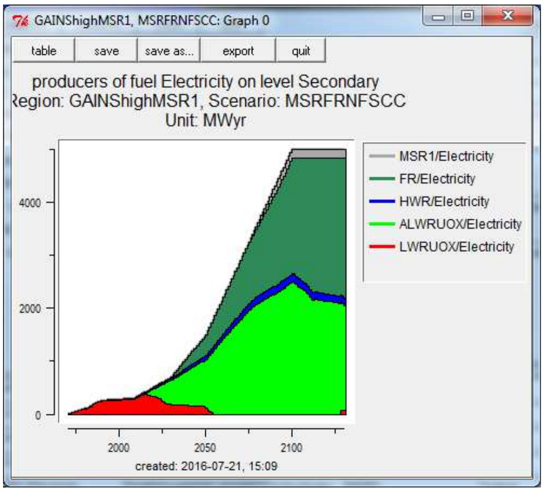


FIG. 235. Nuclear power demand structure for scenario with ADS introduction.

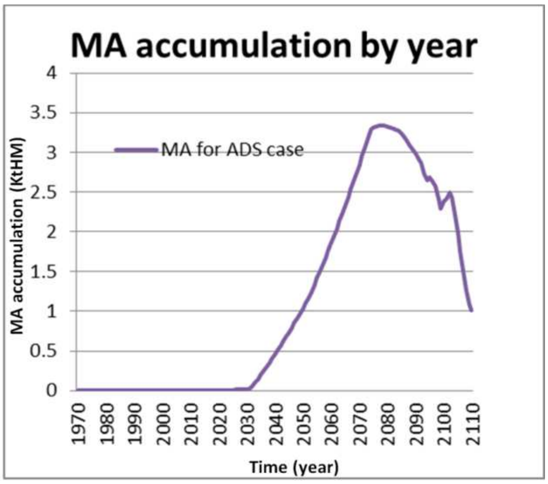


FIG. 236. MA accumulation for scenario with ADS introduction.

Effect of introduction of MSR into the BAU+ scenario with FR break-even

Introduction of an MSR in the NFC also improves the situation with respect to MA accumulation problem, as in the previous case. In order to reduce the amount of MA in the above mentioned scenarios, there is a need to introduce about 160 GW of the MSR installed capacities. That accounts for about 3% of the total installed capacities (Fig. 237). Figure 238 shows the amount of MA that is accumulated by 2110. The MSR deployment decreases it to about 1000 t HM.

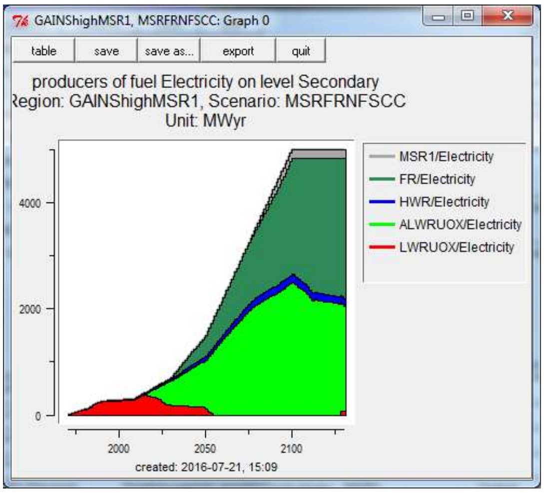


FIG. 237. *Nuclear power demand structure for scenario with MSR introduction.*

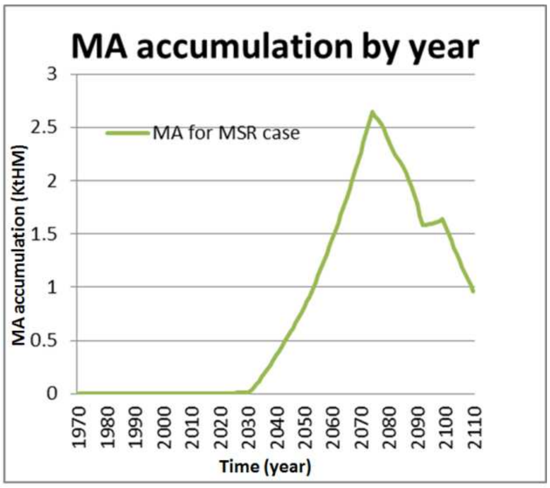


FIG. 238. *MA accumulation for scenario with MSR introduction.*

Conclusions

The study defined incentives and milestones for introduction of AFR, ADS and MSR into the global NES, as burners of MA, and identifies a possible niche for the technologies where they would be compatible with other prospective nuclear technologies aimed at enhancing the sustainability of the NES.

The scenario study confirmed a significant potential of the ADS and MSR as prospective technologies for MA burning, provided that technical and economic challenges are overcome. Availability of the proven ADS and MSR technologies by the third part of the century would present an opportunity to avoid over-burdening of the fast reactors with the function of MA burning at the first stage of their commercial introduction.

Being a small portion of the NES, the ADS and MSR could also be considered an integral part of the future multilateral NFC centre in possible combination with other types of MA burners, such as specialized FRs.

3.3.6. Feedback on NES modelling with the MESSAGE tool

In the study performed MESSAGE has demonstrated itself to be a powerful tool to model scenarios incorporating the closed nuclear fuel cycle with Pu and MA utilization. Material flow calculations included several flows of reprocessed material. The main issue was to balance Pu and Ma flows to render the considered scenarios feasible. MESSAGE provided a good platform for solving the tasks of this kind. A feasible solution could have been found reasonably quickly in comparison with other simulation tools. The main issue that still needs to be addressed is the accounting of ^{241}Pu decay into ^{241}Am in an external fuel cycle after SNF cooling and in the long term Pu and MA storage facilities. If this decay is not taken into account, this can lead to an underestimation of the total MA accumulation.

4. FEEDBACK FROM CASE STUDIES

The MESSAGE tool was applied for modelling several nuclear energy systems in Member States and in INPRO collaborative projects. It was used to analyze and design national, regional and global nuclear energy strategies aimed at sustainable energy development. MESSAGE has been developed for evaluating alternative energy supply options, including nuclear technologies. It has been extensively used at national, regional and global levels. It gives an optimal development strategy for long term development of the energy sector. This section presents the feedback from the country case studies and the INPRO studies on NES modelling using the MESSAGE code.

4.1. FEEDBACK FROM COUNTRY CASE STUDIES

The country case studies on NES analysis employing MESSAGE included:

— The case study from Argentina on modelling of the NFC that incorporated an analysis of the growth strategy of the Argentine nuclear energy system based on diversification of the electricity mix in the long term, considering a larger share for nuclear, hydropower and variable renewables.

— The China demo-scenario with plutonium multi-recycling considered to study development scenarios based on FBR and CNFC technologies; this study used the MESSAGE software to model and optimize options for such NESs.

— The case study from Romania was focused on the modelling of national NES development in the short and medium terms by using the MESSAGE tool and the recently updated guide for MESSAGE use for nuclear energy system modelling.

— The case study from Russian Federation that modelled regional collaborative deployment scenarios aimed at solving the problem of accumulation of the spent nuclear fuel inventory. This study simulated regional architecture with a complete spectrum of the nuclear fuel cycle elements.

— The case study from Ukraine evaluated the deployment of nuclear energy capacities after 2030, based on different NFC strategies. The comparison of different NFC strategies was based on the criteria of minimization of the material flows and financial expenditures.

Feedback from the country case studies on NES modelling with the MESSAGE tool concluded that the can be effectively used to analyze different NES scenarios and solve different relevant problems. The key comments regarding the usefulness of the MESSAGE model are as follows:

— Use of the MESSAGE modelling tool provides an opportunity to analyze different short and long term scenarios of energy system development, including the set of initial conditions, the assumed strategy, the output data, the challenges and steps for scenario realization.

— The tool is a very versatile and sophisticated IAEA planning tool.

— The capabilities of the code provide for modelling of NESs with the inclusion of innovative components.

— The extended capabilities of the MESSAGE tool for NFC simulation make it possible to model cases related to multilateral cooperation in the NFC front and back end.

— The MESSAGE code has the advantages of simple operation and a ‘friendly’ interface.

— For the closed NFC, the MESSAGE model is capable of reflecting important logistics and economics of the each step, with the optimization goal being simple and clear.

— MESSAGE offers flexible modelling and allows the users to decide on the NFC components to be included in the model.

— Each component of the NFC can be modelled with additional technical and economic details if enough information and data are available for the users. If only minimal technical and economic data are available to the users, MESSAGE allows a simple but still quite useful representation of the NFC components.

— The model allows to represent the entire nuclear energy system with time dependent parameters for medium and long term planning.

— MESSAGE is able to perform energy system optimization and selection of the best alternative for energy generation by considering different kinds of the objective function (cost, uranium use, waste generated, etc.).

— The users have a possibility to perform the assessment of different energy chains of the reactor and fuel cycle technologies in order to choose an optimal energy chain alternative in terms of the cost competitiveness.

The developers of the country case studies also suggested certain areas for improvement of the MESSAGE model to further enhance its capabilities of complex nuclear energy system modelling:

— The NES analysis is particularly dependent on the data used for technical and economic parameters which may be varying among the users. In order to ensure the effectiveness of nuclear energy applications of the MESSAGE model, it was suggested to collect reliable technical and economic data related to all the nuclear fuel cycle steps included in the system. These data could be updated periodically.

— The role of nuclear energy is increasingly dependent *inter alia* on the economic environment of energy markets and the competitiveness of the alternative energy technologies. As such, the entire energy/electricity market could be modelled and the role of nuclear energy in the entire system setting could be assessed.

— The multi-lingual versions (English, French, Russian and Spanish) of the MESSAGE interface are already available. However, the release of MESSAGE versions in other languages may also be considered for further enhancement of its understanding and use.

— The MESSAGE code allows to model discreet capacities of the nuclear power corresponding to the input on individual nuclear power units. This feature is especially important for evaluation of the plutonium amount for the first and annual loadings in fast reactors using MOX fuel. However, this feature should be carefully used because it expands the complexity and size of the model, requiring more sophisticated commercial solvers.

— The discount cash flow analysis involved in the tool is very useful for modelling purposes in the short term, but in the long term case studies (more than 50 years) the discounting of investments on fuel cycle back-end facilities substantially reduces their contribution to the overall cost function compared to the front-end elements which produce a higher contribution. Being so, it becomes important that sensitivity analyses are performed for assessing the impact of a discount rate on the results. It is generally recommended that a reduced discount rate is used in long term analyses.

— The MESSAGE framework, being focused on economic issues, does not model a detailed isotopic composition evolution of the multi-recycled fuel during operation of a NES. Therefore, MESSAGE needs to be used in package with other sophisticated physical codes to perform relevant analysis required for NES analysis.

— The technical and economic data used in the country case studies provide useful references for future users, but additional efforts on development and presentation of reliable reference data are needed, particularly for certain elements of the closed NFC chain.

— Some operational problems have been identified by the contributors to this document. For example, some input parameters or switches in user interface of MESSAGE could change its value or state. Such changes yield unexpected output results. Creating of 'log' for changed parameters or options like 'return to previous parameters' could help solve this problem. Similarly, the aspect 'consa' of technology does not work and needs to be fixed in the next version of the MESSAGE tool.

4.2. FEEDBACK FROM STUDIES ON ELABORATION OF MESSAGE FOR SIMULATION OF HETEROGENEOUS WORLD MODEL, THORIUM FUEL CYCLE AND MINOR ACTINIDE TRANSMUTATION

The presented studies elaborated the MESSAGE tool for simulation of a heterogeneous world model, thorium fuel cycle and minor actinide transmutation. A case study on the simulation of a heterogeneous world nuclear energy system illustrates a global NES in which countries have different policies on the fuel cycle back end. The study explored the positive effects of technology innovation for minimization of the natural resource depletion and the radioactive waste accumulation brought out through cooperation among countries that could amplify the positive effects of technology innovation in achieving sustainable nuclear energy by bringing the sustainability benefits from innovations in technology to those countries that do not pursue innovation programmes domestically. The INPRO global and regional scenarios with the introduction of thorium considered the potential role of the thorium fuel cycle for enhancing nuclear power sustainability. The INPRO case studies on global scenarios also considered the implementation of MA transmutation based on innovative technologies including fast reactors, ADS and MSR.

Feedback from the INPRO case studies made it possible to derive the following conclusions:

— The model helps: (a) confirming the feasibility of an NES through the correlation and consistency of all NES components, constraints and boundary conditions; (b) balancing fissile material in a closed nuclear fuel cycle and determine the related requirements to fuel cycle components; (c) taking into account the cost of RD&D, the construction cost, the cost of generated electricity and the costs of spent fuel management and storage and (d) assisting the user in optimization of an NES by comparing the alternatives with different needs for fuel, different volumes and the toxicities of waste, etc.

— The MESSAGE model provides an adequate platform for creating a nuclear energy system model of the world consisting of multiple nuclear energy groups operating separately from each other, or operating synergistically with interactions (collaborations) among the different nuclear energy group of countries.

— MESSAGE is able to model various possible options and variants of interregional cooperation between groups of countries, which can become quite complex.

— Sensitivity studies can be easily performed with the MESSAGE tool by varying demand in groups of nuclear energy countries of a global NES, with MESSAGE updating the nuclear material flows and nuclear infrastructure accordingly. Comparison of results from sensitivity studies is quite simple and practical with MESSAGE.

— MESSAGE is quite a flexible tool to be used for modelling nuclear technologies with the necessary details, such as first loading and final unloading of fuel in reactors, cooling time for spent fuel discharged from a reactor, lag and lead time for processes, and losses.

— The model has the capabilities to simulate and optimize scenarios of advanced NES options such as MSR and ADS with inclusion of MA multi-recycling and thorium fuel cycle based on thermal and fast reactors with spent fuel reprocessing and Pu/^{233}U recycling.

— MESSAGE proved to be a powerful tool to model scenarios with a closed fuel cycle with the two kinds of recycled material, such as Pu and MA.

— The calculation speed of the MESSAGE code is sufficient to enable making comparisons of different NES options in a reasonable time frame.

The INPRO studies on NES modelling and scenario analysis also suggested the following improvements that would result in a refinement of the MESSAGE code for further application in advanced NES evaluations:

— It would be very useful to extend the MESSAGE capability to simulate the movement of cooled spent fuel from cooling storage to long term storage after a fixed cooling time during modelling of the cooling time at reactor storage sites.

— In modelling a scenario for a closed fuel cycle with the two kinds of recycled materials, such as Pu and MA, MESSAGE may be improved to take into account the ^{241}Pu decay into ^{241}Am in an external fuel cycle after SNF cooling and in a long term Pu and MA storage. This decay, if not taken into account, can lead to an underestimation of the total MA accumulation.

The experience gained from NES modelling in the various case studies presented in this document confirms the usefulness of the MESSAGE code for supporting the technological, the collaboration and the economic aspects of sustainability analysis for different nuclear energy system scenarios.

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LIST OF ABBREVIATIONS

ADS	accelerator-driven system
advHWR	advanced heavy water reactor
advPWR	advanced pressurized water reactor
AECL	Atomic Energy of Canada Limited
AFR	advanced fast reactor
ALWR	advanced light water reactor
APWR	advanced pressurized water reactor
AWWER	advanced water cooled, water moderated power reactor
BAU	business as usual
BN	fast reactor with sodium coolant
BR	breeding ratio
CANDU	Canada deuterium–uranium reactor
CNA	Central Nuclear Atucha
CNE	Central Nuclear Embalse
CNEA	Comisión Nacional de Energía Atómica
CNFC	closed nuclear fuel cycle
CNU	Uranium National Company, Romania
CP	collaborative project
CSNFSF	Central Spent Nuclear Fuel Storage Facility
d	day
drate	discount rate
EFPD	effective full power days
EGP	graphite-steam power reactor
ENPEP	Energy and Power Evaluation Program
EU	European Union
FC	fuel cycle
FOAK	first of a kind
FP	fission products
FBR	Fast breeder reactor
FR	fast reactor
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GDP	gross domestic product
GHG	greenhouse gases
GIF	Generation-IV International Forum
GW	gigawatt
GW/year	gigawatt-year
GW·d/t	gigawatt-days per tonne
HM	heavy metal
HWR	heavy water reactor

INL	Idaho National Laboratory
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IPCC	International Panel on Climate Change
IR	inferred resources
IRR	internal rate of return
kt U	kilo-tonne of uranium
kW(e)	kilowatt (electrical)
LEU	low enriched uranium
LUAC	levelized unit amortization cost
LUEC	levelized unit energy cost
LUOM	levelized unit operation and maintenance cost
LWR	light water reactor
MA	minor actinide
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
MOX	mixed oxide
MSR	molten salt reactor
MW(e)	megawatt (electrical)
NES	nuclear energy system
NESA	Nuclear Energy System Assessment
NEST	NESA Economic Support Tool
NFC	nuclear fuel cycle
NG	nuclear strategy group
NGS	nuclear generating stations
NPP	nuclear power plant
NPV	net present value
O&M	operations and maintenance
OECD	Organisation for Economic Co-operation and Development
PESS	Planning and Economic Studies Section
PHWR	pressurized heavy water reactor
PLEX	Plant life extension
PR	prognosticated resources
PRIS	Power Reactor Information System
PWR	pressurized water reactor
RAR	reasonably assure resources
RATEN ICN	Technologies for Nuclear Energy State Owned Company, Institute for Nuclear Research Pitesti
RBMK	high-power channel-type reactor
R&D	research and development
RD&D	research, development and demonstration
RI	robustness index
ROI	return on investment

ROSATOM	State Atomic Energy Corporation ‘Rosatom’
SCWR	Supercritical water reactor
SNF	spent nuclear fuel
SRES	Special Report on Emissions Scenarios
SWU	separative work unit
SYNERGIES	Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability
t HM	tons of heavy metal
TECDOC	IAEA Technical Document
UOX	uranium oxide
WWER	water cooled, water moderated power reactor
depU	depleted uranium

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