EDITORIAL NOTE

ANNEX VIII. TRIAL APPLICATIONS OF THE ROADMAP TEMPLATE TO COUNTRY NESS

VIII.1. STRUCTURE FOR THE PRESENTATION OF RESULTS

A typical roadmap template structure for case studies of national NESs is presented below. Using this template allows experts to examine and document long term national nuclear energy strategies, presenting inputs and results in a structured and unified format for the illustration of approaches to transition NESs towards enhanced sustainability.

(a) General country information

The section on ‘general country information’ specifies the national case study background, including strategy and development scenarios in the energy sector, macroeconomic conditions and motivations for the establishment and development of an NES. It presents the nuclear energy status and the projected share in the national energy mix.

(b) National decision on and vision for the nuclear energy strategy

The section on the ‘national decision on and vision for the nuclear energy strategy’ clarifies the national vision and nuclear energy deployment strategy, including the government’s nuclear energy policy and commitment to develop, implement and maintain a sustainable nuclear energy programme; governmental and industrial institutional infrastructure; stakeholder involvement; the status of cooperation with other countries in the nuclear sector; and possible scenarios for long term nuclear energy development beyond official plans.

(c) Purpose of the roadmap

The section on the ‘purpose of the roadmap’ explains the purposes of the national case study and its relevance to the objective of the ROADMAPS collaborative project, which is to provide the formulation of targets for moving towards NESs with enhanced sustainability locally and globally and the identification of prospective partners for cooperation.

(d) Metrics on nuclear energy position and development

The section on ‘metrics on nuclear energy position and development’ discusses the NES status indicators, including official plans as well as prospects analysed by experts, projections for nuclear energy evolution and country group classification, technology options and collaboration with other countries.

(e) Key developments to enhance sustainability

The section on ‘key developments to enhance sustainability’ presents key events and developments in different subject areas (for example, economics, safety, resources, waste management, proliferation resistance and infrastructure including political support and public acceptance) that would enhance nuclear energy sustainability through technological options and collaboration among countries.

(f) Nuclear power planning and scenarios

The section on ‘nuclear power planning and scenarios’ illustrates NES deployment plans and scenarios including reactor fleet, energy production, and supply and demand balances for uranium mining, conversion, enrichment, fuel fabrication, spent nuclear fuel storage and reprocessing, and geological disposal. All relevant information regarding reactor and nuclear fuel cycle parameters, initial data and specific tools used for mass flow evaluations can be provided within this section.

(g) Progress monitoring

The optional section on the ‘roadmap template for cross-cutting analysis and monitoring of progress’ may contain the results of cross-cutting analyses of national and potential partner countries’ roadmaps to examine models of cooperation, joint action plans, the results of metrics aggregation and monitoring of progress towards enhanced NES sustainability based on different performance metrics.

(h) Summary

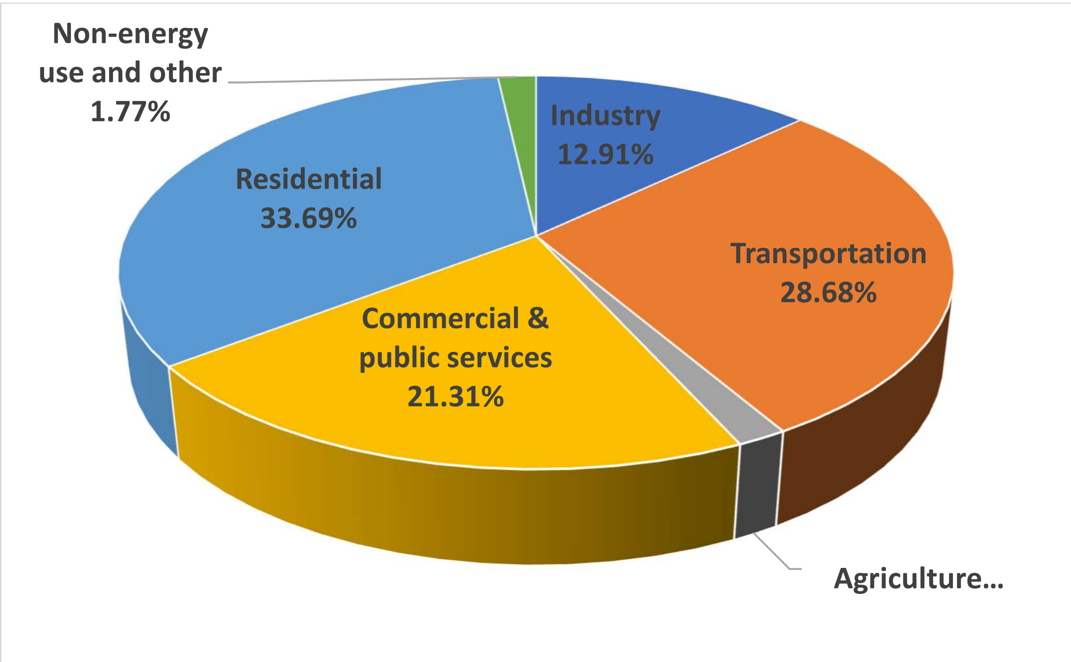
The ‘summary’ section presents the main conclusions and observations from the case study. Relevant information should be compiled as a condensed roadmap.

VIII.2. THE APPLICATION OF THE ROADMAP TEMPLATE TO THE NES OF ARMENIA

VIII.2.1. General country information

Republic of Armenia is a small landlocked mountainous country in the South Caucasus region bordered on the north by Georgia, on the east and south-west by Azerbaijan, on the south by the Islamic Republic of Iran and on the west by Turkey. The population of Armenia, according to the country statistical data, is about 2.9986 million inhabitants. The GDP in 2015 was US $10.5291 billion and the GDP per capita was US $3511 [VIII.1].

Armenia has very limited domestic natural energy resources, and these are mainly hydro, wind and solar power. All oil products, natural gas and nuclear fuel are imported resources. The total primary energy supply in 2015 amounted to 2.97 million tonnes of oil equivalent (toe). This energy demand is shown by economy sector in Fig. VIII.1.



The structure of energy demand in Armenia by economy sector in 2015. In the category ‘energy use and other’, ‘non-energy use’ indicates activities where energy is used for the production of non-energy goods, and ‘other’ indicates the energy consumption that cannot be included in any predefined sector. In Armenia, some amount of natural gas is used as a source for the production of other goods.

According to [VIII.2] the total installed capacity of the power system of Armenia is approximately 4336.6 MW(e), of which only 2589.6 MW(e) is available owing to the degraded condition of the ageing equipment.

The installed capacity of thermal power plants (TPP) is 2347 MW(e). The TPPs have dual firing capabilities and may burn either natural gas and/or mazut. The TPP Hrazdan has an installed capacity of 1110 MW(e), the separate but collocated Hrazdan Unit 5 power plant 445 MW(e), Yerevan TPP 550 MW(e), and Yerevan closed cycle gas turbine plant 242 MW(e). Total available thermal capacity is 1380 MW(e)[1].

The first and second units of the Armenian NPP (ANPP) were put into operation in 1976 and 1980, respectively. They are water–water energy reactors (WWERs), specifically WWER-440/270 type reactors that have an aggregate capacity of 815 MW(e). In 1989, after the 1988 Armenian earthquake (December 7 1988), ANPP was shut down for safety considerations, even though no safety related technical reasons existed. In 1995, after the severe energy crisis in Armenia (1993—1995), Unit 2 was re-commissioned with an installed capacity of 407.5 MW(e). At the time of writing, the available capacity of the ANPP was 385 MW(e).

The installed capacity of all hydropower plants is approximately 1182 MW(e), including 222 MW(e) provided by small hydropower plants. There is one pilot wind farm with 2.6 MW(e) of installed capacity.

The system internal peak in 2015 was 1352 MW(e). Electricity production was 7.8 billion kW·h. Table VIII.1 shows the historical statistics of electricity production by the different plant types. Figure VIII.2 shows the structure of electricity production in 2015 by different types of power plants for both the total generation mix and for domestic use.

ELECTRICITY PRODUCTION, CONSUMPTION AND CAPACITY [VIII.3]

Item	1988	2000	2005	2010	2012	2015
Capacity of electrical plants (GW(e))						
— Thermal	1.74	1.74	1.74	1.99	2.43	2.35
— Hydro (incl. small hydropower plants) &Wind	1.00	1.00	1.00	1.10	1.21	1.19
— Nuclear	0.76	0.38	0.38	0.38	0.38	0.38
— Total	3.51	3.12	3.12	3.47	4.02	3.92
Electricity production (TW·h)						
— Thermal	8.94	2.69	1.83	1.41	3.37	2.8
— Hydropower (incl. small hydropower plants) &wind	1.52	1.26	1.66	2.59	2.31	2.21
— Nuclear	4.82	2.01	2.72	2.49	2.31	2.79
— Total	15.28	5.96	6.21	6.49	8.03	7.8
Total electricity consumption (TW·h)	12.39	4.77	4.89	5.21	5.92	7.43

[1] There are two reasons for the big difference between the installed and available capacities. The first is that some of the existing TPPs are very old and their technical conditions do not allow them to produce much electricity. For example, of 1110 MW of the Hrazdan TPP installed capacity, only around 370 MW is technically available for electricity generation. The second reason is related to the country's climatic conditions and the power plants' altitude. For example, the Yerevan closed cycle gas turbine plant can produce only 220 MW in winter and 210 MW in summer of an installed capacity of 242 MW.

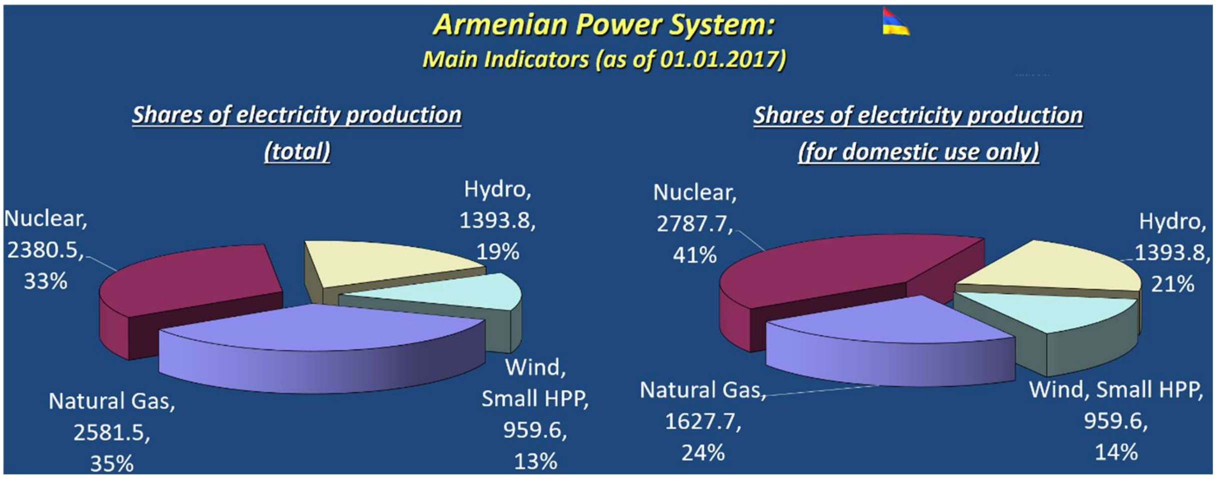


FIG. VIII.1. Structure of electricity production in Armenia in 2016 (based on data from [VIII.4]).

The ANPP plays a significant role in the stability and independence of power supply. Therefore, Armenia has decided to keep the nuclear option available in the longer term. Future official plans and expert studies of long term energy system development are given in the next section.

VIII.2.2. National decision on and vision for nuclear energy strategy

VIII.2.2.1. Long term development plan of the Armenian energy system (up to 2036)

To identify and unify the strategically important projects in the energy sector, a document entitled “Long term development of the energy system of the Republic of Armenia (till 2036)" was developed and was adopted by the Government of Armenia in December 2016 [VIII.5]. The programmes for energy strategy development have been designed to ensure the energy security of the Republic of Armenia aligns with the regulations of the national security strategy of the Republic of Armenia [VIII.6] and considers such factors as:

- Evaluations of fuel and energy markets in the country during the last years;
- The technologies applied in the energy sector in the last decade;
- The trends of broader regional integration;
- The results of negotiations with Georgia, the Islamic Republic of Iran, the Russian Federation and other countries.

According to the scheduled programme plan, the main development scenario will take measures aimed at:

- Reducing the physical degradation of existing equipment and mechanisms in the energy sector;
- Extending the operational lifetime of ANPP by 10 years;
- Constructing an approximately 1000 MW(e) nuclear unit on the existing ANPP site;
- Constructing a 220 MW(e) and a 400 MW(e) closed cycle gas turbine plant;
- Promoting further development of renewable energy and ensuring regional integration.

Table VIII.2 presents the existing and planned generation capacities for the period up to 2036 as indicated in the country’s energy system development plan [VIII.5]. Small and medium sized HPPs are to be deployed as soon as possible. Two thermal units were rated necessary by 2018 and 2021 to cover electricity export obligations according to the agreement with the Islamic Republic of Iran. Solar photovoltaic systems are not economically attractive and only 40 MW(e) are expected, based on governmental promotional programmes. The lifetime extension of the existing ANPP was planned to take place in 2018 and a new nuclear unit WWER-1000 is to be built there in 2027. New wind farms are to be constructed starting in 2030 and will reach 150 MW(e) by the end of the planning horizon.

The development document concludes with the following main recommendations:

- There is no economically justified alternative to ANPP life extension through 2026.
- Deploying a new WWER nuclear unit of approximately 1000 MW(e) in 2027 is cost effective in all scenarios except when there is no swap after 2027 and cheaper Russian Federation gas is assumed to be available, in which case the cost effective option is a smaller nuclear unit.
- Deploying new HPPs (Shnokh, Loriberd, Meghri and small HPPs), together with wind and geothermal energy sources, is a cost effective option, whereas solar energy is not competitive and will be deployed only under stimulus measures.
- To cover the current swap requirements, there is a need for the installation of 620 MW(e) of additional thermal capacity starting in 2018.
- Energy efficiency promotion demonstrates fuel and economic savings resulting in a power sector composition with 180 MW(e) less new thermal capacity.

TABLE VIII.1. POWER GENERATION CAPACITIES [VIII.5].

Power plant (MW(e))	2015	2018	2021	2024	2027	2030	2033	2036
Hrazdan 5	440	440	440	440	440	440	440	440
Hrazdan TPP	370	370	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
New CCGT 220	n.a.	n.a.	220	220	220	220	220	220
New CCGT 400	n.a.	400	400	400	400	400	400	400
Yerevan CC	220	220	220	220	220	220	220	220
Loriberd HPP	n.a.	n.a.	66	66	66	66	66	66
Meghri HPP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	130	130
New small HPPs	60	120	148	148	148	148	148	148
Sevan-Hrazdan HPP cascade	550	550	550	550	550	550	550	550
Shnokh HPP	n.a.	n.a.	70	70	70	70	70	70
Small HPPs	222	222	222	222	222	222	222	222
Vorotan HPP cascade	400	400	400	400	400	400	400	400
ANPP	385	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
ife extension of existing plant	n.a.	385	385	385	n.a.	n.a.	n.a.	n.a.
New WWER-1000	n.a.	n.a.	n.a.	n.a.	1028	1028	1028	1028
Geothermal power plant	n.a.	n.a.	n.a.	30	30	30	30	30
Lori Wind Farm	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
New wind farms	n.a.	n.a.	n.a.	n.a.	n.a.	50	100	150
Solar photovoltaic systems	n.a.	20	40	40	40	40	40	40
Total	2649	3129	3164	3194	3837	3887	4067	4117

Note: n.a. — not applicable; CC — gas fired combined cycle power plant; CCGT — closed cycle gas turbine plant; HPP — hydropower plant.

VIII.2.2.2. Additional points to be considered

This section presents the Armenian energy demand forecast for the twenty-first century and the power technologies considered for implementation. The presented material is based on a study performed by experts under the INPRO collaborative project SYNERGIES as briefly summarized below.

Analyses of long term energy system development strategies were based on expected country demand projections up to 2100 and on consideration of export/import opportunities with neighbouring countries. First considered was a continuation of the average annual growth rate of electricity consumption in Armenia over the past 10 years (i.e. 3.72% growth per year). Then a de-escalation rate of minus 0.05% per annum was assumed and the average annual demand growth rate for the whole planning period (up to the end of 2100) was calculated at 1.54% per year. In addition to domestic consumption, long term electricity export opportunities amounting to 6.9 billion kW·h per year were also considered. The results of the generation calculations are summarized in Fig. VIII.3.

Analyses of the data in Fig. VIII.3 show that around 3340 MW(e) of additional capacities will be required to fully cover domestic electricity demand and ensure electricity export obligations during this century. Three power plant types are foreseen for Armenia and considered for future investigation. They are natural gas fired power plants, renewables (large, medium and small HPPs, wind farms and solar photovoltaic systems) and NPPs.

It is noted that the existing gas transportation system would be used to cover the growing demand for domestic natural gas. It is assumed that the capacity of gas pipelines will be enough to also supply thermal unit capacities.

Armenia has very limited domestic sources for electricity generation, all of which are renewables. According to the national strategy for power system development [VIII.7], all the nation's economically feasible renewable energy sources (RESs) should be utilized in Armenia until 2035. Figure VIII.4 presents the structure of RES generation over the period of their introduction into the system, which will continue to the end of the planning period (the end of the twenty-first century). Therefore, only 714 MW(e) of new renewable capacities of the additionally requested 3340 MW(e) will be introduced to the power system.

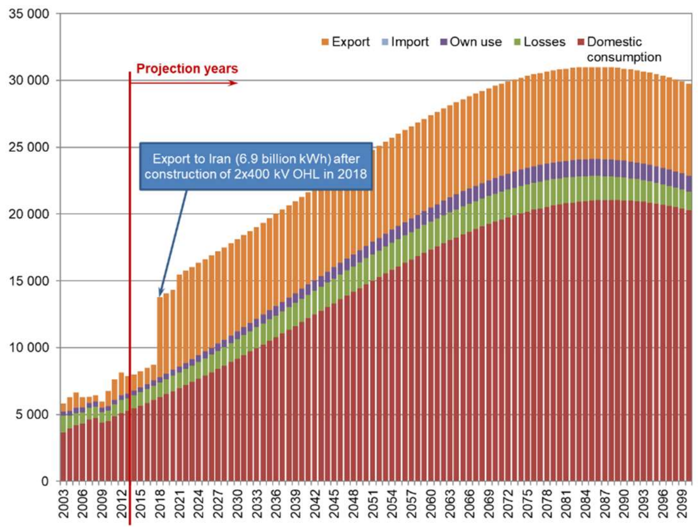


FIG. VIII.2. Structure of electricity generation (electricity generation and import). 'Own use' or 'power plant self-consumption' refers to the difference between the electricity generated by generators and the amount of electricity provided to the network from the power plant bus bars. 'Own use' is different from 'domestic consumption' and both are represented in the picture separately

Finally, only the deployment of nuclear power can be proposed to cover the remaining demand (that is, 3340 – 714 = 2626 MW(e)). It is assumed that a WWER-1000 unit will replace the existing ANPP in 2026. Starting from 2035, six VBER-300 reactors will be put into operation at the rate of one unit per decade. The last (sixth) VBER-300 will be introduced to the power system in 2095, and will replace the first one. Some of the technical, economic and operational parameters of the reactors are summarized in Table VIII.3.

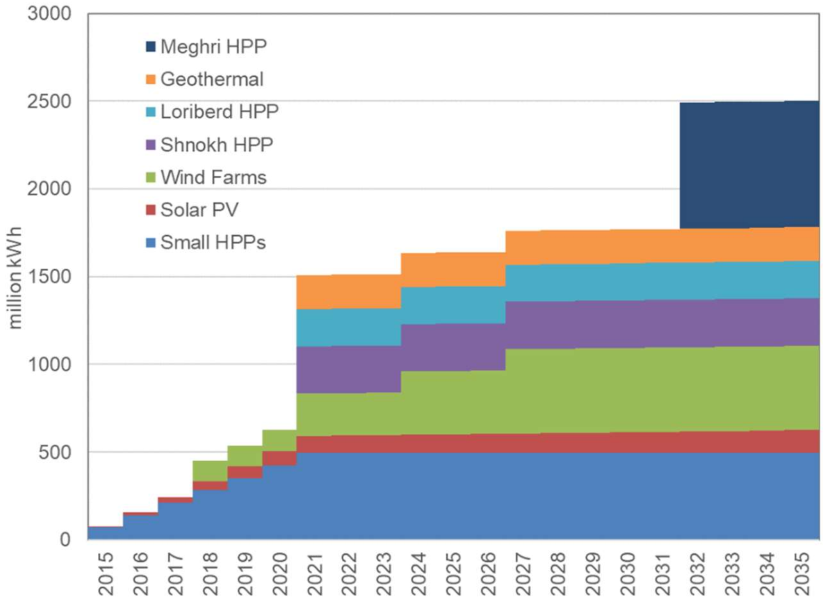


FIG. VIII.3. Structure of electricity generation by RESs.

TABLE VIII.2. TECHNICAL AND ECONOMIC PARAMETERS OF THE SELECTED REACTORS

Parameter	WWER-440	WWER-1000	VBER-300
Heat capacity (MW)	1375	3000	912
Electric capacity (MW(e))	375	1060	325
Efficiency (%)	27.3	35	—
Installed capacity utilization factor (%)	72	85	85
Fuel enrichment (%)	3.82	4.7	5%
Average burnup for fuel assemblies (GW/day^{-1}/t^{-1})	42.66	60	60
First load (t HM)	40.2048	72.844	22.2144
Annual reload (t HM)	8.9856	16.088	4.44
Overnight cost (US $/kW)	—	5000	5500
Fixed costs (US $/KW)	50	50	50
Variable costs (US $/MWh)	1	1	1
Operational lifetime (years)	13	60	60
Construction period (years)	—	6	5
Cost of fuel fabrication (US $/kg)	300	300	300

Construction cost of spent nuclear fuel dry storage (US $/kg)	150	150	150
Cost of spent nuclear fuel disposal (US $/kg)	600	600	600
Cost of the processing without the return of HLW (US $/kg)	2000	2000	2000

Figure VIII.5 below shows the structure of electricity generation by different types of power plants for the whole planning period.

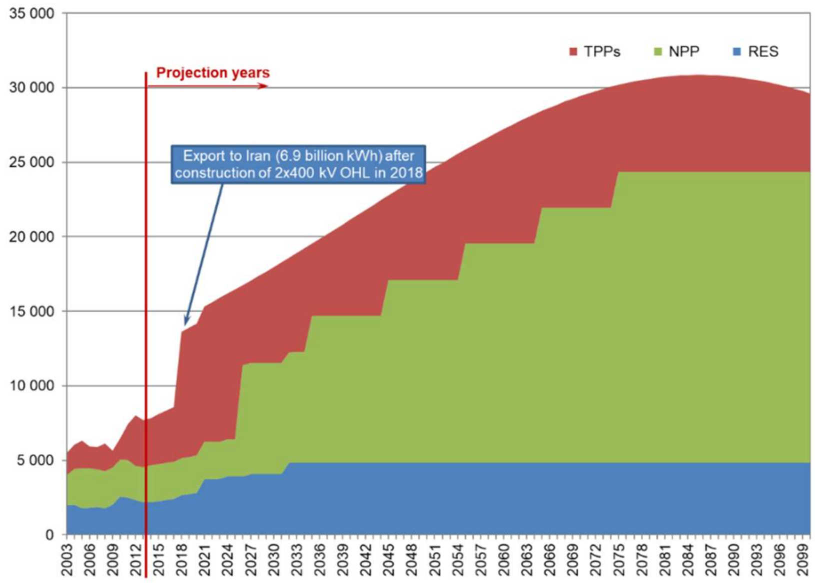


FIG. VIII.4. Generation of electricity by type of power plants.

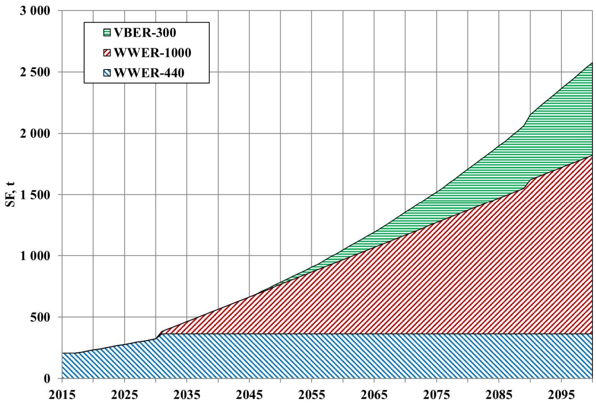
VIII.2.2.3. Management of spent nuclear fuel and radioactive waste

A total of 3148 spent nuclear fuel assemblies will be accumulated from the WWER-440, which amounts to 362.6 tonnes [VIII.8]. Spent nuclear fuel from the WWER-440 will be removed after five years of storage in a cooling pond. This fuel includes:

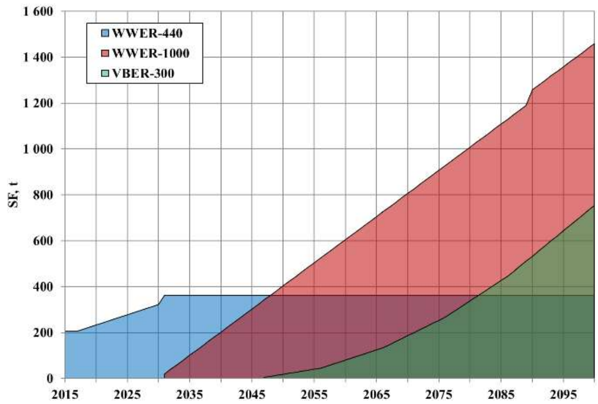
- The 1785 assemblies (205.6 tonnes) already accumulated by 2013;
- The 1014 more assemblies (78 assemblies × 13 years = 1014) (116.8 tonnes), which will accumulate in 13 more years (from 2013 to 2025);
- The 349 assemblies that will result from the complete unloading of the reactor core, which will subsequently be unloaded from the cooling pond in 2026.

The total accumulation of spent nuclear fuel assemblies from the WWER-1000 will be 1022 tonnes (16.08 tonnes × 59 years + 72.8 tonnes). During reactor refuelling, the fuel stored in the spent fuel pool is transferred into the spent nuclear fuel storehouse (SNFS). The SNFS is intended for the dry storage of spent nuclear fuel at the NPP site in dual purpose containers intended for transportation and storage. The SNFS capacity is designed for the long term storage of the spent nuclear fuel accumulated in the 10 years of operation of two units.

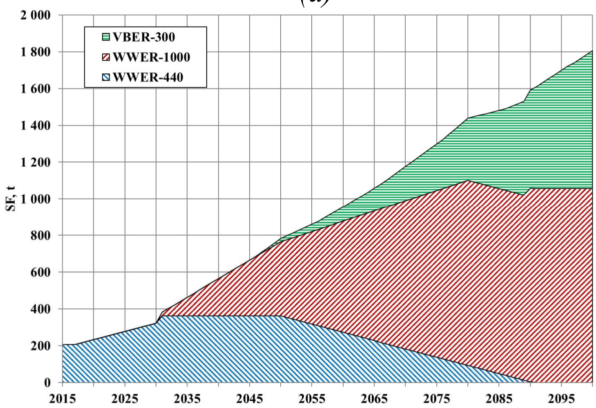
For the WWER-1000, therefore, it is expected that the fuel assemblies will be unloaded after 10 years of storage in the SNFS. The first group of fuel assemblies will be unloaded from the SNFS in 2037, and the last in 2099. In total, 1385 tonnes of spent nuclear fuel will be accumulated from the WWER-440 and WWER-1000 nuclear units by 2100.



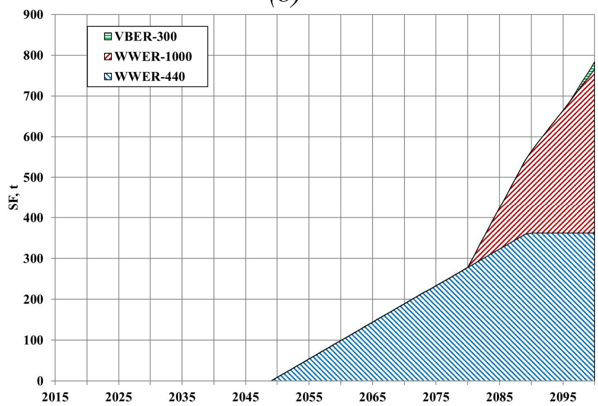
(a)



(b)



(c)



(d)

FIG. VIII.5. Spent nuclear fuel accumulation. (a) Total amount of spent nuclear fuel (without export); (b) amount of spent nuclear fuel by reactor type (without export); (c) Spent nuclear fuel in storage considering export (in total); (d) Export of spent nuclear fuel (in total).

Amounts of spent nuclear fuel are shown in Fig. VIII.6 (a)–(b). Approximately 2226 tonnes of spent nuclear fuel will be produced by 2100. In total, there will be 1507 tonnes of spent nuclear fuel in spent fuel dry storage collected from all the reactors taking the exported fuel (Fig. VIII.6(c)) into account. The rates of spent fuel export from dry storage are taken at the level of annual loads for both WWER-440 and WWER-1000 reactors and the rates of export for small reactors equal to the spent nuclear fuel supply rate. Spent nuclear fuel export is shown in Fig. VIII.6(d). Only 700 tonnes of spent nuclear fuel will be exported by 2100. The volume of exported spent nuclear fuel from the WWER-1000 will be 350 tonnes for the period up to 2100.

Amounts of spent nuclear fuel exports for the WWER-440 and WWER-1000 are limited by the annual loads for the respective reactors. The volume of spent nuclear fuel unloaded from all reactors in a given year determines the export of spent nuclear fuel from the VBER-300s. In this roadmap, cases with the return of some amount of spent nuclear fuel to the supplier have been considered.

VIII.2.3. Purpose of the roadmap

The main goal of the roadmap is to evaluate the options of sustainable NES development including fuel cycle perspectives and to assess the opportunities for cooperation among countries. One of the main steps in roadmap preparation is the approval of a nuclear energy development policy by a country's government. It can include short term (up to 20 years), medium term (up to 50 years) and long term (up to 100 years) development action plans. Action plans need to indicate necessary and planned activities for the given periods in as much detail as possible.

Below, study results on the identification of fuel and energy resource demands and options for how to meet the demands in Armenia are provided. Energy sector and system development scenarios and projections of options for the share of nuclear generation based on economic, financial, energy security and other factors are also provided.

Having very limited natural resources to cover the growth in electricity demand, Armenia needs to utilize all economically feasible domestic electricity generation sources. At the same time, many studies by officials and individual experts clearly demonstrate that it is impossible to supply sufficient electricity without importing fossil fuel and/or implementing the nuclear option. Taking into consideration the limited capacities and logistical opportunities of import, the Government has declared in all development programmes that the nuclear option is the only way to overcome energy security issues [VIII.9, VIII.10].

Preparation of the Armenian nuclear energy roadmap is dictated by the necessity to present different targets in time steps for moving towards locally and globally sustainable NESs and to identify prospective partners for cooperation. Various aspects of governmental decisions related to sustainable development can be examined, condensed and clearly demonstrated in the roadmap and considered in recommending future improvements in the main development areas. In this regard, being a nuclear technology user country, Armenia needs to collaborate with foreign states on the construction of NPPs and their implementation in the national grid, as well as on sustainability issues of the once-through nuclear fuel cycle.

VIII.2.4. Metrics on nuclear energy position and development

Starting from the year of independence (1991), Armenia evaluated many energy sector development strategies, the necessity of which were dictated by fast changes to the country's economic conditions and the regional geopolitical situation. The main goal of all those strategies was to formulate the lowest cost solution for ensuring the highest possible level of energy security and energy independence of the energy system. It was clearly shown that the operation of NPPs in Armenia not only guarantees the uninterruptable supply of electricity but also strongly supports economic growth.

The above mentioned studies concluded that availability of an NES in the frame of country and regional conditions is economically viable and is also competitive with other energy supply options (natural gas fired power plants), especially when considering the GHG emission costs and global warming issues. Based on the above mentioned evaluations, the Armenian Government officially declared that the country should have an NES in the electricity production mix for a long period. Currently, the official plan covers the period up to 2036, but it is obvious that nuclear energy will remain available beyond that time.

Recommended Government plans have been widely presented within the country. They were discussed in many meetings with the involvement of interested stakeholders (such as ministries, political and public organizations, and universities), and with the Prime Minister and other Government officials and so on. There were also two public hearings. The feedback from the participants and mass media shows that the majority of the country's citizens fully supports nuclear energy. It needs to be noted that power production by ANPP provides more than 40% of the domestic electricity consumption at an average load factor of around 85%.

Owing to the high importance of NPPs in the total electricity production mix, the Government decided to first extend the life of ANPP up to 2027 and then to find financial resources to build a new NPP after decommissioning the existing NPP. The main nuclear option considered in the strategy is the WWER-1000 reactor, but additional small and medium sized reactor types could be implemented in the power system after 2036. As mentioned above, six VBER-300 reactors are expected to be commissioned in the system during this century. It is important to note that in the development strategy, the construction of a new NPP is scheduled to take seven years.

Currently, only one supplier is providing the fresh nuclear fuel for the existing NPP. It is estimated that such a bilateral agreement option will remain up to 2030, after which fuel supply can be organized through more than one bilateral agreement. In the second half of the century, both multilateral and multiple bilateral agreements may come into force to ensure fresh nuclear fuel supply for the expected six reactors. Only dry storage for spent nuclear fuel is foreseen up to the end of this century.

Based on the above description, Armenia can be considered an NG3 type of country according to the GAINS classification formulated as follows:

> "The general strategy is to use fresh fuel, and send used fuel abroad for either recycling or disposal, or the back end strategy is undecided — the group has no plans to build, operate and manage used fuel recycling facilities or permanent geological disposal facilities for highly radioactive waste. They may obtain fabricated fuel from abroad and may arrange for export of their used fuel."

VIII.2.5. Key developments to enhance sustainability

There are different activities planned and executed in Armenia related to the country's sustainable development, as well as to ensuring an economically viable level of energy security and energy independence. One of the main directions is the continuous operation and development of the NES in different subject areas [VIII.11].

VIII.2.5.1. Economics

Official research studies show that in the economics area, electricity produced by NPPs is comparable in cost with that produced from renewable sources (solar photovoltaic systems, wind farms) and will remain so until at least 2036. Expert studies carried out in the framework of some scientific research efforts assume NPP electricity production at the level of average system cost up to 2085, after which nuclear will become a fully attractive option in the power system.

VIII.2.5.2. Safety

In the safety area, it is officially announced that the nuclear option in Armenia will always be compliant with the IAEA Safety Standards, requirements and recommendations in any time frame.

VIII.2.5.3. Resources

Armenia has no uranium resources and therefore plans to acquire natural uranium from international suppliers for the once-through nuclear fuel cycle.

VIII.2.5.4. Waste management

Armenia is planning to have at-reactor site storage of spent nuclear fuel throughout the planning period. Neither centralized long term storage nor final geological disposal of spent nuclear fuel are foreseen in the country.

VIII.2.5.5. Nuclear non-proliferation

Armenia will continue the improvement of legislation to successfully address any problem with proliferation resistance issues. It is planned that at the end of the first quarter of the century all relevant laws and sublegislation will meet international standards in all non-proliferation areas. It is assumed that after 2075, Armenia will continue its efforts to lower the attractiveness of nuclear materials and nuclear technologies in the interest of proliferation resistance.

VIII.2.5.6. Political support and public acceptance

The Armenian population is generally aware that a severe energy crisis in the early 1990s was overcome only owing to the restart of the second unit of ANPP. Therefore, nowadays, the Government and majority of the population have a positive attitude towards the nuclear option. Most probably this situation will remain unchanged throughout the century and the development of nuclear energy in Armenia will be continuously supported by the country's Government and population.

VIII.2.5.7. Informational support

In Armenia, all the important events related to the development of the country are being actively discussed with the population and related stakeholders. Communication with stakeholders on nuclear activities will be organized through public hearings, special meetings and conferences and by providing information on nuclear energy in popular forms through the mass media and so on. Possible communications with stakeholders on Generation IV nuclear systems are foreseen in the last third of the century.

VIII.2.5.8. Legal framework

One of the important directions of Government activities is the improvement of legislation in all aspects of nuclear energy development. It is obvious that country authorities will continuously work on the nuclear legislation base, regulations and other documentation important for the NES, including improvements on the legal framework for nuclear safety and for strengthening nuclear security and combating nuclear terrorism. These activities are foreseen for the entire century.

VIII.2.5.9. Facilities

Armenia has a research reactor and the assumption is that it will be in operation until 2100.

The described key development events for enhanced sustainability are graphically summarized in Fig. VIII.7 below.

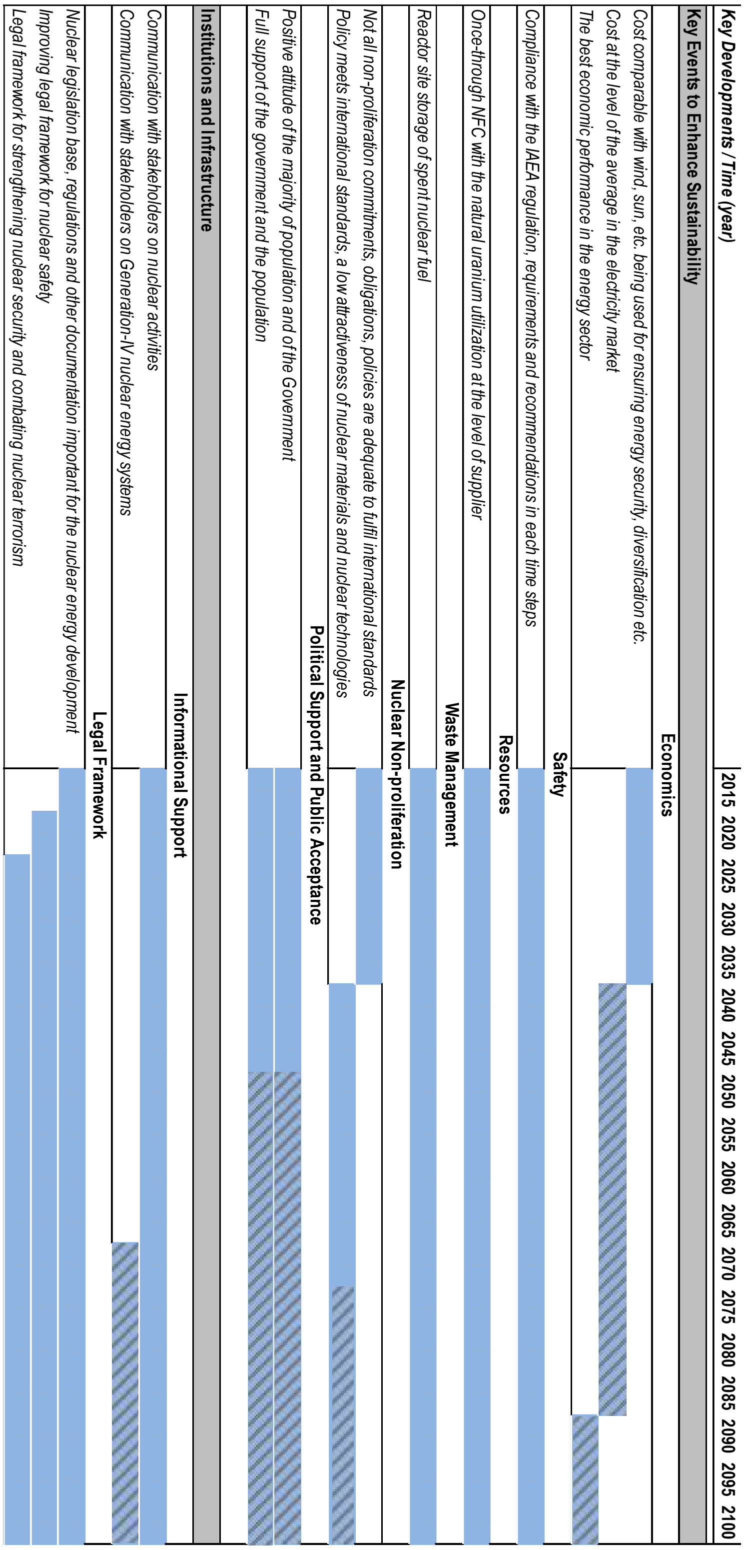


FIG. VIII.6. Key developments for Armenian NES (shaded areas indicate prospects).

VIII.2.6. Nuclear power planning and scenarios

VIII.2.6.1. Reactor fleet

In this section the numbers and types of anticipated nuclear reactors are presented. Figure VIII.8 presents the commissioning schedule and the capacities of the anticipated nuclear reactors.

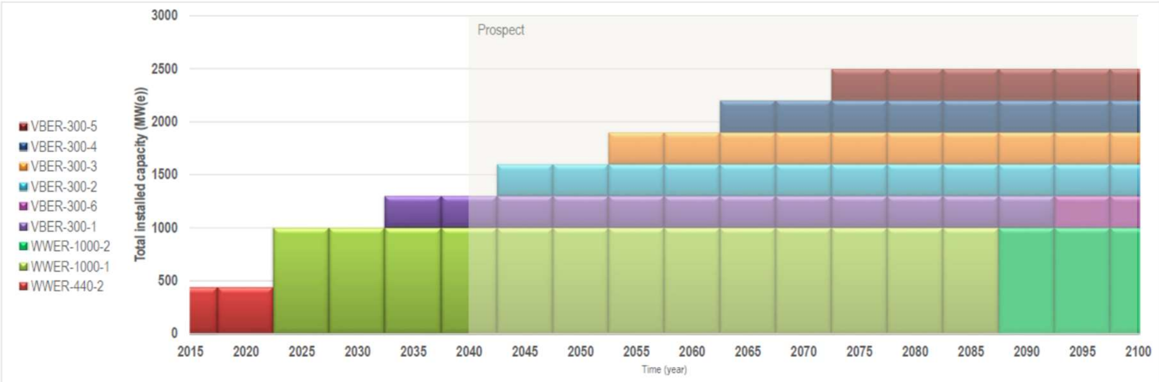


FIG. VIII.7. Installed capacities of nuclear reactors. This figure reflects the planning period of the officially approved programme (up to 2036). Data after 2036 are based on expert opinion.

VIII.2.6.2. Energy production

The defined reactor fleet will produce electricity in the amounts presented in Fig. VIII.9. For the WWER-440, the plant capacity factor is set to 0.82 and increased to 0.84 after extension of its lifetime. For the new power plants, the value of the plant capacity factor is assumed to be in the range of 0.88–0.9. The electricity produced will reach 2250 MW(e)·year in 2075, which will cover around 70% of requested demand. After that year, it will remain constant up to the end of the century.

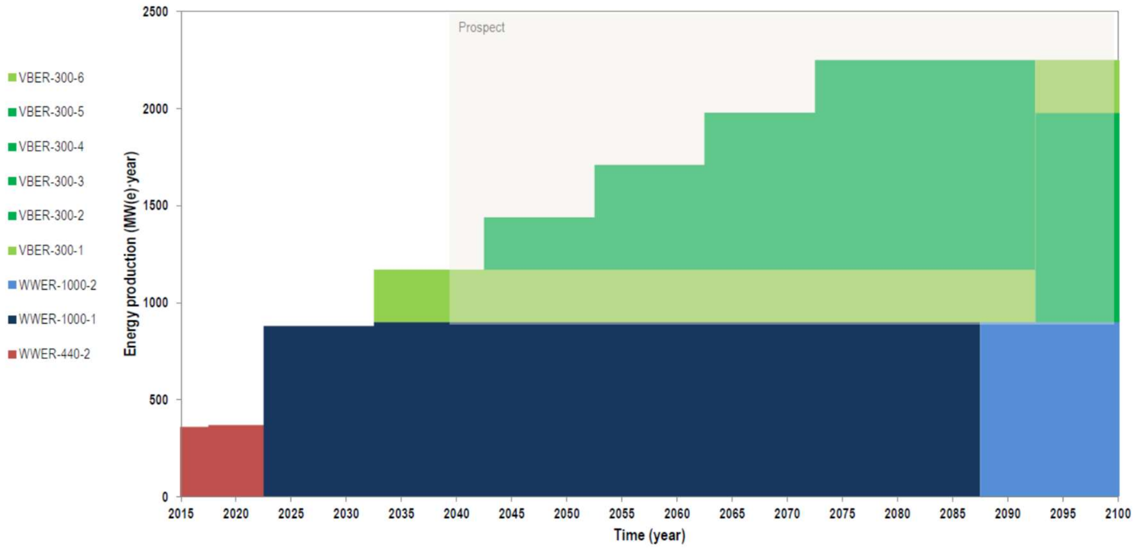


FIG. VIII.8. Electricity generation of nuclear reactors.

VIII.2.6.3. Uranium mining

To supply sufficient amounts of nuclear fuel to the above mentioned reactor fleet, around 450 t of uranium will be necessary in 2090 (Fig. VIII.10). The general assumption made for uranium mining and milling, conversion, enrichment and fuel fabrication is that the existing fuel supplier for WWER reactors will remain unchanged for all the uranium transformation processes, that a second supplier will be chosen for VBER reactors and that a third supplier should enter the market at the end of the century (after 2090). As a result, the amounts of the necessary uranium in each transformation step presented above will remain in the same proportion (shape) over the projected years.

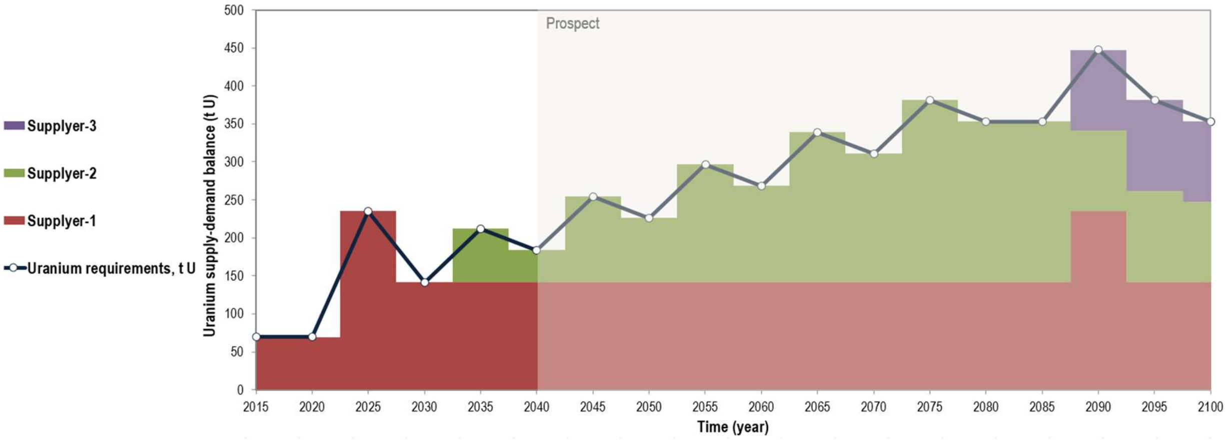


FIG. VIII.9. Uranium mining and milling requirements.

VIII.2.6.4. Conversion

It is assumed that the necessary amount of uranium for conversion will be the same as in the mining and milling process (Fig. VIII.11). For the existing WWER-440, the selected enrichment/conversion factor is 7.29 t U per t HM, while for all others it is assumed to be at the level of 8.51 t U per t HM.

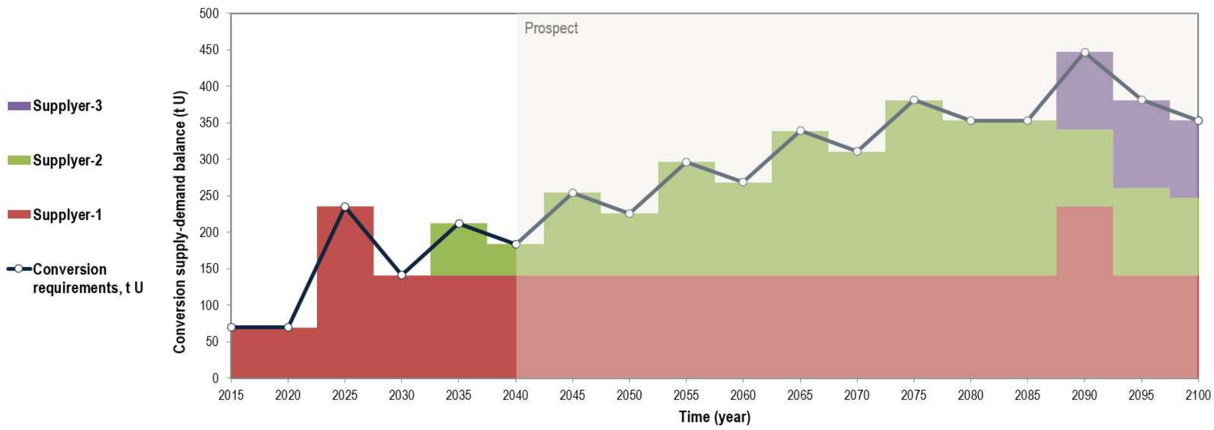


FIG. VIII.10. Uranium conversion requirements.

VIII.2.6.5. Enrichment

The requested enriched uranium amounts are presented in Fig. VIII.12. The maximum quantity will reach the level of 374 t SW in 2095. For the existing WWER-440, the selected enrichment/fuel fabrication factor is 5.80 t SW per t HM, while for all others it is assumed to be at the level of 7.11 t SW per t HM.

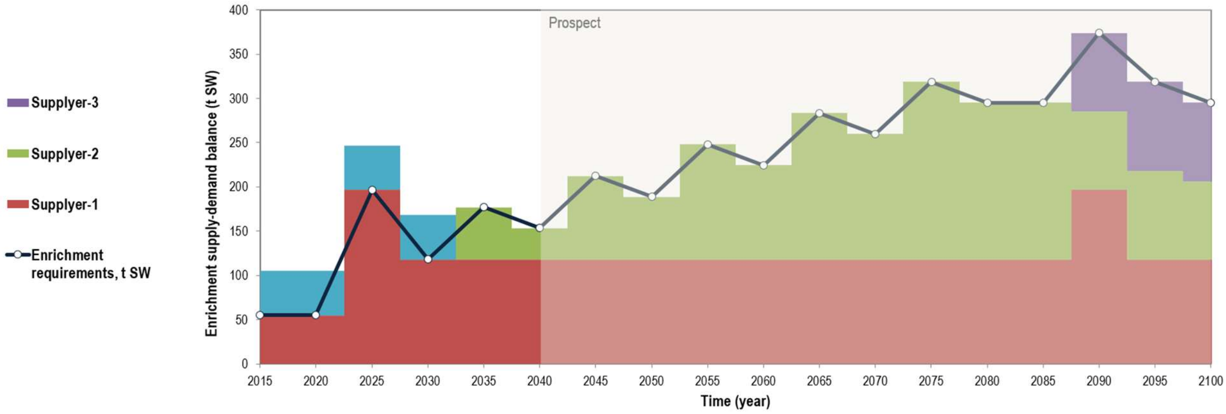


FIG. VIII.11. Uranium enrichment requirements.

VIII.2.6.6. Fuel fabrication

Fuel fabrication requirements are presented in Fig. VIII.13. The maximum amount will be around 55 t HM in 2095. For the existing WWER-440, the selected fuel fabrication/reactor fleet factor is 21.6 HM per GW, while for all others it is assumed to be at the level of 16.6 t HM per GW.

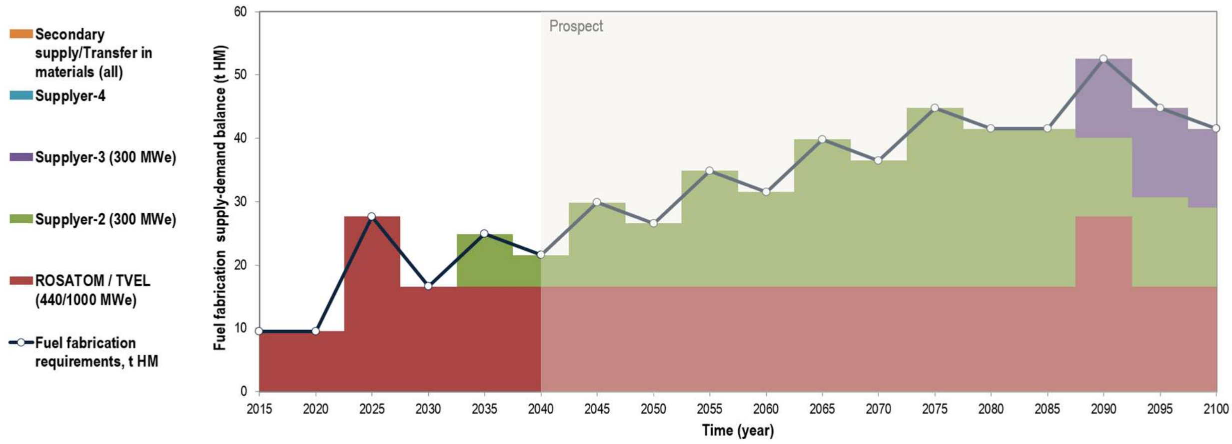


FIG. VIII.12. Fuel fabrication requirements.

VIII.2.6.7. Spent nuclear fuel storage and reprocessing

The spent nuclear fuel storage requirements are presented in Fig. VIII.14. At the end of the century, around 3100 t HM spent nuclear fuel storage capacity is foreseen. It is expected that amounts of spent nuclear fuel ranging from 44 to 134 t HM will be sent back to the fuel provider for reprocessing (Fig. VIII.15).

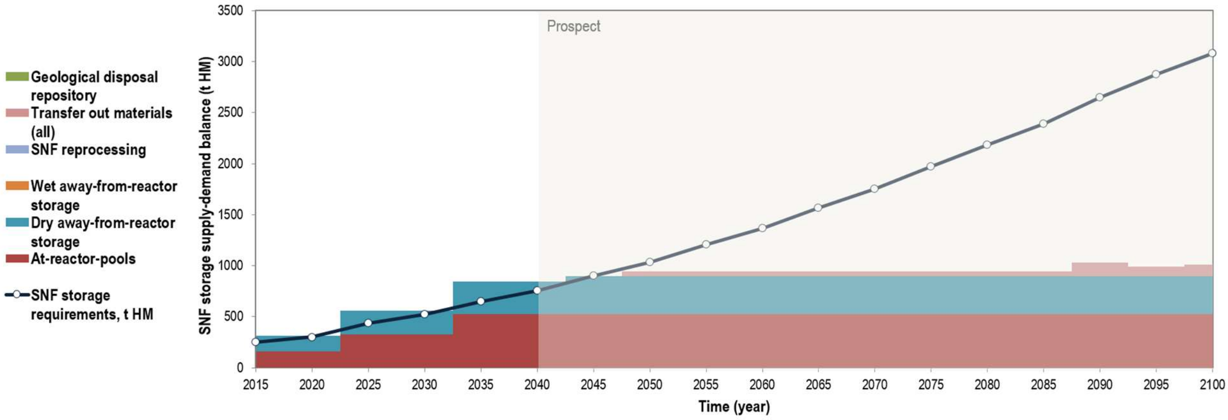


FIG. VIII.13. Spent nuclear fuel storage requirements. Legend: SNF — spent nuclear fuel.

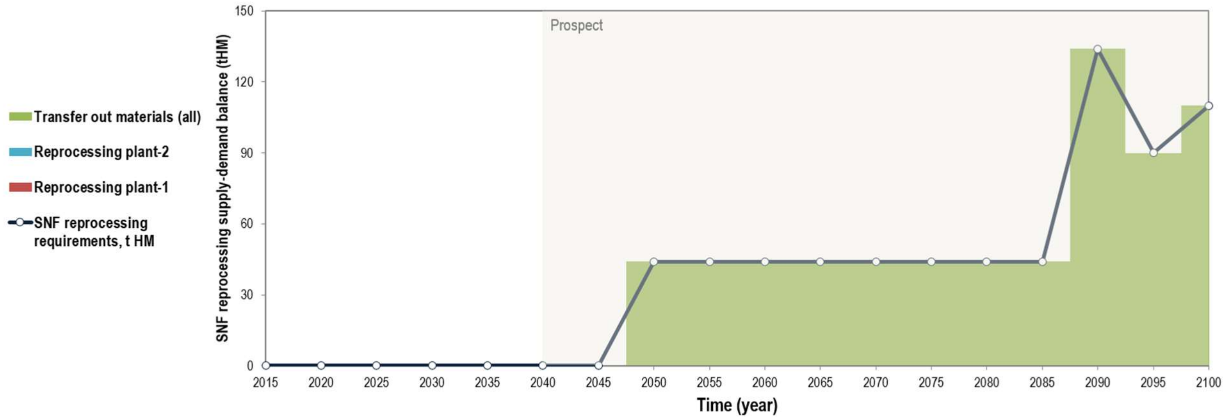


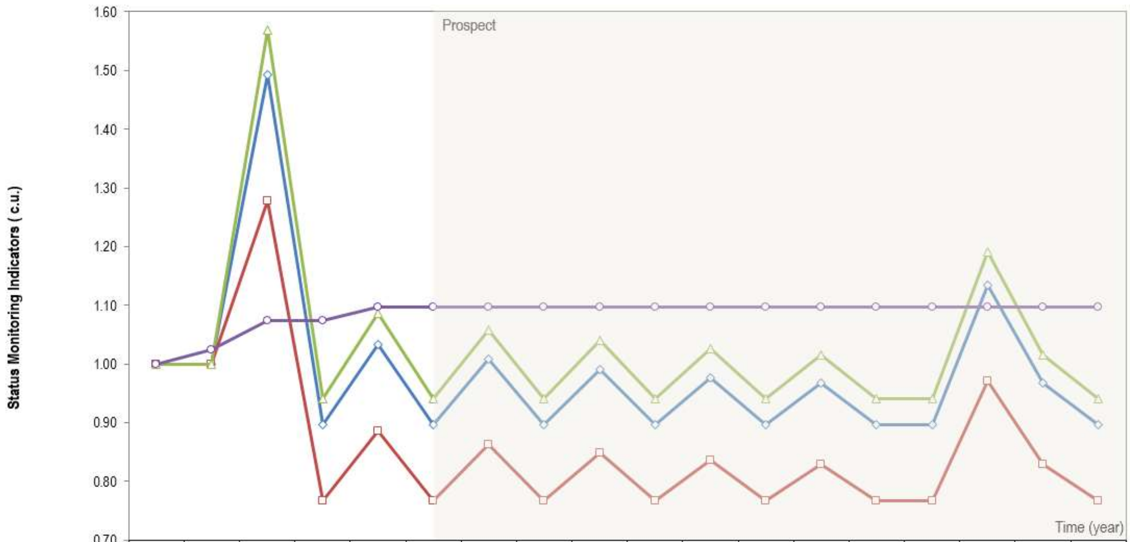
FIG. VIII.14. Spent nuclear fuel reprocessing requirements.

VIII.2.6.8. Geological disposal

No geological disposal is foreseen in Armenia in the current century.

VIII.2.7. Progress monitoring

Figure VIII.16 presents the status of the monitoring of selected key indicators such as energy production, enrichment utilization, geological waste production and uranium or thorium utilization, which are relative values of reactor fleet capacities and base year (2015) quantities. The stabilization of the energy production indicator after 2035 is the result of implementing more efficient reactors in the system. Three other indicators, namely enrichment utilization, geological waste production and uranium or thorium utilization, have the same shape and their numerical values illustrate improvements in most years over the base year numbers. Based on analyses of the graphs, it can be concluded that the considered development scenario results in better performance with regard to the utilization of natural resources (uranium) and can be proposed for deeper investigation in the future.



	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium/thorium utilization	1.00	1.00	1.49	0.90	1.03	0.90	1.01	0.90	0.99	0.90	0.98	0.90	0.97	0.90	0.90	1.13	0.97	0.90
Geologic waste production	1.00	1.00	1.28	0.77	0.89	0.77	0.86	0.77	0.85	0.77	0.84	0.77	0.83	0.77	0.77	0.97	0.83	0.77
Enrichment utilization	1.00	1.00	1.57	0.94	1.09	0.94	1.06	0.94	1.04	0.94	1.03	0.94	1.02	0.94	0.94	1.19	1.02	0.94
Energy Production	1.00	1.02	1.07	1.07	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10

FIG. VIII.15. Status of monitoring of selected key indicators.

VIII.2.8. Summary

The lack of domestic energy resources in Armenia dictates a need to find ways to guarantee the continuous and firm supply of electricity to consumers. In the context of country and regional conditions, only nuclear energy is foreseen as the main source of electricity production in Armenia that can cover growing future electricity demands in a sustainable manner.

Increasing the share of nuclear energy in the total electricity production mix will serve to ensure an adequate level of energy independence and energy security.

The existence of nuclear energy in Armenia is expected to be continuously supported by the country's Government and population throughout the century.

The development of the nuclear option in Armenia in the current century is foreseen through the life extension of the existing ANPP (WWER-440) until 2027, and by deployment of two WWER-1000 and six VBER-300 reactors.

The Armenian nuclear energy roadmap presents different targets in time steps for moving towards an NES with enhanced sustainability and identifies prospective collaboration areas for nuclear fuel cycle options with possible partner(s). It is assumed that cooperation will be established for new NPP construction, for fresh nuclear fuel supply and for returning some spent nuclear fuel amounts to the supplier for reprocessing.

Fresh nuclear fuel supply is expected to be obtained through one bilateral agreement until 2030, then by multiple bilateral agreements until 2050 and finally by both multilateral and multiple bilateral agreements up to the end of the century.

Only dry storage for spent nuclear fuel and a once-through nuclear fuel cycle is foreseen in this study. No geological disposal facility is expected to be constructed in Armenia in the current century.

Armenia is considered an NG3 type of country according to the GAINS classification. Based on analysing the monitoring status of selected key indicators such as energy production, enrichment utilization, geological waste production and uranium and thorium utilization, it can be concluded that the considered development scenario results in better performance on the utilization of natural resources (uranium) and can be proposed for deeper investigation in the future. The main findings of the case study are summarized in the condensed roadmap flow chart presented in Fig. VIII.17 below.

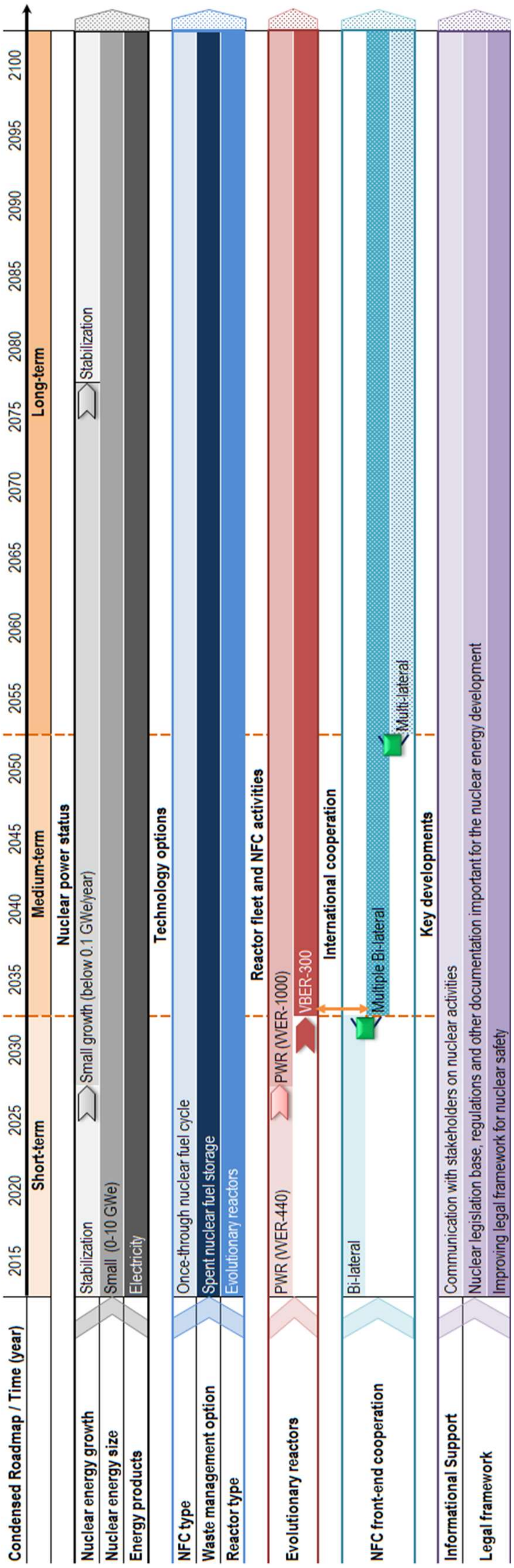


FIG. VIII.16. Condensed roadmap flow chart.

VIII.3. APPLICATION OF THE ROADMAP TEMPLATE TO THE NES OF BELARUS

VIII.3.1. General country information

VIII.3.1.1. Geography and climate

According to [VIII. 12], Republic of Belarus is situated in the East European Plain, in the central part of Europe. Belarus shares borders with Lithuania to the north-west, Latvia to the north, the Russian Federation to the north-east and east, Ukraine to the south and Poland to the west. The total area of the country is 207 600 km^2, making Belarus the thirteenth biggest country in Europe. The country is divided into six administrative territories: Brest, Vitebsk, Gomel, Grodno, Mogilev and Minsk, the capital of Belarus.

The average altitude is approximately 160 m above sea level. The landscape of the country is dominated by plains. The typical landscape consists of uplands, plains and lowlands interlaced with swamps and lakes. Lowlands occupy 70% of the country's territory.

The climate in Belarus is moderately continental, being influenced by the Atlantic Ocean. The average temperature in January ranges from −4 to −8°C, and in July from 17 to 19°C. The average annual precipitation is 550 to 650 mm in the lowlands and 650 to 750 mm in the plains and highlands.

There are over 10 800 lakes in Belarus, covering roughly 2000 km^2. The country has around 20 800 rivers and streams which flow to the Black Sea and to the Baltic Sea. The biggest rivers, which span more than 500 km, are the Dnieper, the Neman and the Western Dvina.

VIII.3.1.2. Population

From the end of World War II until the beginning of the 1990s, the total population of Belarus grew continuously. However, the growth rate started to decelerate in the early 1970s, and after 1993 the country entered the depopulation phase despite a migration surplus. Since 2013, this trend has reversed again. The population in 2014, 2015 and 2016 was higher than in 2010 and has increased by 0.18%. Information on the population of Belarus is presented in Table VIII.4.

TABLE VIII.3. POPULATION INFORMATION FOR BELARUS [VIII.13]

Year	1970	1980	1990	1995	2000	2005	2010	2015	2016
Population (millions)at the end of each year	8.992	9.663	10.190	10.177	9.957	9.630	9.481	9.498	9.505
Population density (inhabitants/km^2)	43	47	49	49	48	46	46	46	46
Urban population as percentage of total	43.3	54.9	65.4	66.1	69.7	71.8	75.1	77.3	77.6
Population employed in economy (millions)	4.321	4.959	5.151	4.410	4.444	4.414	4.703	4.496	—

VIII.3.1.3. Available energy

The information in this section is taken from Ref. [VIII.14].

(i) Fossil resources

Belarus is not rich in energy resources. Recoverable oil reserves are the most valuable energy resources of Belarus and consist of about 160 million tonnes. Until 1999, 102 million tonnes of oil and 10.5 billion m^3 of associated gas had been produced. Residual commercial oil reserves are about 55 million tonnes and associated gases are about 5.5 billion m^3. Undiscovered oil reserves are estimated at 190 million tonnes.

In addition to oil and peat, Belarus has brown coal (reserves estimated at 152 million tonnes) and oil shale (estimated at 11 billion tonnes). However, these energy resources have a low calorific value and are not currently being considered as fuel for the power system.

(j) Renewable sources

The theoretical hydropower potential of water resources in Belarus is 850 MW(e), of which about 300 MW(e) is considered economically and ecologically feasible to exploit at present.

Preliminary forecasts show the maximum potential of wind power plants to be about 2.8 billion kW·h per year. Solar installations have not yet been considered as sources of thermal energy, since they require too much space for their placement.

Among the RESs, wood has the greatest potential. The ecologically feasible potential for the use of wood from existing forests, including wood waste, as fuel, is estimated at 2.5–2.7 million toe per year.

VIII.3.1.4. The electricity system of Belarus

The balance of electrical energy in Belarus in recent years, including production by type of electrical sources, is shown in Table VIII.5 [VIII.15].

TABLE VIII.4. THE BALANCE OF ELECTRICAL ENERGY IN BELARUS

million kWh	**2010**	**2013**	**2014**	**2015**	**2016**	**2017**
Total production	34 890	31 495	34 737	34 232	33 572	34 515
Production by:						
Thermal power plants	34 844	31 349	34 605	34 073	33 331	33 924
Hydropower plants	45	138	121	111	142	405
Wind turbines	1	8	9	39	73	97
Solar installations	—	0.4	2	9	26	89
Import	2971	6716	3826	2816	3181	2733
Export	271	346	508	194	160	148
Consumption in Belarus including:	37 590	37 865	38 055	36 584	36 593	37 100
Commercial and public services	31 701	31 479	31 658	30 253	29 904	30 508
Residential	5889	6386	6397	6601	6689	6592

The Ministry of Energy of Belarus (Minenergo) develops and implements the state policy in the field of energy. It includes the State Electricity Production Association Belenergo, which is responsible for the reliable, secure, cost effective operation and innovative development of the production, transmission, distribution and sale of electricity and heat[2]. The centralized maintenance control of the Belarus grid system is implemented by the central dispatch unit of the Republican Unitary Enterprise of the Electric Power Industry.

VIII.3.1.5. Energy policy

As can be seen from the preceding information (Section VIII.3.1.3 and Table VIII.5), Belarus has a deficit in its own fuel and energy resources. The share of domestic resources in the national fuel and energy balance is about 18%. More than 80% of fuel and energy resources are imported, mainly from the Russian Federation. Natural gas is the dominant component of the national fuel and energy balance. The relative proportion of natural gas in the domestic electricity power industry has reached 95–96%. This factor significantly affects the energy security of Belarus.

The main directions of the development of the national fuel and energy sector are presented in the document Concept of Energy Security of Belarus, which was approved by the Ordinance of the President of Belarus in September 2007 [VIII.16] and updated in December of 2015 [VIII.17].

The implementation in 2007–2009 of the provisions of the concept resulted in the reconstruction and modernization of the three largest hydropower and thermal electrical power stations, and the construction of a number of small hydropower stations and of seven modular power plants fuelled with local fuels.

These activities, as well as the implementation of energy saving programmes, made it possible to save more than a million tonnes of coal equivalents per year during 2007–2009. In 2009, the use of RESs was 1.5% of the annual fuel consumption in the electrical energy sector. Emissions of GHGs were reduced by 1.7 million tonnes in 2006–2009.

Within the framework of implementation of the Kyoto Protocol, eight project proposals aimed at reducing emissions by the electrical energy facilities were developed.

The Concept of Energy Security of 2007 [VIII.16] also assumed the construction of a two unit NPP with a total electrical capacity of about 2000 MW(e) by 2020. The implementation of this began in 2008 based on the decision made by the Security Council of Belarus, this decision being confirmed in an updated document in 2015 [VIII.17].

The need to develop a nuclear power programme results from the following:

- Scarcity of available fuel and energy resources;
- A significant share of natural gas in the fuel and energy balance;
- High expenditures for the import of energy resources;
- Difficulties in creating considerable reserves of natural gas.

The Russian Federation project AES–2006 with Generation III+ advanced PWRs, characterized by enhanced safety features, was selected based on its compliance with stringent safety standards and IAEA recommendations.

Information regarding the infrastructure established and activities for the implementation of the nuclear programme in Belarus is presented in Table VIII.6.

TABLE VIII.5. INFRASTRUCTURE ESTABLISHED FOR THE IMPLEMENTATION OF THE NUCLEAR POWER PROGRAMME AND CONSTRUCTION OF THE PROJECTED NPP IN BELARUS

Date	Infrastructure element or activity	Notes

[2] Belenergo consists of six republican unitary regional power system enterprises (Oblenergo), the central dispatch unit and a multiplicity of electricity related businesses (construction, R&D, repair and maintenance etc.)

2007-11-12	The republican unitary enterprise Belarusian Nuclear Power Plant is founded for the implementation of functions of the construction, customer and operator (operating organization) for commissioning, operation, control performance, lifetime extension and decommissioning of the NPP in Belarus The Department of Nuclear and Radiation Safety of the Ministry for Emergency Situations of the Republic of Belarus is created for the implementation of activities under state supervision in the field of nuclear and radiation safety The state scientific institution Joint Institute for Power and Nuclear Research Sosny of the National Academy of Science of Belarus is founded as the organization for scientific support of works on the construction of the NPP	Ref. [VIII.18]
2008-09-10	The Department of Nuclear Energy of the Ministry of Energy of Belarus implements state policy in the field of nuclear energy development	Ref. [VIII. 19]
2008-07-15	In the framework of compliance with the Espoo Convention, the Ministry of Natural Resources and Environmental Protection of the Republic of Belarus sends advance notice of the intention to build an NPP in the territory of the Republic of Belarus to its neighbouring countries (Latvia, Lithuania, Poland, Russian Federation and Ukraine).	Notice was also sent to the Espoo Secretariat
2008-07-30	Adoption of the Law of the Republic of Belarus On the Use of Atomic Anergy	Parliament of the Republic of Belarus
2009-05-28	An agreement between the Government of the Russian Federation and the Government of Belarus on cooperation in the field of nuclear energy for peaceful purposes is signed	
2009-09-17	A preliminary report on the assessment of the environmental impact of the NPP in Belarus is sent to interested parties (Austria, Latvia, Lithuania, Poland, the Russian Federation and Ukraine)	
2010-07-14	A state ecological examination of the report on the assessment of the environmental impact of the NPP in Belarus carried out by the Ministry of Natural Resources and Environmental Protection is completed	After the completion of the public hearings and consultations, including with neighbouring countries
2011-03-15	An intergovernmental agreement with the Russian Federation on cooperation in NPP construction on the territory of Belarus is signed	
2011-07-12	The investment substantiation for the construction of an NPP in Belarus is approved	Ref. [VIII.20]

2011-09-15	A site for the NPP in the Ostrovets district of the Grodno region is selected	Ref [VIII.21]
2011-09-25	An intergovernmental agreement on the provision of state export credit for Belarus for the construction of an NPP is signed with the Government of the Russian Federation	
2012-05-31	The development of the ditch under the first power plant is begun	
2012-06-16–30	An IAEA mission conducts a comprehensive assessment of the nuclear power infrastructure of the country	The mission confirmed the readiness of Belarus to build an NPP
2012-07-18	The General contract for the construction of the NPP is signed	With the Government of Russian Federation
2012-08-09	The ceremony of laying a capsule with a message for future generations is held	With the participation of the President of the Republic of Belarus
2013-02-01	An intergovernmental agreement in the field of nuclear safety is signed with the Government of the Russian Federation	
2013-09-13	A licence is obtained for the construction of nuclear installation Unit 1 of the NPP in Belarus (in terms of the construction of foundations and basements of buildings and structures)	From the Ministry for Emergency Situations of the Republic of Belarus
2013-09-30	Adoption of the NPP in Belarus to consist of two units with an installed nominal capacity of 1194 MW(e) each	Ref. [VIII.22]
2013-11-02	Allowance for the general contractor to start construction of the NPP in Belarus is granted	Ref. [VIII.23]
2013-11-06	Works on pouring the concrete foundations for Unit 1 facilities are begun	
2014-02-14	A licence for the construction of a nuclear installation Unit 2 of the NPP in Belarus (in terms of the construction of foundations and basements of buildings and structures) is granted	From the Ministry for Emergency Situations of the Republic of Belarus
2014-04-22	A licence for the complete construction cycle of Unit 1 is granted	
2014-04-27	Start of the construction works on Unit 2	
2014-05-04	Start of the construction work for the training centre, equipped with full scale analytical simulators	The work was completed at the beginning of 2016
2014-08-21	Start of construction of the new NPP information centre in Ostrowietz	The work was completed in 2015
2014-08-29	The construction of the NPP in Belarus passes into the above ground stage	

2014-11-14	The equipment for the core melt catcher of Unit 1 is installed	
2014-12-30	A licence for the full construction of Unit 2 is granted	
2015-06-02	The Strategy for Radioactive Waste Management of the Belarusian Nuclear Power Plant is approved	Ref. [VIII.24]
2015-11-20	The installation of the core melt catcher equipment of Unit 2 is completed	
2015-12-31	A complex of buildings and structures of the fire station is put into operation	
2016-01-04	The training centre of the NPP in Belarus starts its work in test mode	
2016-06-09	A polar crane of the reactor building of the Unit 1 is successfully installed at the construction site of the NPP in Belarus	
2016-08-05	The upper stage of the dome of the inner containment shell of the reactor building of Unit 1 is successfully installed at the construction site of the NPP in Belarus	
2016-12-29	The reactor vessel for Unit 1 arrived at the construction site of the NPP in Belarus	
2017-01-17	The training of operational personnel on the full scale and analytical simulators of the unit control room of the training centre of the NPP in Belarus starts	
2017-03-15	The stator of the turbo generator of Unit 1 is installed at the construction site of the NPP in Belarus	
2017-04-01	The reactor vessel of Unit 1 was installed in project position	Before the installation, the vessel passed an entrance control meeting all regulatory requirements
2017-04-14	Four steam generators for Unit 1 are installed in the reactor building	
2017-09-07	The welding of the main circulation pipe of Unit 1 is completed	
2017-10-10	The dome of the internal containment shell of the reactor building of Unit 2 is installed	
2017-10-21	The reactor vessel for Unit 2 is delivered to the construction site of the NPP in Belarus	
2017-12-02	The reactor vessel for Unit 2 of the NPP in Belarus is installed in the design position	
2017-12-04	Transport gateway for Unit 1 delivered to the construction site of the NPP in Belarus	

2018-01-12	The installation of steam generators in the building of the reactor of Unit 2 is completed
2018-01-28	The hydraulic capacitances of the emergency core cooling system are mounted in the building of the reactor of Unit 2
2018-03-23	Closing of the cylinders and supports of the turbine of Unit 1 is completed
2018-06-07	Welding of Unit 2 main circulation pipeline is completed
2018-06-25	The ventilation pipe on Unit 1 is mounted
2018-10-26	Spillage systems in the open reactor of Unit 1 are completed
2018-11-11	The water supply from the river Vilia to the construction site is implemented
2018-12-05	Voltage is supplied to the 330 kV complete distribution gas insulated device from the first Postavy-1 external line
2018-12-29	The project construction of NPPs in the Republic of Belarus, Power Output and Grid Connection is implemented

Actual information on the development of nuclear power and NPP construction projects in Belarus is regularly posted on the web site of the republican unitary enterprise Belarusian Nuclear Power Plant**Error! Hyperlink reference not valid.**. The web site also offers a contact point for users to ask questions concerning the construction and operation of NPPs.

VIII.3.2. National decision on and vision for nuclear energy strategy

At present, the national nuclear power programme is limited to the construction and commissioning of two AES-2006 units with a total electric capacity of 2340 MW(e).

The construction of the NPP in Belarus is being implemented within a framework of international cooperation with the Russian Federation, based on the intergovernmental agreements described below. “The agreement between the Government of the Republic of Belarus and the Government of the Russian Federation on cooperation in the field of use of atomic energy in the peace purposes” from 28 May 2009 entered into force on November 16 2009. [VIII.25] The agreement was concluded with a view to developing and strengthening cooperation in the field of the peaceful use of atomic energy. Within the framework of this agreement, cooperation is carried out in various areas, including:

— The development, design, construction, operation and decommissioning of NPPs;
— The supply of nuclear fuel for NPPs;
— The handling of irradiated nuclear fuel and radioactive waste;
— Nuclear and radiation safety;
— The production of radioisotopes and their use in industry, medicine and agriculture;

- The training of specialists in the use of nuclear energy for peaceful purposes and personnel in the operation of NPPs.

The agreement between the government of the Republic of Belarus and government of the Russian Federation “About cooperation in construction in the territory of the Republic of Belarus nuclear power plant” from March 15 2011 [VIII.26] was ratified on November 25 2011. This agreement provides for cooperation in the design, construction and commissioning (on a turnkey basis) of units of an NPP on the territory of the Republic of Belarus.

Atomstroyexport (Russian Federation) is the general contractor for the construction of the NPP on the territory of Belarus, and the Republican Unitary Enterprise Belarusian Nuclear Power Plant (Belarus) is the customer.

The agreement defines the obligations of the parties and its provisions were the basis for the preparation of the general contract for the construction of the NPP in Belarus. On July 18 2012, the general contract for the construction of the NPP was signed.

The agreement between the Government of the Republic of Belarus and the Government of the Russian Federation on Granting to the Government of the Republic of Belarus of a State Export Credit for the Construction of a Nuclear Power Plant on the Territory of the Republic of Belarus of November 25 2011 entered into force on January 18 2012 [VIII.27].

In accordance with this agreement, the Russian Federation gives Belarus a loan of up to US $10 billion to finance 90% of the cost of the contract for the construction of the NPP.

The Agreement between the Government of the Russian Federation and Government of the Republic of Belarus from 01 February 2013 “About cooperation in the field of nuclear safety” entered into force on June 18 2013 [VIII.28].

This agreement was concluded for the development and expansion of cooperation under the Russian Federation project in order to improve the nuclear safety infrastructure of Belarus in connection with the construction of the first NPP on the territory of the country and to thereby achieve a sustainably higher level of nuclear safety, to create and maintain effective means of protection against potential radiation hazards at the nuclear power facilities of Belarus, and to use Russian Federation experience in developing emergency preparedness and response systems for emergency situations at NPPs.

The agreement provides for various areas of cooperation, including the improvement of the nuclear safety infrastructure, safety regulatory systems, the development and improvement of the regulatory framework in the field of nuclear safety, taking into account IAEA safety requirements, the development of a system of crisis centres in Belarus, and the training of specialists in nuclear safety and other aspects.

In addition to agreements with the Russian Federation, there is also an agreement with the Republic of Armenia as presented below.

The Agreement between the Government of the Republic of Belarus and the Government of the Republic of Armenia on Cooperation in the Field of Peaceful Uses of Nuclear Energy [VIII.29] was signed in Yerevan on 12 December 2016 and ratified by the National Assembly of the Republic of Belarus.

The agreement provides for the development of bilateral cooperation in:

- Ensuring the safety of NPPs;
- The development and improvement of systems for diagnostics and control of the main equipment of NPPs, the operation support system and the system for eliminating accidents at NPPs;
- Development, design, construction and operation of NPPs, research reactors and other nuclear installations on the territory of Belarus and Armenia;
- The storage and processing of radioactive waste;
- Accounting and control of nuclear materials;

- The physical protection of nuclear power facilities and facilities for storing spent radioactive sources;
- Training both for specialists in the peaceful use of nuclear energy and for NPP operational personnel in the universities and training centres of Belarus and Armenia according to the agreed programmes.

Thus, the further development of the national nuclear programme is taking place within the framework of international cooperation and is aimed at improving the nuclear energy infrastructure and all its aspects for the sustainable development of both the national energy system and the NES.

There are no official decisions on the further construction of NPPs in the country. The most probable scenario is that experts from the Joint Institute for Power and Nuclear Research Sosny recommend the introduction of similar nuclear units after decommissioning the units currently under construction.

The further development of the nuclear programme with the construction of new nuclear power facilities will largely depend on several factors related to the future operational experience of the first NPP in Belarus, which are:

- The justification of the expectations of the safe and reliable operation of the NPP;
- The integration of NPPs, ensuring the necessary balanced and sustainable operation of the entire energy system of the country;
- The obtaining of acceptable economic characteristics of electricity generation both for NPPs and in the energy system as a whole;
- The solution of the problem of radioactive waste, both operational and spent nuclear fuel and highly active products of its processing.

The success of the first NPP operation would also be important for the positive opinion and attitude of the public towards nuclear energy, without which further development of the nuclear programme can become problematic.

VIII.3.3. Purpose of the roadmap

The aim of the case study of Belarus within the framework of the ROADMAPS collaborative project is to provide information on the general situation in the energy supply field and about the planned NES. This kind of information on a national level is necessary to support analyses of the global NES in terms of its sustainable development.

VIII.3.4. Metrics on nuclear energy position and development

Studies conducted at the national level in 2009 showed the economic attractiveness of the introduction of nuclear power to the energy system of Belarus [VIII.30]. Later economic results, considering the updated initial data in accordance with the AES-2006 project, confirmed these conclusions [VIII.31]. Public opinion towards nuclear energy introduction in Belarus is generally positive, as can be seen from the results of a survey [VIII.32] presented in Table VIII.7.

TABLE VIII.6. PUBLIC OPINION ON NUCLEAR ENERGY [VIII.32]

Should Belarus have and develop nuclear power?	2005	2006	2008	2010	2011	2012	2013	2014	2015	2016	2017
Yes (%)	28.3	28.8	54.8	57.0	59.4	53.5	47.6	49.8	47.8	49.8	50.0
No (%)	46.7	41.8	23.0	19.6	24.7	21.1	18.8	19.7	19.4	20.2	22.0
Difficult to say (%)	25.0	28.6	21.8	22.5	15.8	25.2	33.3	30.3	32.4	29.0	27.8
No answer (%)	—	0.8	0.4	0.9	0.1	0.2	0.3	0.2	0.3	1.0	0.3

Both units of the NPP in Belarus have been constructed. The first unit has obtained a license for commercial operation on 2 June 2021, and the second one is scheduled to be commissioned in 2022. However, in the calculations carried out within the framework of the ROADMAPS collaborative project, the first year of commercial operation of the first unit was assumed to be 2020, and of the second unit 2021.

Fuel supplies for both units are expected to be provided by Rosatom (Russian Federation), the contract for the supply of fuel being in the preparation stage.

The strategy for handling operational waste from an NPP in Belarus was officially adopted in 2015, the strategy for spent fuel management being under development. All activities related to the final stage of the fuel cycle, including the management of spent fuel and HLW from its processing, are planned to be carried out in close cooperation with Rosatom.

Although Belarus is a newcomer to nuclear power technology, the country has experience in operating a nuclear research reactor and critical and subcritical assemblies and experience in handling nuclear fuel and associated radioactive waste. The main indicators summarizing the current state of the nuclear programme in Belarus and the performance in construction and operation are shown in Fig. VIII.18.

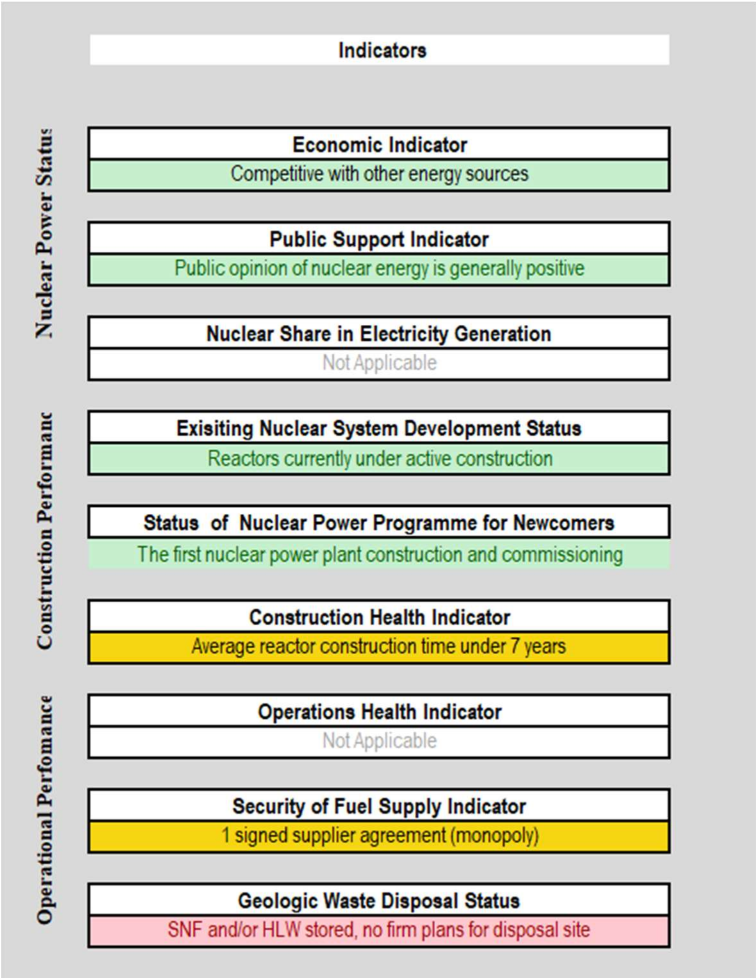


FIG. VIII.17. Signal indicators for the national nuclear programme.

Figure VIII.19 shows the proposed technology options that will be used in the development of the nuclear programme. At the present time, certain decisions to deal with the spent nuclear fuel and HLW from its processing have not been taken.

National Technology Options

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle		☑	☑	
Recycle of SNF with only physical processing				
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				✓

☑ official plan ✓ prospect

Access to Technology Options Abroad

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle				
Recycle of SNF with only physical processing				
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				✓

☑ official plan ✓ prospect

FIG. VIII.18. Technology options of the nuclear programme.

International cooperation will be carried out on a bilateral basis with the Russian Federation, as shown in Fig. VIII.20.

Collaboration Strategy

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Participate in information exchange activities	☑			
Joint R&D programs		✓	✓	✓
Sharing of R&D facilities				
Collaboration on NFC front end				
NPP selling				
NPP purchasing	☑			✓
Offer NPP operations services				
Use NPP operations services		☑	☑	✓
Offer NPP refuelling outage services				
Use NPP refuelling outage services		☑	☑	✓
Collaboration on NFC international centres		✓	✓	✓
Share an NPP with another country				
Offer NFC back end services				
Use NFC back end services			☑	✓
Offer NFC full services				
Use NFC full services			☑	✓

☑ official plan ✓ prospect

FIG. VIII.19. Collaboration with other countries.

VIII.3.5. Key developments to enhance sustainability

The introduction of nuclear power in Belarus will significantly increase the country's energy security by diversifying the types of primary fuel used to generate electricity. Based on the expected project load factor, the NPP in Belarus will be able to cover more than 40% of electricity demand.

Despite the high capital costs for the construction of NPPs, the low cost of nuclear fuel will make it possible that the cost of electricity from NPPs will be at least at the level of power stations using natural gas. However, most likely this will be possible after the payment of the loan funds provided by the Russian Federation for the construction of the first NPP. In the longer term, due to the inevitable steeper rise in gas prices in comparison with nuclear fuel, the cost of nuclear power will be lower.

Ensuring the safe operation of the NPP in Belarus is the highest priority of the country's nuclear programme. The reactor and the entire AES-2006 project meet all modern safety requirements through a combination of active and passive safety systems. A detailed analysis of the AES-2006 safety properties using the INPRO methodology can be found in Ref. [VIII.31]. The AES-2006 project meets most of the INPRO methodology requirements.

Belarus does not plan to develop a complete nuclear fuel cycle in the country. The front end and back end services of the nuclear fuel cycle are planned to be purchased from the Russian Federation. The spent fuel pool capacity of the AES-2006 reactors allows spent fuel storage at least until 2035, after which the export of spent fuel to the Russian Federation is required.

There is a sufficiently developed infrastructure in Belarus for the implementation of the nuclear programme. The main infrastructure elements are described below.

The regulatory body in the field of nuclear energy is the Ministry of Emergency Situations of the Republic of Belarus. The Department of Nuclear and Radiation Safety of the Ministry of Emergency Situations of the Republic of Belarus carries out practical activities on licensing and supervising the nuclear power programme development. Detailed information about the System of Normative and Legal Regulation of Nuclear and Radiation Safety can be found on the Ministry web site [VIII.33].

The legislative base ensuring the nuclear power programme development includes:

- Normative acts of the President;
- Laws;
- Resolutions of the Council of Ministers;
- Resolutions of the Ministry for Emergency Situations;
- Technical legal acts, norms and rules for ensuring nuclear and radiation safety;
- Guidance documents and methodological instructions.

Accomplished or planned key events in the nuclear programme aimed at the sustainable development of the country's NES are presented in Fig. VIII.21.

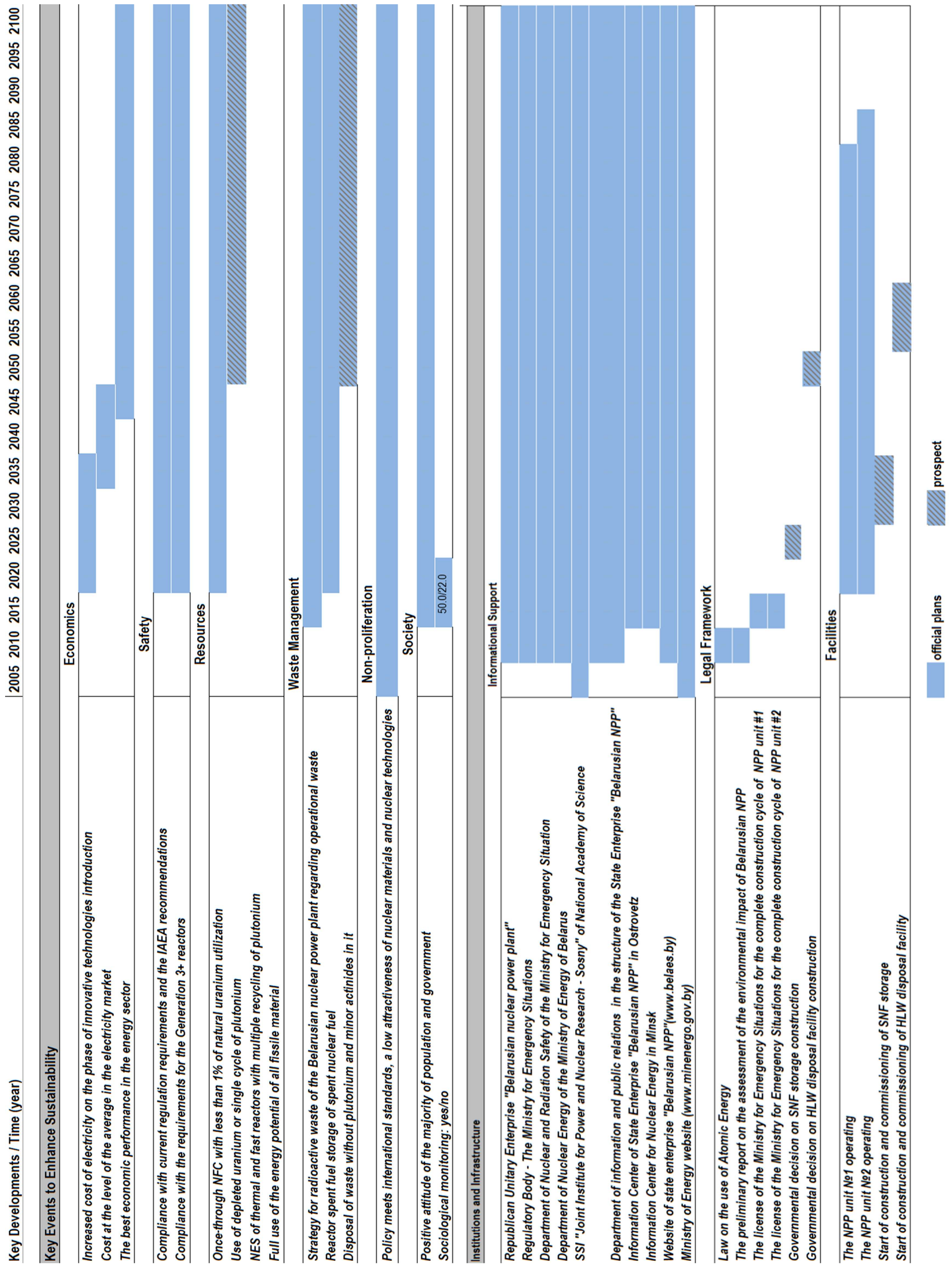


FIG. VIII.20. Key developments for the NES of Belarus (shaded areas indicate prospects).

VIII.3.6. Nuclear power planning and scenarios

As mentioned above, the reactor fleet of Belarus will consist of two PWR units with an electrical capacity of about 1200 MW(e) each. The initial data for calculating the characteristics of the nuclear fuel cycle are taken from Ref. [VIII.34] (see Table VIII.8).

TABLE VIII.7. REACTOR AND NUCLEAR FUEL CYCLE DATA

Parameter	Value
Electric capacity of unit (MW(e))	1200
Thermal capacity of unit (MW)	3200
Annual electricity generation (GW/year)	1.075
Number of fuel assemblies	163
Number of fuel assemblies discharged per fuelling outage	42
The amount of heavy metal in the assembly (t HM)	0.47
Conversion losses (%)	0.5
Average uranium enrichment in loaded fuel (%)	4.79
Uranium content in tails (%)	0.3
Fuel fabrication losses (%)	1.0
Average fuel burnup (GWd/t U)	55.5

The annual electricity generation corresponds to the load factor of the AES-2006 project, equal to 0.9.

It was assumed that all reactors in the considered timeframe operate in the once-through nuclear fuel cycle. The material balance was calculated using the Nuclear Fuel Cost Calculator [VIII.35].

The ROADMAPS-ET worksheets ‘Energy production’, ‘Uranium mining and milling’, ‘Conversion’, ‘Enrichment’ and ‘Fuel fabrication’ show the mean values for the corresponding five year periods. The worksheet ‘Spent fuel storage’ shows the cumulative results of the calculations for the five year periods.

The reactor fleet of Belarus is shown in Fig. VIII.22. The construction of Units 3 and 4, which are likely to be models similar to the WWER-1200 after the end of the lifetime of Units 1 and 2 is the expert’s assumption. There are no official decisions on this matter.

Every year, the NPP in Belarus will consume about 39.5 tonnes of fresh fuel (in units of heavy metal, HM). The total quantity of fresh fuel including the first cores will be 3405 tonnes by 2100.

Each unit of the NPP in Belarus needs 219 tonnes of natural uranium per year. The total demand for the NES of Belarus taking in the account the first cores will amount to 38 184 tonnes of natural uranium by the year 2100. Figure VIII.23 shows the yearly average demand and supply of natural uranium.

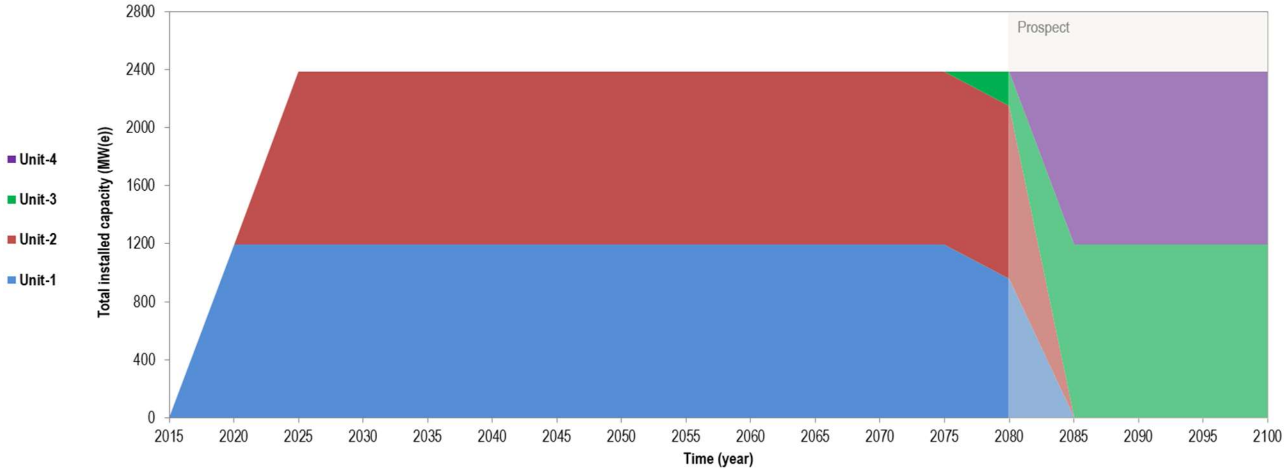


FIG. VIII.21. The reactor fleet of Belarus.

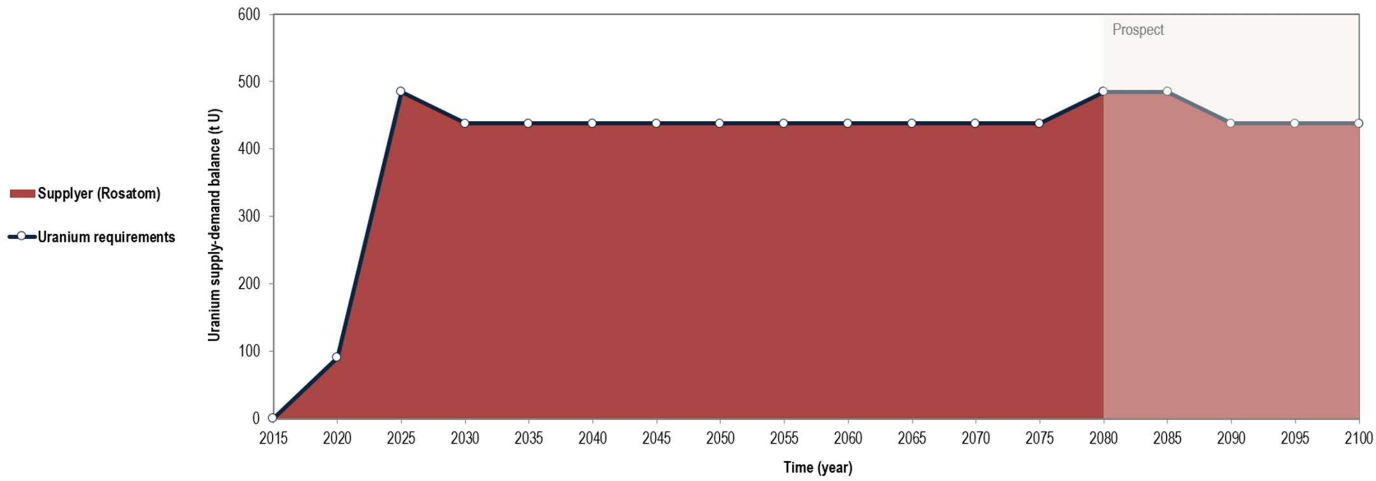


FIG. VIII.22. Annual demand and supply for natural uranium.

The number of units of separative work for enrichment is equal to about 271 tonnes per year for two units; the cumulative requirements by 2100 are 22 152 SWU. The annual demand and supply for enrichment services are shown in Fig. VIII.24.

Starting from 2036, the export of spent nuclear fuel becomes necessary with the amount of about 191 t HM being annually foreseen.

The results of the spent nuclear fuel amount calculation are cumulative for the entire timeframe from the beginning of the operation of the NPP. The spent nuclear fuel removal from the reactor pools and its export to the Russian Federation starts in 2036. At that time, there would still be space for unloading the entire reactor core of each unit into the pools.

As mentioned earlier, the strategy for handling spent nuclear fuel is under development. Now it is clear only that the stage of its processing will be in the Russian Federation. The handling of HLW will be the subject of an agreement between Belarus and the Russian Federation.

Figure VIII.25 shows the annual demand and supply of fresh fuel, with the previous mentioned assumption regarding the introduction of Units 3 and 4.

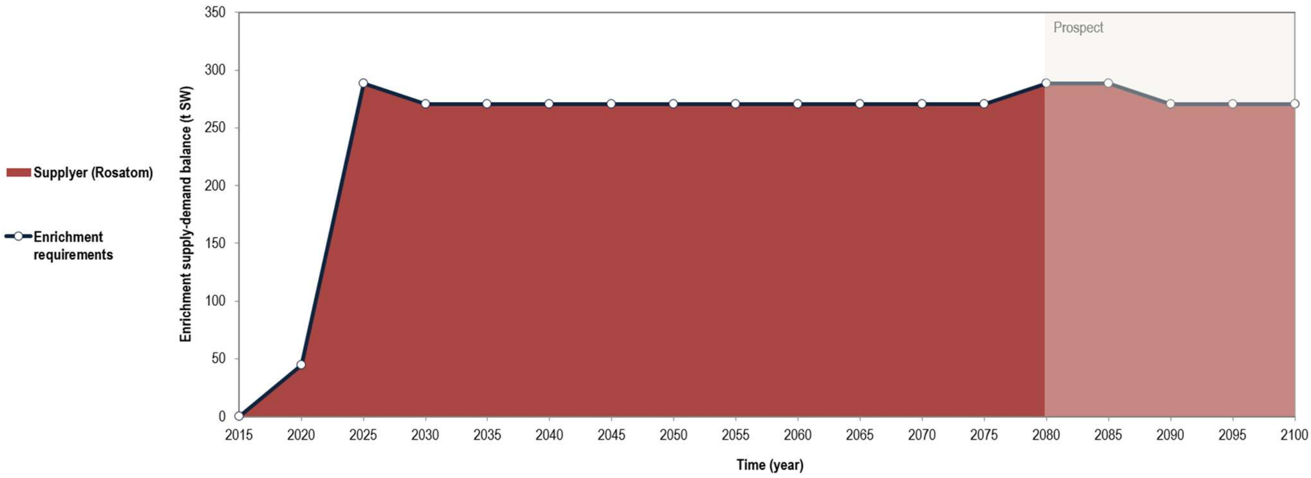


FIG. VIII.23. Annual demand and supply for enrichment services.

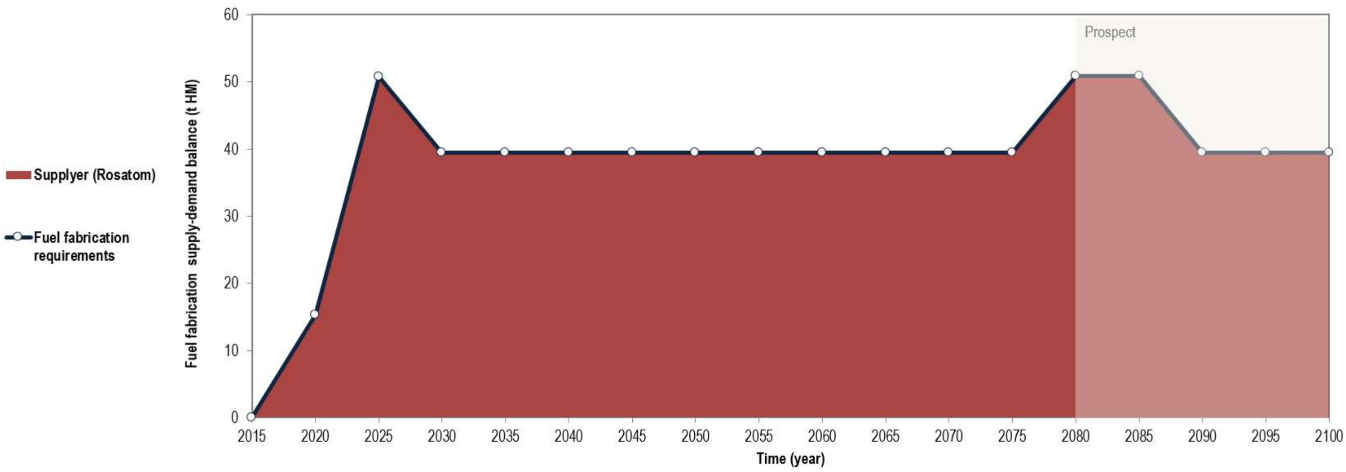


FIG. VIII.24. Annual demand and supply for fresh fuel.

The spent nuclear fuel pool capacity of each WWER-1200 unit is 756 cells. However, 163 cells are needed for unloading the entire reactor core when necessary. Another 42 cells are needed to accommodate fresh fuel in the process of refuelling. Finally, 24 cells are needed for defective fuel assemblies. Thus, 527 cells remain for storage of spent nuclear fuel in the reactor pool. Under such conditions, the volume of spent nuclear fuel storage facilities and the need for storage services in two WWER-1200 units are calculated and shown in Fig. VIII.26. As can be seen from the figure, spent nuclear fuel export is required owing to the exhaustion of at-reactor storage capacities from 2035.

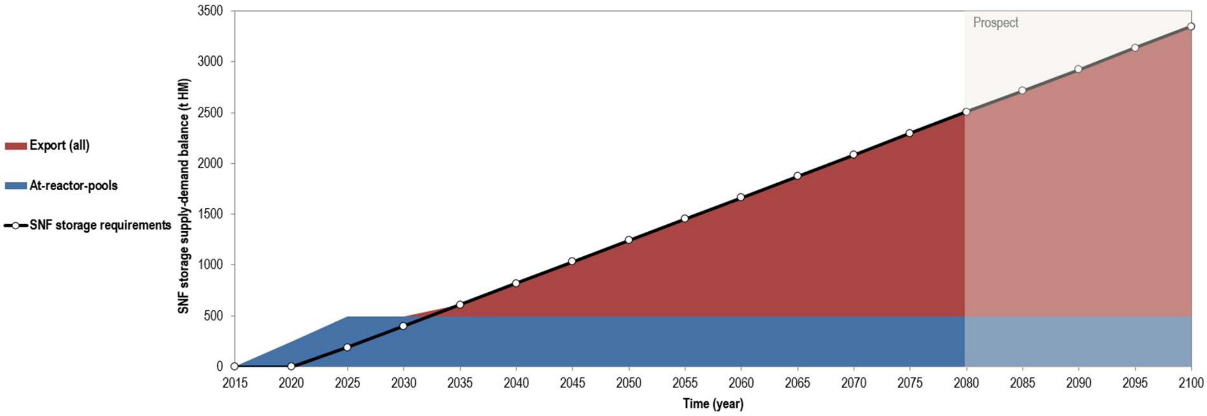


FIG. VIII.25. Spent nuclear fuel storage facilities in Belarus and the need for storage services.

A condensed roadmap of the NES development in Belarus is shown in Fig. VIII.27.

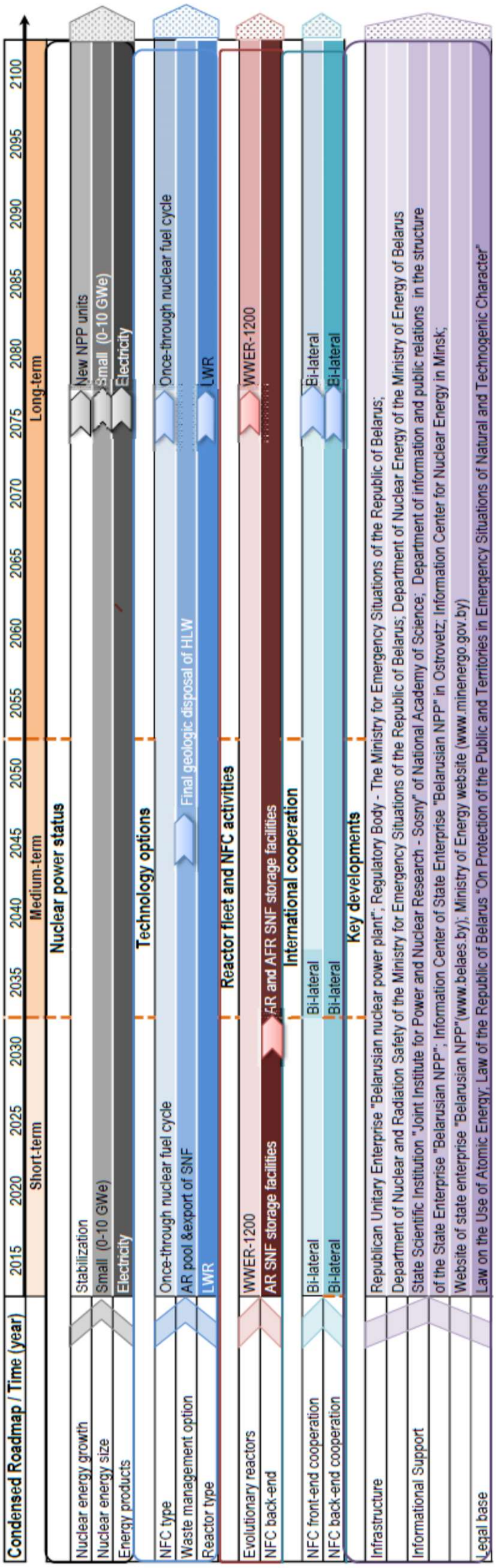


FIG. VIII.26. Condensed roadmap of the NES development in Belarus. Legend: SNF — spent nuclear fuel.

VIII.3.7. Summary

The development of the national nuclear programme of Belarus is summarized in Fig. VIII.27. This figure presents briefly the most basic aspects of the development of the nuclear power programme of Belarus in the short, medium and long term perspectives. As can be seen from Fig. VIII.27, the nuclear power programme is characterized in its development by the following features:

- Stabilization of installed nuclear generating capacity at 2.4 GW(e).
- The most likely technological option before the end of the century will be a once-through fuel cycle with water cooled thermal reactors. In the second half of the century, it is possible, according to expert opinion, that there will be geological disposal of the highly active products of reprocessing spent nuclear fuel in the territory of Belarus.
- The main type of international cooperation will be the bilateral cooperation with the Russian Federation.
- Belarus has a sufficiently developed organizational structure (the republican unitary enterprise Belarusian Nuclear Power Plant; Department of Nuclear Energy of the Ministry of Energy of Belarus, Ministry for Emergency Situations of the Republic of Belarus; Department of Nuclear and Radiation Safety of the Ministry for Emergency Situations of the Republic of Belarus) and legislative base (the main laws being the Law on the use of Atomic Energy; and the Law of the Republic of Belarus On Protection of the Public and Territories in Emergency Situations of Natural and Technogenic Character).

VIII.4. APPLICATION OF THE ROADMAP TEMPLATE TO THE NES OF ROMANIA

VIII.4.1. General country information

Romania is situated in south-eastern Central Europe and is the 12th largest country in Europe, with an area of 238 391 km^2. Its natural landscape is characterized by a concentric display of the major relief levels, proportionally combining the Carpathian Mountains, hills and plateaus, plains and meadows, and the Danube Delta natural reservation (the youngest relief unit under permanent formation). Romania benefits from a diversity of primary energy resources (both fossil and mineral): oil, natural gas, coal and natural uranium, and has an important and valuable potential of RESs.

Romania became a member of the European Union in 2007. According to official estimates for 2016 [VIII.36–VIII.39], Romania has a population of 19.8 million inhabitants; the national GDP is US $187 billion, with a GDP of US $9500 USD per capita, and a value of 55 for the living standard given in GDP per capita in purchasing power standard, which addresses the price of a range of goods and services in each country relative to income [VIII.37].

Two of the major concerns and challenges for Romanian society are (a) the need to increase energy supply security at an affordable cost and (b) the need to deal with climate change. These major challenges have also been considered in European Union energy policy with respect to assuring energy security based on competitive and ‘clean’ energy, while taking into account the mitigation of climate change, the escalation of global energy demand and the uncertainties of future access to energy sources.

Romania is the European Union Member State with the lowest energy imports per capita; in 2015, the net imports represented 16% of primary energy consumption. The Romanian Government has a considerable involvement in the energy sector as a regulator, law maker and implementer of energy policies, and as an owner of capacities for energy production, transport and distribution. For economic, social and national security reasons, the Government will maintain its majority position in companies with natural monopolies in natural gas and energy transport, as well as in companies involved in the nuclear fuel cycle.

The Eurostat data for 2016 reveal that the final cost of electricity in Romania was well below the European average level. Thus, in 2015 Romania had the sixth lowest electricity average cost in the European Union for household consumers (132 €/MWh), after Bulgaria (96 €/MWh), Lithuania, the Czech Republic, Estonia and Croatia (131 €/MWh). For industrial consumers, Romania had the third lowest electricity cost (80 €/MWh), after Bulgaria and the Czech Republic (78 €/MWh).

The Romanian national energy mix is diverse and equilibrated, based mostly on domestic primary energy resource utilization, and including energy production capacities using fossil fuels (coal and natural gas), nuclear power and RESs (hydro, wind, solar and biomass).

Figures VIII.28– VIII.31 give structured information on energy supply and demand, and electricity supply and emissions, according to official monitoring reports available on the Romanian Energy Regulatory Authority web site [VIII.40] and the data provided by Romanian authorities for European Union [VIII.41] and IEA statistics for 2016.

Total Primary Energy Supply, Mtoe	26.37
Coal	4.45
Oil	4.28
Natural gas	8.77
Nuclear	3.01
Hydro	1.62
Renewables	0.7
Energy imports	0.24
Energy exports	0.86
Energy supply per capita, toe/c	1.3
Energy supply per unit GDP, toe/10^3 USD	0.1

FIG. VIII.27. Total primary energy supply in Romania [VIII.41, VIII.42].

Energy Demand by Sector, Mtoe	
Industry	6.47
Transportation	5.47
Agriculture	0.42
Commercial & public services	1.77
Residential	7.4
Non-energy use and other	0.18

FIG. VIII.28. Energy demand by sector in Romania [VIII.40, VIII.41].

Total Electricity Supply, TWh	65.68
Coal	17.76
Oil	0.49
Natural Gas	8.15
Nuclear	11.68
Hydro	19.28
Renewables	8.32
Imports	2.81
Export	9.94
Electricity supply per capita, MW·h/c	3.3
Electricity supply per unit GDP, kW·h/USD	0.4

FIG. VIII.29. Total electricity supply in Romania [VIII.40, VIII.41].

CO_2 Emissions, Mt	74
Industry	47.7
Transport	15.4
Non-energy use	0.7
Others	10.2
CO_2 emissions per capita, t/c	3.7
CO_2 emissions per unit GDP, t/10^3 USD	0.4

FIG. VIII.30. CO_2 emissions in Romania [VIII.40, VIII.41].

About 50% of the total amount of CO_2 emissions and of the CO_2 emissions reported for the industry sector are due to fuel combustion.

In 2016, according to official monitoring reports of the Romanian Energy Regulatory Authority web site [VIII.40], the structure of electricity generation by primary energy sources was the following: 29% hydro, 25% coal, 18% nuclear, 15% natural gas, 10% wind, 2% photovoltaic and 1% biomass. About 42% of the national energy mix was from RESs, 60% being without GHG emissions and 75% with low emissions of CO_2 [VIII.40]. The CO_2 emission intensity per unit of produced electricity was 300 g CO_2/kW·h, which is close to the average European level.

About 30% of the installed capacities for electricity generation have already exceeded their useful technical life and would ideally be replaced or upgraded. Taking into consideration that in the last 15 years only 10% of the installed capacities have been upgraded and equipped with modern facilities for pollution reduction and minimization of GHG emissions, this is a major challenge for the Romanian energy sector. Based on its characteristics of security of energy supply, reliability, economic efficiency and low GHG emissions, nuclear power represents a stable component of the balanced energy mix in Romania.

Romania started its nuclear power programme in 1950. There are two nuclear research sites, both with research reactors, namely: the IFIN-HH site, with the VVR-S research reactor (commissioned in 1957), located in Magurele (near Bucharest), where the reactor has been defueled and is being decommissioned; and the RATEN ICN site, with a TRIGA research reactor (commissioned in 1979), located in Mioveni (near Pitesti). This is a dual core TRIGA reactor containing a 14 MW steady state reactor and an annular core pulsing reactor able to test materials at 20 000 MW pulses.

Romania adopted the once-through nuclear fuel cycle based on indigenous facilities, in which the enrichment of uranium and/or reprocessing of spent fuel are not allowed by national laws. Under the current Romanian legislative and regulatory framework, spent fuel is considered radioactive waste since no further processing is foreseen. Therefore, the policies, strategies and programmes for radioactive waste management address the spent fuel as waste.

The front end activities are carried out in the uranium ore mines (uranium production capacity of 40 kt U/year [VIII.42] tailored to meet the requirements of the national nuclear power programme [VIII.43]), including the Feldioara UO_2 Powder Factory (which has a milling and concentration capacity of 300 t U (U_3O_8)/year, and refining and conversion capacity of 300 t U (UO_2)/year [VIII.43, VIII.44]), the nuclear fuel factory located in Mioveni and certified in 1994 as a CANDU 6 fuel manufacturer (production capacity of 110 t HM/year, which can be extended to meet requirements for the operation of four CANDU reactors [VIII.42, VIII.43]) and the Heavy Water Factory.

The Cernavoda NPP is equipped with HWR reactors of the CANDU 6 type, located on the Cernavoda site (about 250 km from Bucharest). Two CANDU 6 reactors (each with a 705 MW(e) gross capacity) are in commercial operation (Unit 1 since December 1996 and Unit 2 since November 2007). Another three reactors are located on the Cernavoda site and have been under preservation since 1992. The political decision is to continue the works at Units 3 and 4, but difficulties created by the national and international financial context have led to many delays of the project. The construction of Unit 5 has been cancelled by the National Company Nuclearelectrica, owner and operator of Cernavoda NPP; the existing structures will be used for supporting different activities connected to the operation of the other units [VIII.44].

Spent nuclear fuel management at the Cernavoda NPP is assured by intermediate wet storage in the NPP pools (at least for six years), the intermediate dry storage of the MACSTORE type (with a planned operational period of 50 years; 2 300 t HM were stored at the end of 2013 [VIII.45]), and the intermediate storage for solid radioactive waste (1 400 m^3 total capacity) [VIII.46]. For the final disposal of LILW from Cernavoda NPP, a near surface repository with multiple barriers is planned to be built (disposal area $\approx$ 25 ha) and the siting process is in progress in the Saligny area. Research is being conducted on the geological environment for spent nuclear fuel and HLW in the deep geological repository.

For the Romanian research reactors, it is foreseen that the spent fuel will be returned to the country of origin [VIII.46]. The C-36 spent fuel from the VVR-S research reactor has already been shipped back to the Russian Federation. The TRIGA research reactor core has been converted to operate with LEU fuel. All highly enriched uranium fuel has been repatriated to the United States of America. Future spent LEU fuel arising from reactor operation is intended to be returned to its country of origin. The National Repository for LILW is a near surface repository located at Baita (in the north-western part of Romania) and operated for institutional radioactive waste since 1985 [VIII.46].

VIII.4.2. National decision on and vision for nuclear energy strategy

In 2007, the Romanian Government approved (by Government Decision 1069/2007) the short term Energy Strategy of Romania for the period 2007–2020, the main objective of which was "…to satisfy the energy needs on short, intermediate and long term, with costs as low as possible, adequate to a modern market economy and a civilized life standard, in conditions of quality, supply security and with respect of the sustainable development principles". The security of energy supply, sustainable development and competitiveness were promoted as strategic objectives [VIII.42].

A couple of updating attempts have to be mentioned [VIII.47, VIII.48]. Nuclear energy development is envisaged to entail completing construction by 2020 and starting the operation of another two HWR reactors of CANDU type (720 MW) — Units 3 and 4 at Cernavoda NPP

— and potentially constructing a new NPP (Generation III+ or Generation IV) reactor technology to be selected after 2030 [VIII.47].

The Romanian Government programme for 2013–2016 [VIII.49] promoted as its main objective that "Energy should play an essential role in Romania's economic and social development … Energy policy is based on the development of infrastructure and competitiveness".

Some of the strategic objectives were, as follows [VIII.49]:

- The security of energy supply: "Ensure the security for energy critical infrastructure, storage capabilities, including nuclear facilities".
- Energy efficiency and environment protection: "Promoting clean technologies… Implementing the technical solution for Cernavoda NPP spent nuclear fuel final disposal".
- Encouraging investment: "Upgrading and increasing uranium refining capabilities; Partnership on external markets for concession of uranium ores to be further explored and exploited". The priority projects related to nuclear energy are:
  - Reiterate the offer for construction of Cernavoda NPP reactors Unit 3 and Unit 4;
  - Heavy water production at competitive costs;
  - Stimulation of R&D in nuclear energy field and technology transfer of Generation III and Generation IV reactors.

A new national energy strategy was conceived by the Department of Energy (within the Ministry of Economy) in the period 2014–2016. The new strategy pictures the current state of the national energy system, the objectives for the period 2016–2030 with perspectives for 2050, and agreements between Romania and the European Union on energy policy [VIII.50].

The main objectives of the strategy are to ensure a safe and secure energy supply in order to support the social and economic development in the context of future energy demand growth; to ensure economic competitiveness by maintaining affordable prices of energy; to protect the environment by preventing and mitigating the impact of climate changes; the modernization of the energy governance system; and the reduction of energy poverty and the protection of vulnerable consumers. Addressing these five major objectives, Romania will consider the construction of a diversified energy mix, balanced with the efficient use of all energy resources, domestic primary and modern technologies that allow long term use of fossil fuels with low GHG emissions, RESs and nuclear energy. The investment level in the energy sector is projected at €30 billion by 2030 and up to €30 billion in 2030–2050.

Nine main scenarios (grouped in three categories according to the consideration of EU policies) and nine sensitivity analyses have been developed to prepare the strategy. The global prices for fossil fuels (average, low and high prices, and European Union projection on prices according to the reference scenario presented by the European Commission in July 2016) were used for the main scenarios; the same projection on the GDP, population and activity per sector was considered [VIII.50].

The central scenario of the new energy strategy assumes that the following targets have to be reached by 2030 without the European Union imposing any mandatory national targets:

- Reduction by 40% of the total GHG emissions (relatively to 1990);
- Reduction by 43% of the emissions in the Emission Trading System (a European Union transaction system for the emission of GHGs) relative to 2005;
- Reduction by 30% of the non-emission-trading-system emissions after 2005;
- Reduction by 27% of the primary energy consumption (relative to the projection used in the European Commission's PRIMES 2007 model), increasing by 27% the RES share in the final energy consumption at the European level;

— Reduction by 80–85% of the total GHG emissions by 2050 (relative to 1990) [VIII.50].

The sensitivity analyses included the following assumptions related to nuclear energy development in Romania: (a) the construction of Units 3 and 4 of the Cernavoda NPP is stopped; and (b) the investment in new nuclear capacities (the capital cost) is evaluated.

The results of all the scenarios and sensitivity analyses have been used to shape the optimum scenario [VIII.50] with the following projections related to nuclear energy support and development:

— The final demand for electricity will increase from 44 TW·h in 2015 to 51 TW·h in 2030.
— Romania will remain an important regional energy provider.
— The main strategic objective is to preserve the equilibrated and diverse national energy mix, based on domestic energy sources with competitive costs and increasing the share of energy production without GHG emissions.
— About 4.2 GW of the total installed capacity (1.8 GW gas fired and 2.4 GW coal fired power plants, respectively) will be withdrawn or decommissioned by 2030. They need to be replaced with new capacities that have high efficiency and are flexible and in line with the conditions imposed by the national network and the European regulations.
— Nuclear energy is a strategic option for Romania and the construction of new nuclear capacities represents a strategic decision.
— The construction of two new reactors is projected as a primary option in the National Energy Strategy, in conditions of economic efficiency and according to European technical and environmental requirements — existing infrastructure and national expertise will be used, the continuity and development of the highly skilled, qualified and productive human resources in the nuclear sector will be sustained, and the development and exploitation of new uranium ore mines will be ensured.
— The contribution of each unit of Cernavoda NPP to the reduction of GHG emissions represents about 2 million t CO_2 equivalent per year if it replaces natural gas fuelled capacities, and about 4 million t CO_2 equivalent per year if it replaces coal fuelled capacities, respectively.
— During the reactors' initial operational life, without taking refurbishment into account, each nuclear unit could contribute to the reduction of GHG emissions in the region by 50–100 million t CO_2 equivalent, which would be a significant contribution to European decarbonization targets.
— The construction of Units 3 and 4 at Cernavoda NPP would have a significant impact on electric energy exports (increasing from 7 to 11 TW·h per year).
— Based on currently available data, the energy production from offshore natural gas deposits discovered in the Black Sea is estimated for about 10 years. At the same time, doubling nuclear power production will replace the energy generated by the coal fuelled capacities in the national energy mix, and to some extent, that of the natural gas fuelled capacities.
— After 2035, conditions will be created for the introduction of Generation IV nuclear reactors and small modular reactors, thus increasing the share of energy production with low GHG emissions.
— The high investment cost projects (RESs and nuclear projects) will still need supportive schemes until the levelized cost of electricity (LCOE) decreases to €65–85/MW·h for 2030–2050.

Table VIII.9 summarizes the national mix of installed gross capacity in 2015 and 2030 (projected), while the production of energy for the same selected timeframes is illustrated in Fig. VIII.32.

TABLE VIII.8. NATIONAL MIX OF GROSS CAPACITY INSTALLED IN 2015 AND 2030 (PROJECTED) [VIII.50]

2015 — 21.1 GW (total installed gross capacity)			2030 (projected) — 21.7 GW (total installed gross capacity)		
Primary energy source	Capacity	Share	Primary energy source	Capacity	Share
Nuclear	1.31 GW	6%	Nuclear	2.65 GW	12%
Coal	4.98 GW	24%	Coal	2.02 GW	9%
Natural gas	3.75 GW	18%	Natural gas	2.41 GW	11%
Hydropower	6.62 GW	31%	Hydropower	6.84 GW	31%
Wind	2.95 GW	14%	Wind	4.47 GW	21%
Solar photovoltaic	1.36 GW	6%	Solar photovoltaic	3.19 GW	15%
Biomass	0.13 GW	1%	Biomass	0.14 GW	1%

For the transition from 2015 to 2030, the optimum scenario considered in the Romanian Energy Strategy reveals significant reductions, by 15% and 7%, respectively, of coal and natural gas fuelled capacities in the total installed capacity. In these conditions, the total installed capacity is projected to slightly increase from 21.1 GW to 21.7 GW, based on the growth of nuclear capacity (by 6%) and of RES capacity (by 16%).

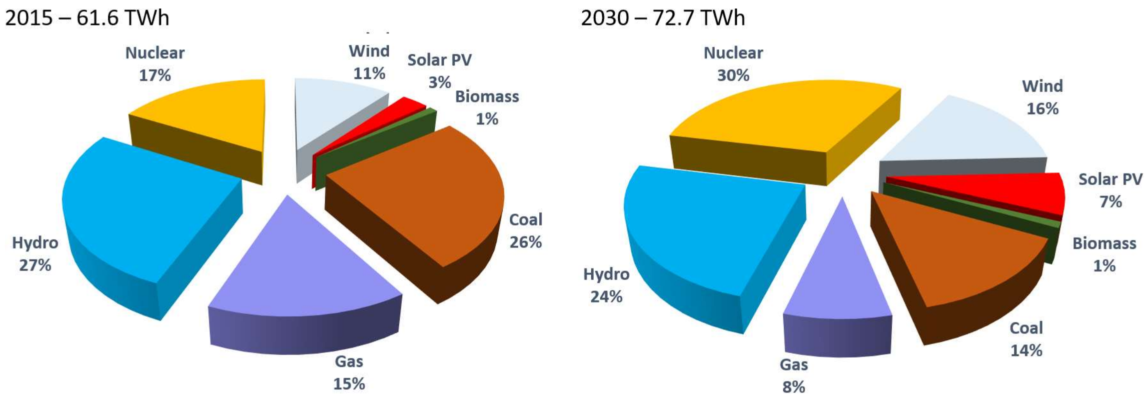


FIG. VIII.31. National energy production in the national energy mix in 2015 and 2030 (projected) [VIII.50].

As related to the production of energy in the national mix, for the transition from 2015 to 2030, the optimum scenario considered in the Romanian Energy Strategy reveals significant reductions of the energy produced by coal (from 15.8 TW·h to 10 TW·h) and natural gas (from 9.2 TW·h to 5.8 TW·h) power plants, the corresponding share in the total energy production being reduced by 12% and 7%, respectively. The total energy production will increase from 61.6 TW·h to 72.7 TW·h, based on the growth of the energy production shares of nuclear (by 13%) and RESs (by 9%).

The nuclear policy of Romania encompasses the development and use of nuclear energy and other nuclear fuel cycle activities in Romania, as well as the oversight of the development and enforcement of nuclear legislation and regulations to ensure that all nuclear activities are strictly regulated and controlled to the highest standards in order to ensure public health and safety.

The medium term National Strategy for the Nuclear Energy Field Development and the National Nuclear Plan for its implementation was approved in 2002 (by Government Decision 1259/2002). Its main objective states that “In 2025–2050 Romanian NPPs should contribute with about 40% to the total national electricity production in cost competitive conditions and assuring nuclear safety at the international standard requirements” [VIII.51].

An interesting view can be gained by examining the elements of an analysis identifying the strengths, weaknesses, opportunities and threats associated with business competition or project planning. The analysis of strengths, weaknesses, opportunities and threats (SWOT analysis) applied to the nuclear energy sector in Romania is given below:

— Strengths:

- Existing capabilities and competencies (infrastructure, industry, human resources, specialists with appropriate expertise);
- Successful operation of Cernavoda NPP (high capacity factors, reduced number of incidents, stability in the energy production etc.);
- Affordable costs for society;
- Low impact on the environment (clean and safe energy, contribution to GHG emission reduction);
- Existing natural uranium domestic resources and potential for new uranium ore exploitations;
- Positive public acceptance towards nuclear energy as a high-tech domain with national relevancy and significance;
- Uranium price continuously decreasing on the resources market;
- Retirement of a large number of fossil fuel power plants (replacement with new competitive units or low GHG emissions capacities, i.e. RESs or nuclear).

— Weaknesses:

- Lack of stable funds for large investments and public/private investments not showing an acceptable arrangement for the Government;
- Lack of an updated long term development strategy in nuclear energy;
- Lack of legal coherence in and political willingness for the long term development of nuclear energy in the context of the national energy mix;
- Delays in building the low and intermediate level radioactive waste national storage facility in the context of the lack of a well defined strategy for geological disposal;
- Lack of interest among new professionals to join the nuclear industry and difficulties to ensure an appropriate and effective knowledge transfer;
- Reshaping of public acceptance for nuclear energy development in the context after the accident at the Fukushima Daiichi nuclear power plant.

— Opportunities:

- Clean energy, CO_2 emission free, making a contribution to GHG emission reduction in the energy production as required by the Kyoto Protocol and European Union energy policy;
- Significant increase in national and regional energy needs owing to increasing standards of living, economic restoration and climate change;

- Continuous updating and improvement of energy transport by means of the interconnection of European and regional energy systems;
- Decreasing tendency in the number of operating nuclear plants in the region not counterbalanced by the development of stable energy production capacities using other technologies.

— Threats:

- Increasing perceptions of nuclear energy risks among decision makers and society at large;
- Competition from shale gas;
- Present dominant orientation of HWR of the CANDU type in the European and regional context of significant progress steps already made in other types of nuclear plants;
- RES competition and the green certificates market;
- Initial investment costs for installed capacity being higher for nuclear energy projects than for other technologies;
- Reshaping of public acceptance for nuclear energy development in the context following the accident at the Fukushima Daiichi NNP.

From the point of view of medium term development and also from a research, development and implementation infrastructure perspective, Romanian efforts in the field of lead cooled fast reactor (LFR) technology are notable. In February 2011, the Romanian Government expressed in a memorandum (initiated by the Ministry of Economy, Trade and Business Environment) the availability for hosting the Generation IV Advanced Lead Fast Reactor European Demonstrator (ALFRED) in Romania. In December 2013, Ansaldo Nucleare (Italy), ENEA (Italy), and RATEN ICN Pitesti (Institute for Nuclear Research, Romania) signed the FALCON Consortium Agreement [VIII.52] committing them to cooperation on the development of ALFRED. A new memorandum (initiated by the Department for Energy) approved by the Government in January 2014 was devoted to the preparatory actions for the implementation of the ALFRED demonstrator in Romania.

ALFRED [VIII.53] is a 300 MW(th) scaled demonstrator for LFR technology, developed to show the viability of LFR technology to be used in a future commercial power plant. It will be connected to the grid in order to prove economic viability. ALFRED, with an electric power of 125 MW(e), is designed to use MOX fuel. The siting process considers the RATEN ICN nuclear platform (located in Mioveni, Romania) the reference site.

VIII.4.3. Purpose of the roadmap

The trial application of the roadmap template to the national case study pursued the following objectives:

- The preparation of structured information on the development of the NES until 2100 based on the national energy strategy and official plans (up to 2030) and including available prospects given by expert studies (2030–2100);
- Illustration of Romanian NES development (security and needs for nuclear fuel supply, operation performance indicators, radioactive waste management, including waste disposal) for the period up to 2100 with the goal of achieving a sustainable NES;
- Identification of potential needs for international collaborations in nuclear fuel cycle activities envisaging the benefits for national NES development.

VIII.4.4. Metrics on nuclear energy position and development

In this section, the metrics of the case study of Romania, prepared according to the roadmap template, are presented. Nuclear power is competitive with other energy sources in the national energy mix (economic indicator), with a share of about 20% of total electricity production (nuclear share in electricity generation). It has the benefit of generally positive public opinion (public support indicator), being perceived as a high-tech domain with national significance.

In terms of construction performance, there are firm plans to build new reactors within five years (NES development status indicator), but the average construction time is over seven years (construction health indicator).

Regarding operation performance, for the Romanian NES the average reactor load factor is over 90% (operation health indicator); all needs (uranium, conversion, fuel fabrication) are supplied by domestic facilities (security of fuel supply indicator). Spent nuclear fuel and HLW are stored, but without firm plans for a disposal site (geological waste disposal status). From December 2015, the UO_2 powder needed for CANDU fuel fabrication is assured by a qualified international supplier (Cameco, Canada) [VIII.54].

Figure VIII.33 presents the nuclear energy sector's size and growth in Romania for the actual, near, medium and long term periods, taking into consideration official plans and prospects.

Nuclear Energy Growth	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Decreasing				
Stabilization	☑		✓	✓
Small growth (below 0.1 GWe/year)		☑		
Medium growth (0.1 - 0.5 GWe/year)				
Significant growth (>0.5 GWe/year)				

Nuclear Energy Size	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
No nuclear				
Small (0-10 GWe)				
Medium (10-50 GWe)	☑	☑	✓	✓
Large(>50 GWe)				

☑ official plan ✓ prospect

FIG. VIII.32. Nuclear energy size and growth — official plans and prospects for the Romanian NES.

Romania is a technology user country and will keep this status in the near, medium and long terms, according to official plans (up to 2030) and prospects (2031–2050 and 2051–2100). It is a NG2 country under the GAINS classification (direct disposal of used fuel or reprocessing used fuel abroad; existing plans to build, operate and manage permanent geological disposal facilities for used fuel and/or HLW).

The national technology options include once-through nuclear fuel cycle (supported both by official plans up to 2030, and prospects from 2031 to 2100) and final geological disposal of all wastes (according to prospects from 2051 to 2100). Romanian NES development requires access to technology abroad, especially after the commissioning and during the operation of

ALFRED, the options of interest being the following: limited and complete recycling of spent fuel (according to prospects from 2031 to 2100) and minor actinides or minor actinides and fission product transmutation (according to prospects from 2051 to 2100).

The domestic technology status for the considered periods is summarized in Fig. VIII.34, considering official plans and prospects, the interest for reactors and nuclear fuel cycle activities (uranium mining and conversion, fuel fabrication, spent fuel storage and geological disposal).

c.y.	Research	Prototype	Demonstration	Operating
LWR	☑			
HWR	☑			☑
HTGR				
SMR				
FR	☑			
ADS				
MSR				
Uranium mining and milling	☑			☑
Conversion	☑			☑
Enrichment				
Uranium fuel fabrication	☑			☑
Mixed uranium-plutonium fuel fabrication				
Advanced fuel fabrication	☑			
Wet SNF storage	☑			☑
Dry SNF storage	☑			☑
Aqueous SNF reprocessing				
Advanced SNF reprocessing				
HLW forms	☑			
Geological disposal	☑			
Related industrial activities				
Others				
	☑official plan	✓ prospect		

c.y. – 2030	Research	Prototype	Demonstration	Operating
LWR	☑			
HWR	☑			☑
HTGR				
SMR	✓			
FR	☑			
ADS				
MSR				
Uranium mining and milling	☑			☑
Conversion	☑			☑
Enrichment				
Uranium fuel fabrication	☑			☑
Mixed uranium-plutonium fuel fabrication				
Advanced fuel fabrication	☑			
Wet SNF storage	☑			☑
Dry SNF storage	☑			☑
Aqueous SNF reprocessing				
Advanced SNF reprocessing				
HLW forms	☑			
Geological disposal	☑			
Related industrial activities				
Others				
	☑official plan	✓ prospect		

2031 – 2050	Research	Prototype	Demonstration	Operating
LWR	☑			
HWR	☑			☑
HTGR				
SMR	✓			
FR	☑		☑	
ADS				
MSR				
Uranium mining and milling	☑			☑
Conversion	☑			☑
Enrichment				
Uranium fuel fabrication	☑			☑
Mixed uranium-plutonium fuel fabrication				
Advanced fuel fabrication	☑			
Wet SNF storage	☑			☑
Dry SNF storage	☑			☑
Aqueous SNF reprocessing				
Advanced SNF reprocessing				
HLW forms	☑			
Geological disposal	☑			
Related industrial activities				
Others				
	☑official plan	✓ prospect		

2051 – 2100	Research	Prototype	Demonstration	Operating
LWR				
HWR	☑			☑
HTGR				
SMR	✓			✓
FR	☑		☑	✓
ADS				
MSR				
Uranium mining and milling	☑			☑
Conversion	☑			☑
Enrichment				
Uranium fuel fabrication	☑			☑
Mixed uranium-plutonium fuel fabrication				
Advanced fuel fabrication	☑			✓
Wet SNF storage	☑			☑
Dry SNF storage	☑			☑
Aqueous SNF reprocessing				
Advanced SNF reprocessing				
HLW forms	☑			
Geological disposal	☑			✓
Related industrial activities				
Others				
	☑official plan	✓ prospect		

FIG. VIII.33. Domestic technology status — official plans and prospects (current, near, medium and long term timeframes). Legend: SMR — small and medium sized reactor; ADS — accelerator driven systems; MSR — molten salt reactor; SNF — spent nuclear fuel.

In terms of cooperation with other countries, the collaboration strategy according to official plans in the present and near term (until 2030) includes: participation in information exchange activities, joint R&D programmes and collaboration on the nuclear fuel cycle front end. For the medium (2031–2050) and long terms (2051–2100), the collaboration strategy is supported by prospects in the following activities: participation in information exchange activities, joint R&D programmes, sharing of R&D facilities, collaboration on the nuclear fuel cycle front end and using nuclear fuel cycle back end services. In the long term, the collaboration strategy according to prospects also includes NPP purchasing and collaboration on the nuclear fuel cycle international centres.

The ‘collaboration agreements’ block for cooperation with other countries is presented in Fig. VIII.35, considering official plans and prospects and the defined periods of analysis.

c.y.	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium	☑			
Obtain uranium				
Produce/Offer converted uranium	☑			
Obtain converted uranium		☑		
Produce/Offer enriched uranium				
Obtain enriched uranium				
Fabricate/Offer fuel	☑			
Obtain fuel fabrication service				
Produce/Offer NPP design			☑	
Use NPP design service				
Offer NPP operation service				
Use NPP operation service	☑			
National SNF storage/Offer SNF storage service	☑			
Use SNF storage service				
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service				
National disposal/Offer SNF disposal service				
Use SNF disposal service				
National HLW disposal/Offer HLW disposal service				
Use HLW disposal service				
Others				
	☑ official plan	✓ prospect		

c.y. – 2030	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium	☑			
Obtain uranium				
Produce/Offer converted uranium	☑			
Obtain converted uranium		✓		
Produce/Offer enriched uranium				
Obtain enriched uranium				
Fabricate/Offer fuel	☑			
Obtain fuel fabrication service				
Produce/Offer NPP design			☑	
Use NPP design service				
Offer NPP operation service				
Use NPP operation service	☑			
National SNF storage/Offer SNF storage service	☑			
Use SNF storage service				
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service				
National disposal/Offer SNF disposal service				
Use SNF disposal service				
National HLW disposal/Offer HLW disposal service				
Use HLW disposal service				
Others				
	☑ official plan	✓ prospect		

2031 – 2050	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium	☑			
Obtain uranium		✓	✓	
Produce/Offer converted uranium	☑			
Obtain converted uranium		✓		
Produce/Offer enriched uranium				
Obtain enriched uranium				
Fabricate/Offer fuel	☑			
Obtain fuel fabrication service				
Produce/Offer NPP design			☑	
Use NPP design service				
Offer NPP operation service				
Use NPP operation service	☑			
National SNF storage/Offer SNF storage service	☑			
Use SNF storage service				
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service		✓		
National disposal/Offer SNF disposal service				
Use SNF disposal service				
National HLW disposal/Offer HLW disposal service				
Use HLW disposal service				
Others				
	☑ official plan	✓ prospect		

2051 – 2100	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium	☑			
Obtain uranium		✓	✓	
Produce/Offer converted uranium	☑			
Obtain converted uranium		✓		
Produce/Offer enriched uranium				
Obtain enriched uranium				
Fabricate/Offer fuel	☑			
Obtain fuel fabrication service		✓	✓	
Produce/Offer NPP design			✓	
Use NPP design service				
Offer NPP operation service				
Use NPP operation service	☑			
National SNF storage/Offer SNF storage service	☑			
Use SNF storage service				
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service		✓		
National disposal/Offer SNF disposal service	✓			
Use SNF disposal service		✓	✓	
National HLW disposal/Offer HLW disposal service	✓			
Use HLW disposal service		✓	✓	
Others				
	☑ official plan	✓ prospect		

FIG. VIII.34. 'Collaboration agreements' block giving official plans and prospects (current, near, medium and long term timeframes).

VIII.4.5. Key developments to enhance sustainability

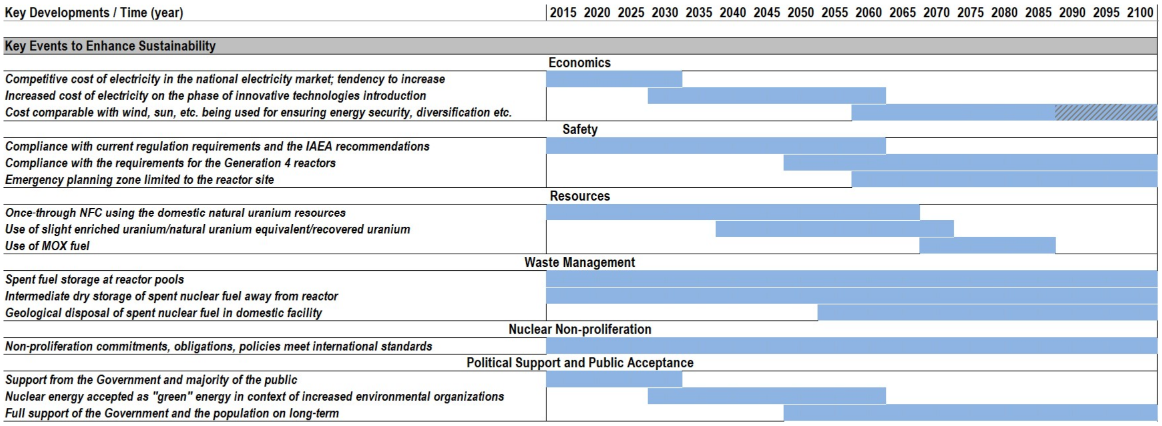
A sustainable NES is characterized by performance, efficiency, safety, security and the ability to produce clean energy with respect to nuclear safety and environmental protection conditions.

Key events to enhance the sustainability of the NES in the areas of economics, safety, resources, waste management, proliferation resistance and society, including official plans and expert projections, are presented below (Fig. VIII.36(a)).

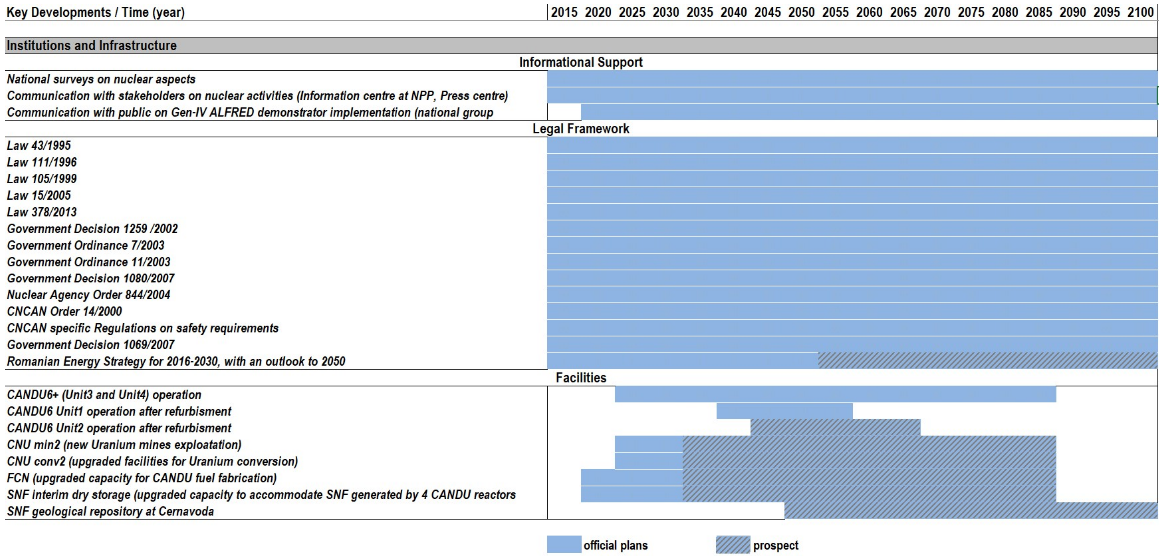
Informational support is assured in Romania by national surveys on nuclear aspects and communication with stakeholders on nuclear activities (through the information centre at the NPP and the press centre). From 2020, communication with the public on ALFRED implementation (through the national group ALFRED) will be added.

The legal framework is well developed in Romania, taking into account that the national nuclear programme started in 1950. Romania operated its first research reactor in 1957 (the VVR-S research reactor in Magurele, near Bucharest), the second one in 1979 (TRIGA 14 MW research reactor at Mioveni, near Pitesti), and in 1996 the NPP (CANDU Unit 1 at Cernavoda) began its commercial operation. During more than 60 years, nuclear fuel cycle facilities have been developed and different research and technical activities involving radioactive materials have been carried out. The legal framework developed by the Romanian Government and responsible authorities for developing nuclear energy in compliance with international standards and regulations is briefly presented in Fig. VIII.36(b).

The key developments of the nuclear infrastructure in terms of facilities for the considered time period, including official and expert opinion perspective, are summarized in Fig. II.36(b).



(a)



(b)

FIG. VIII.35. Key developments in the Romanian case study. (a) Key events to enhance sustainability; (b) Institutions and infrastructure. Legend: CNCAN — National Commission for Nuclear Activities Control; FCN —fuel fabrication facility; SNF — spent nuclear fuel.

VIII.4.6. Nuclear power planning and scenarios

In this section, Romanian NES development including official plans and expert projections are presented, in terms of reactor fleet (type of reactors and installed gross capacity); energy production; uranium mining; conversion; fuel fabrication; spent nuclear fuel storage; and geological disposal.

All data up to 2050 are supported by official plans and existing strategies; after 2050, the data are prospects, based on experts' visions and estimations.

Romania operates one NPP, equipped with five HWR CANDU 6 reactors. Two CANDU 6 units are in commercial operation, the first since 1996 and the second since 2007, with a total installed gross capacity of 1410 MW(e), energy production being about 1270 MW(e)/year, with load factors over 90%.

Another three CANDU 6 units have been under preservation since 1992. There is a political decision to continue the works at Units 3 and 4, despite the delays to the project caused by the national and international financial context. Romania and China signed a partnership in 2014 to supply investment needs; according to the current vision Units 3 and 4 should be commissioned after 2020. The total installed gross capacity at the Cernavoda NPP, with four reactors in operation, will be 2850 MW(e) and the corresponding annual energy production will increase to about 2600 MW(e)/year, assuming that the load factors will be kept over 90%.

Considering the refurbishment and the subsequent reactor operation, the decommissioning of Unit 1 will start after 2055, accompanied by a reduction in annual energy production to about 1900 MW(e)/year. The decommissioning of Unit 2 will start after 2065 (although the refurbishment of Unit 2 is supported by experts' expectations) and annual energy production will decrease to about 1300 MW(e)/year.

The refurbishment of Units 3 and 4 was not taken into consideration even hypothetically; these reactors will finish their operational life after 2085. Strategic decisions are to be taken after 2050, in order to assure the continuation of the nuclear power programme in Romania and the production of clean, affordable, safe and CO_2 emission free energy in the national energy mix.

The ALFRED plant was not included in the Romanian NES reactor fleet and its production of energy was not taken into account.

The demand for natural uranium, technical concentrates of uranium (converted UO_2 powder) and fuel fabrication are illustrated in Figs VIII.37, VIII.38 and VIII.39, respectively.

According to Refs [VIII.42, VIII.43, VIII.51], uranium production capacity is tailored to meet the requirements of the national nuclear power programme; the fuel conversion facilities are considered domestic suppliers to ensure the needed supply of uranium is fulfilled. Assuming that the national production of uranium will continue at the same level, a surplus of about 200 t U per interval is registered until 2055 (the start of Unit 1 decommissioning); this amount increases to 290 t U per interval until 2065 (the start of Unit 2 decommissioning) and reaches about 400 t U per interval until 2085 (when Units 3 and 4 reach the end of their operational life). The surplus can be sold on the uranium market or it can used for other new CANDU units in the country if they exist.

Uranium requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium requirements for CANDU6 (Unit-1)	90	90	90	90	90	90	90	90	90									
Uranium requirements for CANDU6 (Unit-2)	90	90	90	90	90	90	90	90	90	90	90							
Uranium requirements for CANDU6+ (Unit-3)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Uranium requirements for CANDU6+ (Unit-4)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Total, t U	180	180	396	396	396	396	396	396	396	306	306	216	216	216	216	0	0	0
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t U	300	300	600	600	600	600	600	600	600	600	600	600	600	600	600	0	0	0
CNU min-1	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300			
CNU min-2			300	300	300	300	300	300	300	300	300	300	300	300	300			
Secondary supply/Transfer in materials, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)																		
Total supply, t U	300	300	600	600	600	600	600	600	600	600	600	600	600	600	600	0	0	0
Surplus (supply - demand)																		
Surplus, t U	120	120	204	204	204	204	204	204	204	294	294	384	384	384	384	0	0	0

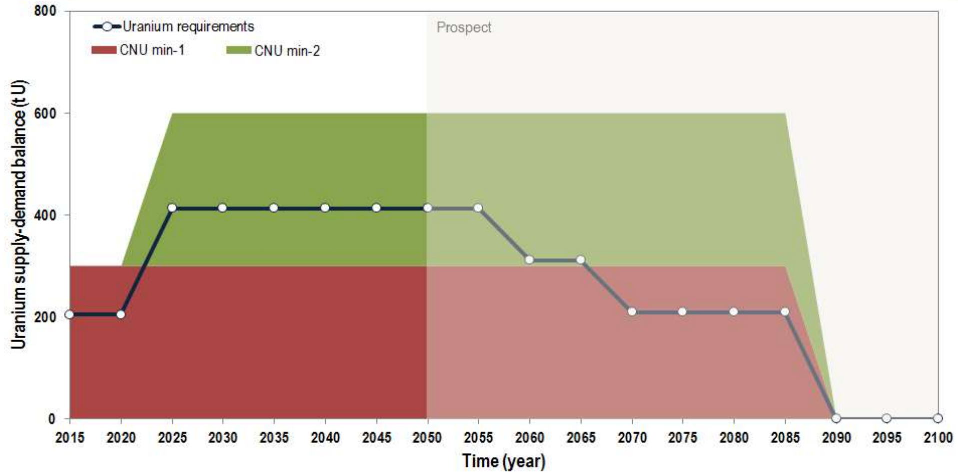


FIG. VIII.36. Uranium requirements for Romanian NES development. Legend: CNU min-1 and min-2 — fuel conversion facilities.

Related to the domestic capacity of UO_2 powder conversion, the CNU conv-1 and CNU conv-2 conversion facilities have been considered in the case study in order to ensure the needed raw material for CANDU fuel fabrication, according to Refs [VIII.42, VIII.43, VIII.51]. A qualified international supplier of converted UO_2 was also considered, owing to the actual situation with the difficulties of Feldioara UO_2 Powder Factory in supplying the raw material for fuel fabrication.

It can be noted that the converted UO_2 powder requirements are fulfilled. Assuming that the actual situation continues (domestic production facilities are not available at a convenient cost, a situation which leads to acquiring the needed UO_2 amounts by import), a surplus of about 380 t U per interval is registered until 2055 (the start of Unit 1 decommissioning); this amount increases to 480 t U per interval until 2065 (the start of Unit 2 decommissioning) and reaches about 570 t U per interval until 2085 (Units 3 and 4 reach the end of their operational life). The surplus can be sold on the UO_2 market or it can be used for other new CANDU units in the country if they exist.

Conversion requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Conversion requirements for CANDU6 (Unit-1)	90	90	90	90	90	90	90	90	90									
Conversion requirements for CANDU6 (Unit-2)	90	90	90	90	90	90	90	90	90	90	90							
Conversion requirements for CANDU6+ (Unit-3)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Conversion requirements for CANDU6+ (Unit-4)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Total, t U	180	180	396	396	396	396	396	396	396	306	306	216	216	216	216	0	0	0
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t U	300	300	600	600	600	600	600	600	600	600	600	600	600	600	600	0	0	0
CNU conv-1	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300			
CNU conv-2			300	300	300	300	300	300	300	300	300	300	300	300	300			
Secondary supply/Transfer in materials, t U	0	180	180	180	180	180	180	180	180	180	180	180	180	180	180	0	0	0
Secondary supply/Transfer in materials (all)		180	180	180	180	180	180	180	180	180	180	180	180	180	180			
Total supply, t U	300	480	780	780	780	780	780	780	780	780	780	780	780	780	780	0	0	0
Surplus (supply - demand)																		
Surplus, t U	120	300	384	384	384	384	384	384	384	474	474	564	564	564	564	0	0	0

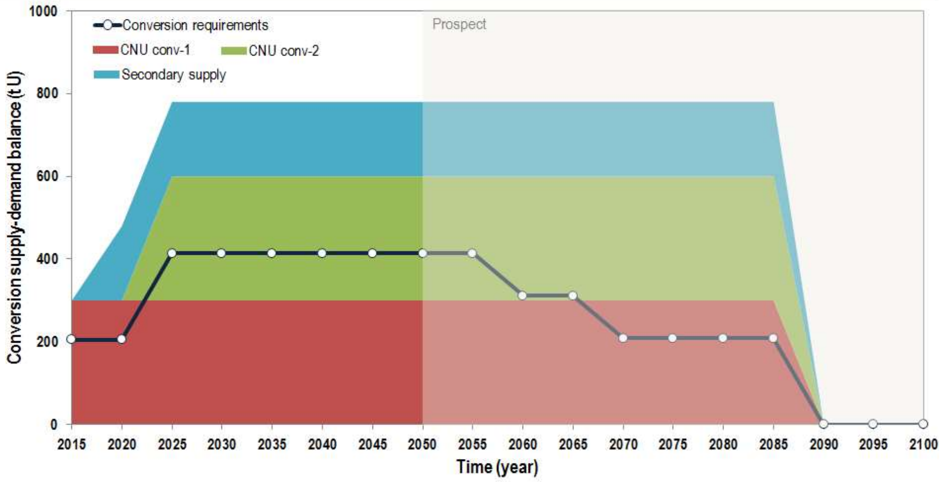


FIG. VIII.37. Converted UO_2 powder requirements for Romanian NES development. Legend: CNU conv-1 and conv-2 — fuel conversion facilities.

Nuclear fuel for the operation of CANDU reactors is fabricated by a domestic certified CANDU 6 fuel manufacturer, with a production capacity of 110 t HM/year that can be extended to meet requirements for the operation of four CANDU reactors [VIII.42, VIII.43]. The fuel fabrication facility FCN Pitesti is able to upgrade its fabrication lines in order to increase annual production from 10 800 bundles/year (actual production of fuel assemblies) to 20 000 fuel bundles/year (ensuring available fuel for all four CANDU reactors). Investment costs were estimated to be €1–2 million for each 5000 bundle production upgrade.

A small surplus of fuel produced (about 45 t HM per interval) is registered until 2055 for the scenario of Cernavoda NPP operation with four CANDU reactors; after that the surplus increases at 130 t HM per interval (three CANDU reactors are operational) and reaches about 220 t HM after 2065 for the scenario of Cernavoda operation with Units 3 and 4.

Fuel fabrication requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Fuel fabrication requirements for CANDU6 (Unit-1)	90	90	90	90	90	90	90	90	90									
Fuel fabrication requirements for CANDU6 (Unit-2)	90	90	90	90	90	90	90	90	90	90	90							
Fuel fabrication requirements for CANDU6+ (Unit-3)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Fuel fabrication requirements for CANDU6+ (Unit-4)			108	108	108	108	108	108	108	108	108	108	108	108	108			
Total, t HM	180	180	396	396	396	396	396	396	396	306	306	216	216	216	216	0	0	0
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t HM	220	440	440	440	440	440	440	440	440	440	440	440	440	440	440	0	0	0
FCN	220	440	440	440	440	440	440	440	440	440	440	440	440	440	440			
Secondary supply/Transfer in materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)																		
Total supply, t HM	220	440	440	440	440	440	440	440	440	440	440	440	440	440	440	0	0	0
Surplus (supply - demand)																		
Surplus, t HM	40	260	44	44	44	44	44	44	44	134	134	224	224	224	224	0	0	0

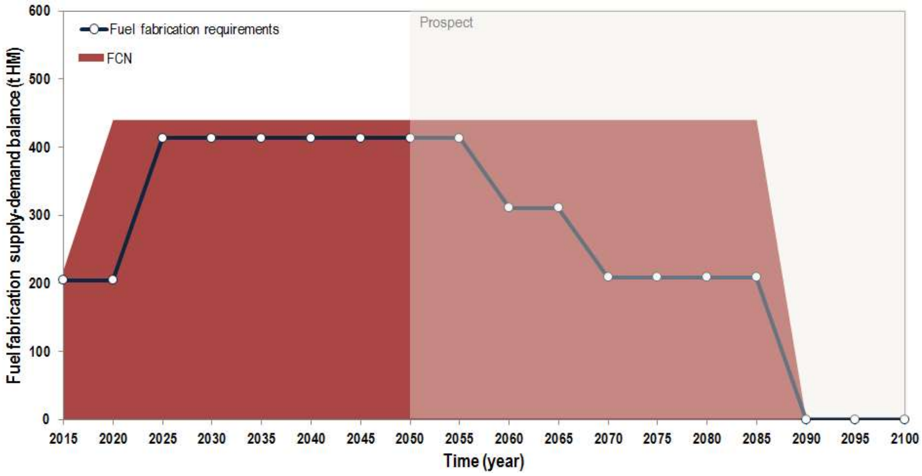


FIG. VIII.38. Fuel fabrication requirements for Romanian NES development. Legend: FCN —nuclear fuel fabrication facility.

In CANDU reactors, spent fuel is discharged from the reactor core and kept for at least six years in wet intermediate storage in the reactor pool, in order to allow radioactive decay and the removal of the decay heat produced by the spent fuel. The intermediate storage of the spent fuel continues for 50 years in dry storage away from the reactor.

Regarding spent fuel storage, the official plans and strategies in force support the national facilities for storage, with both wet (in the reactor pool) and dry (away from the reactor) intermediate storage being used. By 2015, an amount of 2300 t HM spent fuel had already been accumulated [VIII.45].

Figure VIII.40 illustrates the requirements for spent fuel storage. Wet and dry interim storage capacity requirements and the geological disposal capacity requirements are shown.

SNF storage requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SNF storage requirements for CANDU6 (Unit-1)	1780	2230	2680	3130	3580	4030	4480	4930	5380	5380	5380	5380	5380	5380	5380	5380	5380	5380
SNF storage requirements for CANDU6 (Unit-2)	880	1330	1780	2230	2680	3130	3580	4030	4480	4930	5380	5380	5380	5380	5380	5380	5380	5380
SNF storage requirements for CANDU6+ (Unit-3)			540	1080	1620	2160	2700	3240	3780	4320	4860	5400	5940	6480	7020	7020	7020	7020
SNF storage requirements for CANDU6+ (Unit-4)			540	1080	1620	2160	2700	3240	3780	4320	4860	5400	5940	6480	7020	7020	7020	7020
Total, t HM	**2660**	**3560**	**5540**	**7520**	**9500**	**11480**	**13460**	**15440**	**17420**	**18950**	**20480**	**21560**	**22640**	**23720**	**24800**	**24800**	**24800**	**24800**
Provide services/Transfer in materials																		
Provide services/Transfer in materials, t HM	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Provide services/Transfer in materials (all)																		
Supply																		
Primary supply/Utilize services, t HM	**3076**	**4500**	**6380**	**8204**	**10028**	**12308**	**14588**	**16412**	**18236**	**20060**	**21200**	**22340**	**23480**	**24620**	**25760**	**25760**	**25760**	**25760**
At-reactor-pools	1480	2220	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960	2960
Dry away-from-reactor storage	1596	2280	3420	5244	7068	9348	11628	13452	15276	17100	18240	19380	20520	21660	22800	22800	22800	22800
Wet away-from-reactor storage																		
SNF reprocessing																		
Geological disposal repository									1000	2000	3000	4000	5000	6000	8000	10000	12000	14000
Transfer out materials, t HM	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Transfer out materials (all)																		
Total supply, t HM	**3076**	**4500**	**6380**	**8204**	**10028**	**12308**	**14588**	**16412**	**18236**	**20060**	**21200**	**22340**	**23480**	**24620**	**25760**	**25760**	**25760**	**25760**
Surplus (supply - demand)																		
Surplus, t HM	**416**	**940**	**840**	**684**	**528**	**828**	**1128**	**972**	**816**	**1110**	**720**	**780**	**840**	**900**	**960**	**960**	**960**	**960**

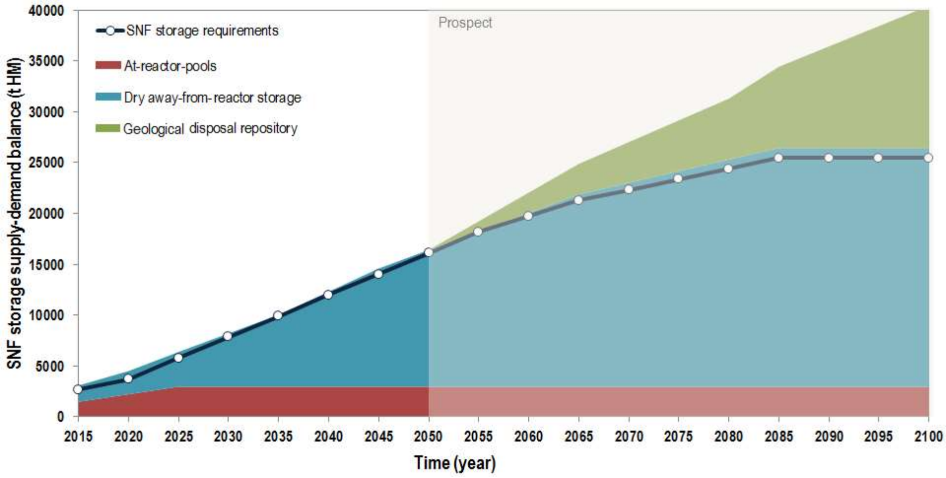


FIG. VIII.39. Spent fuel storage requirements for Romanian NES development. Legend: SNF — spent nuclear fuel.

Romania adopted a once-through nuclear fuel cycle and consequently spent fuel from the power reactors is considered waste and is expected to be disposed in a deep geological repository. Given that the dry store for spent fuel at the Cernavoda site has a design life of 50 years, there is no demand for a geological repository to be operational before 2050 [VIII.45]. As a consequence, current activities are limited, being focused on the planning and preparation of a long term programme for the implementation of the geological repository [VIII.45]. Figure VIII.41 presents the geological disposal requirements and supply capacity for spent nuclear fuel produced by the operation of four CANDU reactors.

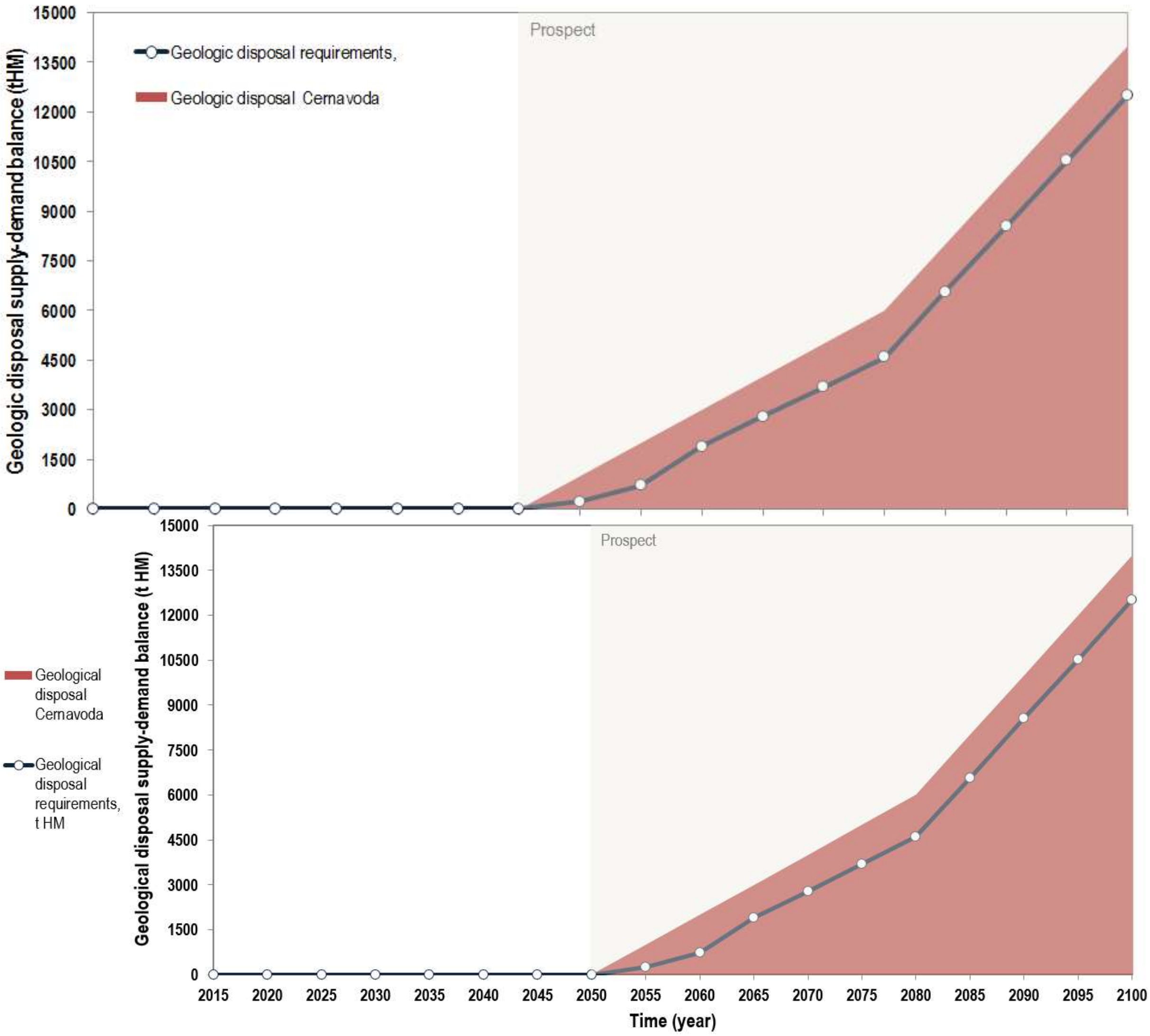


FIG. VIII.40. Spent fuel geological disposal requirements for Romanian NES development.

VIII.4.7. Summary

A long term commitment to nuclear power development, considered one of the drivers of the energy strategy of Romania, builds on the well developed national nuclear infrastructure staffed by experienced professionals, proven and safe technology and the excellent performance of the Cernavoda NPP, as well as on the positive public perception towards nuclear energy.

Romania is a technology user country (NG2 according to the GAINS approach) with a small size NES (less than 10 GW(e)). The prospects for nuclear energy growth are for small growth in the short term and a stabilized level of growth in the medium and long term.

NES development in Romania involves a once-through nuclear fuel cycle and final geological disposal of all waste in the long term. It has to be noted that access to technologies abroad for limited and complete recycling of spent fuel are envisaged in the medium and long term, respectively.

Domestic technology status according to official plans is sustained by research in LWR, HWR and FR technologies and in the once-through nuclear fuel cycle front end and back end activities, but also by the operation of HWR, uranium mining, UO_2 powder conversion, nuclear fuel fabrication and spent nuclear fuel intermediate wet and dry storage.

Research on small and medium sized reactor technology could be envisaged in the near, medium and long terms, as well as FR operation (of the ALFRED demonstrator) and geological disposal in the long term. After ALFRED's construction, spent fuel wet and dry storage is envisaged.

Figure VIII.42 illustrates in a condensed roadmap the nuclear power status, technology options, reactor fleet and nuclear fuel cycle activities for the Romanian NES according to official plans and prospects based on expert opinion.

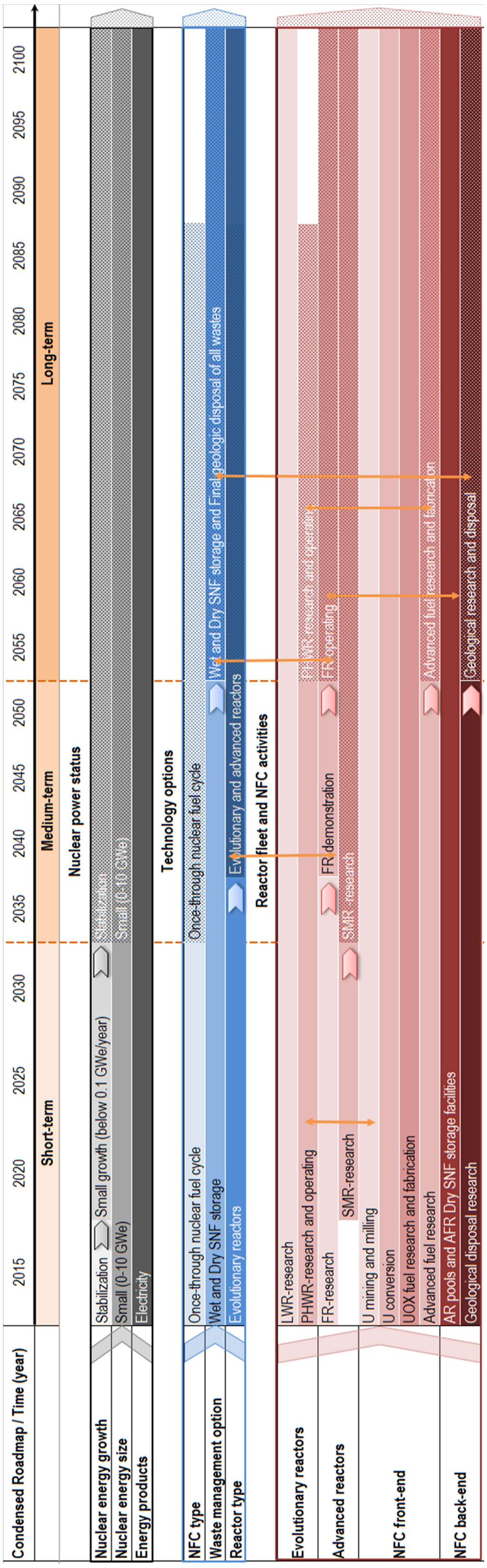


FIG. VIII.41. Condensed roadmap for Romanian NES development in the short, medium and long term regarding nuclear power status, technology options, reactor fleet and nuclear fuel cycle activities. Legend: PHWR — pressurized heavy water reactor; SMR — small and medium reactors; SNF — spent nuclear fuel.

For the current timeframe, nuclear fuel cycle activities are officially based on national efforts.

Obtaining converted uranium by bilateral agreements becomes of interest for the near and medium term. For the medium and long term, obtaining uranium or enriched uranium by bilateral or multilateral agreements could be of interest. Obtaining fuel fabrication services and utilizing reprocessing services could also be of interest for the long term timeframe, based on bilateral or multilateral agreements.

Figures VIII.43 and VIII.44 illustrate in a condensed roadmap the cooperation with other countries for sustaining the Romanian nuclear fuel cycle front end and back end activities, and the key elements of national nuclear institutions, infrastructure and legal framework.

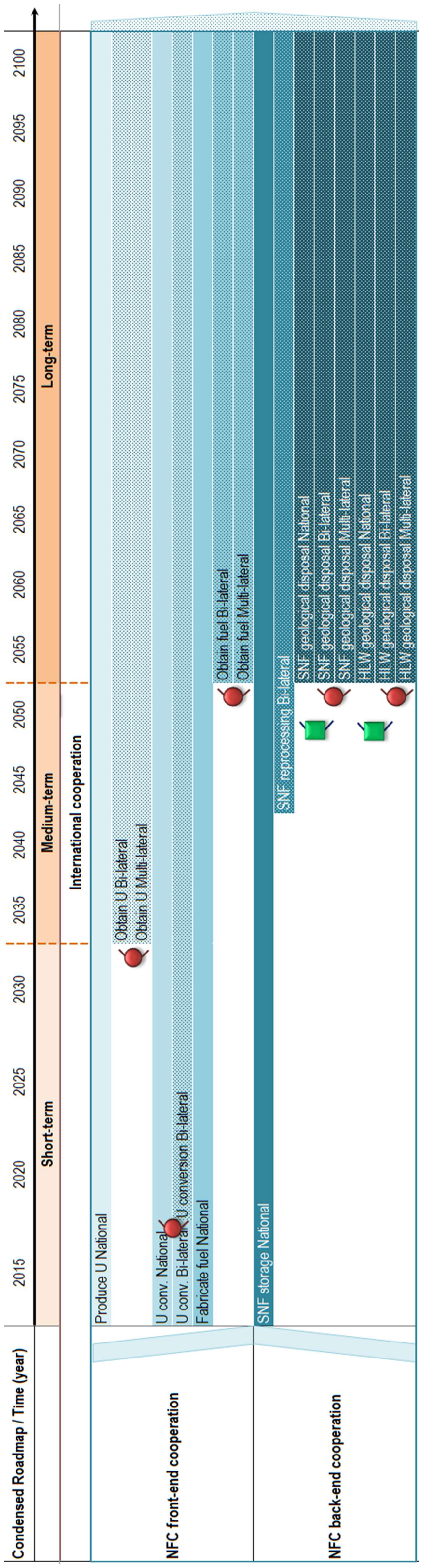


FIG. VIII.42. Condensed roadmap for the Romanian NES development in the short, medium and long term regarding the status of international cooperation in nuclear fuel cycle activities. Legend: SNF — spent nuclear fuel.

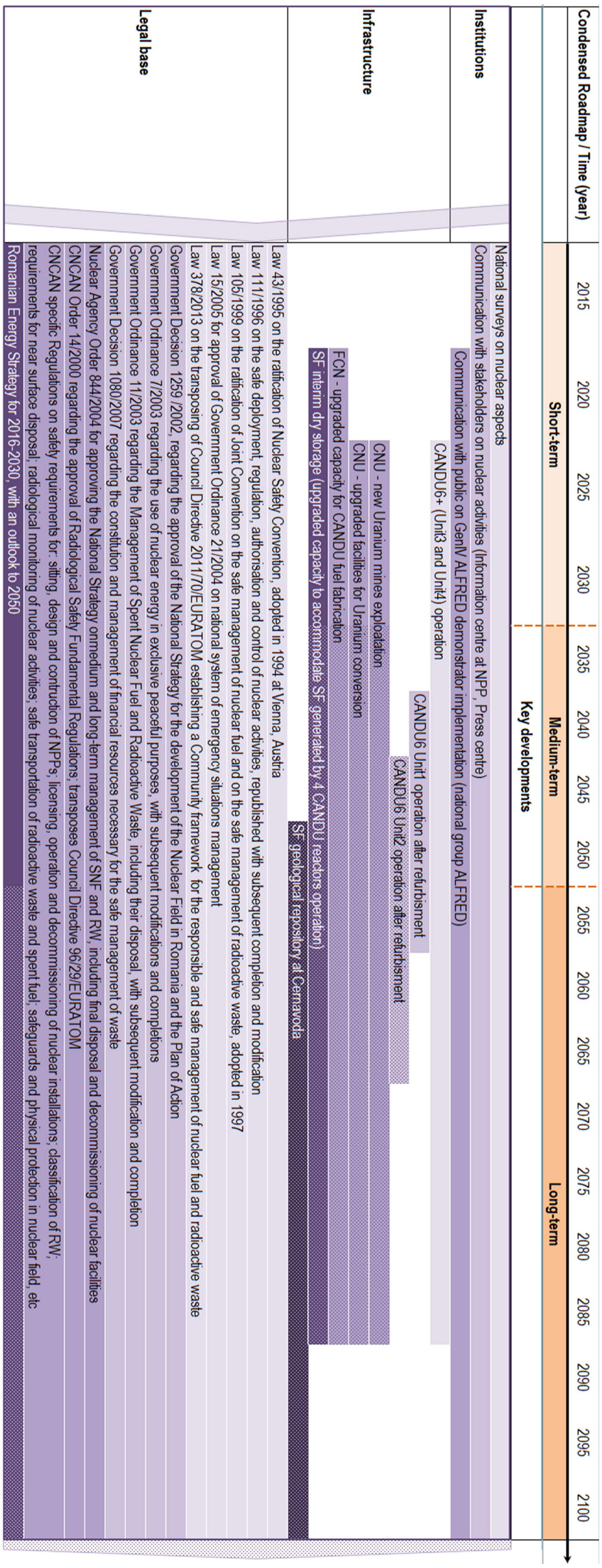


FIG. VIII.43. Condensed roadmap for Romanian NES development in the short, medium and long term regarding the key developments in nuclear institutions, infrastructure and legal framework. Legend: CNU — fuel conversion facilities; FCN — fuel fabrication facility; SF — spent fuel; SNF — spent nuclear fuel; RW — radioactive waste.

VIII.5. APPLICATION OF THE ROADMAP TEMPLATE TO THE ENERGY SYSTEM OF THAILAND

VIII.5.1. General country information

The Kingdom of Thailand is located at the centre of the Mainland Southeast Asia, is composed of 76 provinces and has a total area of 513 120 km^2. The population of Thailand was about 68.863 million in 2016, according to the country's statistical data. In 2016, the GDP and GDP per capita of Thailand were US $411.755 billion and US $5907.91, respectively [VIII.55].

Thailand has several domestic natural resources, mainly natural gas, ligniteand hydropower. The main imports are coal, natural gas, hydropower and petroleum products. In 2016, total commercial primary energy production and consumption were 50.943 million toe and 104.764 million toe, respectively [VIII.56]. Final energy by sector at the beginning of 2018 is shown in Fig. VIII.45 [VIII.56].

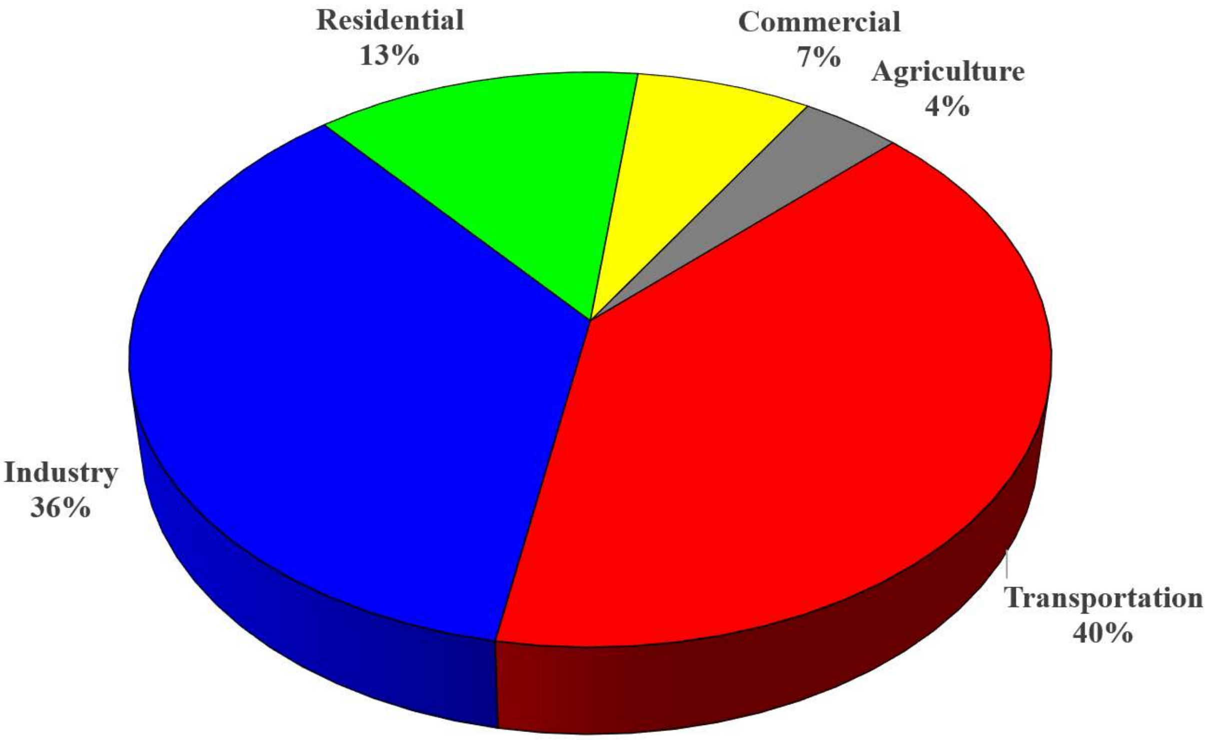


FIG. VIII.44. Share of final energy by sector in Thailand [VII.56]

The Electricity Generating Authority of Thailand (EGAT) was established in May 1969. EGAT is the leading state owned power utility in Thailand under the Ministry of Energy, responsible for electric power generation and transmission for the whole country as well as for bulk electric energy sales. Based on the latest information (April 2018), the system installed electricity generating capacity in Thailand is 42 448 MW, which includes 15 757 MW from EGAT's power plants and 26 691 MW from purchasing (independent power producers, small power producers and imports) [VIII.57]. Table VIII.10 and Fig. VIII.46 show the historical statistics and chart of electricity production for EGAT's power plants by primary source fuel types from 1990 to 2017, respectively [VIII.56, VIII.57].

TABLE VIII.9. HISTORICAL STATISTICS OF ELECTRICITY PRODUCTION FOR EGAT’S POWER PLANTS BY PRIMARY SOURCE [VIII.56, VIII.57].

	Electricity generation (GWh)							
Year	Hydropower	Fuel oil	Lignite	Natural gas	Diesel oil	Geothermal	Renewable	Total
1990	4 900.11	10 012.63	11 052.85	17 765.06	356.85	1.01	0.02	44 088.53
2000	5 891.44	9 611.42	15 852.17	35 642.22	107.95	1.65	0.33	67 107.17
2005	5 671.18	7 640.00	18 334.50	33 064.85	176.85	1.45	0.81	64 889.65
2010	5 346.75	558.31	17 987.63	50 802.50	41.59	1.64	5.65	74 744.08
2015	3 760.73	771.51	16 932.30	51 494.54	125.70	1.35	3.98	73 090.11
2016	3 543.08	296.49	19 059.43	47 963.63	173.69	1.39	5.01	71 042.72
2017	4 687.19	105.19	18 897.78	39 939.96	197.78	1.55	11.05	63 840.50

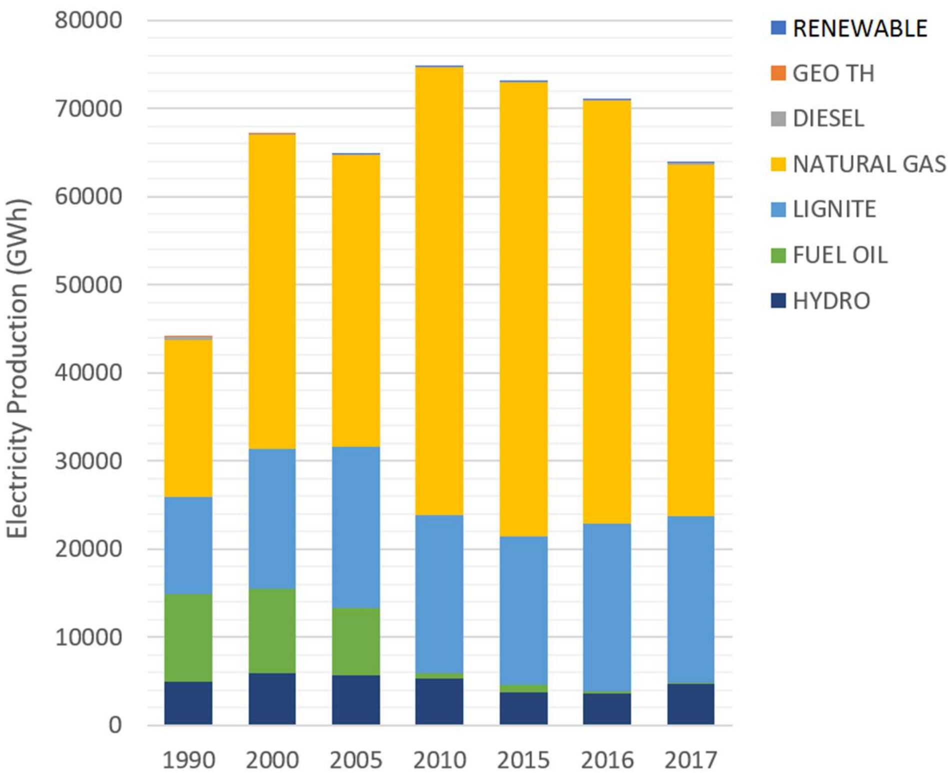


FIG. VIII.45. Chart of electricity production for EGAT’s power plants by primary source [VIII.57, VIII.58]. Legend: Geo th — geothermal.

As shown in Table VIII.10 and Fig. VIII.46, it is obvious that natural gas has played a significant role as the main fuel used for electricity production in Thailand. To diversify energy sources for electricity production, during the last several years nuclear power has been considered by the Government of Thailand as a potential option. According to the latest version of the national Power Development Plan of Thailand [VIII.58], two NPPs (1000 MW(e) each) are planned to be commissioned in 2035 and 2036, respectively.

VIII.5.2. National decision on and vision for nuclear energy strategy

At present, to support a potential and official nuclear power development programme in the near future, several activities for the preparation of a nuclear energy programme are being performed by relevant organizations, which are considering human resource development, stakeholder communication, emergency preparedness and national laws and regulations [VIII.59].

VIII.5.3. Purpose of the roadmap

The trial application of the roadmap template to the national case study pursued the following objectives:

- The preparation of information to support decision making on the development of the NES of Thailand up to 2100. This information may be useful to support a decision in the near future regarding a potential and official national nuclear power development programme.
- The illustration of an example of the NES development programme of Thailand (security and needs for nuclear fuel supply, operation performance indicators and radioactive waste management including waste disposal) for the period up to 2100, tailored as a newcomer contribution to the sustainable development of the regional and global NESs.

The nuclear power development programme presented here has not been officially released by the Government of Thailand. This roadmap is based on publicly available information and the judgements of a group of nuclear professionals in Thailand. It does not represent any official plans or roadmap of the country.

VIII.5.4. Metrics on nuclear energy position and development

In this section, some selected metrics of the case study of Thailand prepared according to the roadmap template are presented. Figure VIII.47 shows signal status indicators for Thailand. The status of a nuclear power programme for newcomers is expressing interest in nuclear energy, while other indicators such as the construction health indicator and operation indicator are not applicable since there is no nuclear power operation or construction. Figure VIII.48 presents the nuclear energy size and growth in Thailand for the actual, near, medium and long term periods, according to official plans and prospects. Official information is available only for 2030–2050 according to the national energy plan [VIII.58]. Figure VIII.49 shows the country group classification for the considered timeframes, according to official plans and prospects. Thailand is expected to be a newcomer country and technology user country in the medium and long term periods, respectively, and should be specified as a NG3 country from 2031 to 2100, according to the GAINS classification.

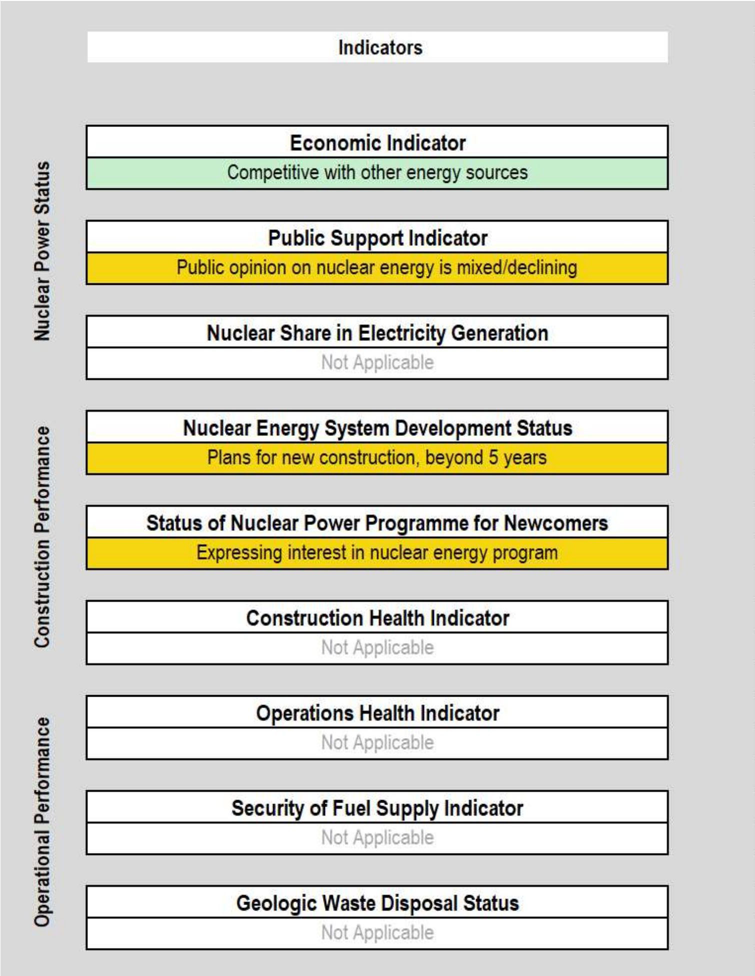


FIG. VIII.46. Signal status indicators for Thailand.

Nuclear Energy Growth

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Decreasing				
Stabilization				
Small growth (below 0.1 GWe/year)			☑	✓
Medium growth (0.1 - 0.5 GWe/year)				
Significant growth (>0.5 GWe/year)				

Nuclear Energy Size

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
No nuclear				
Small (0-10 GWe)			☑	✓
Medium (10-50 GWe)				
Large(>50 GWe)				

☑ official plan ✓ prospect

FIG. VIII.47. Nuclear energy size and growth — official plans and prospects for Thailand.

General Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Holder				
User				✓
Newcomer			☑	

GAINS Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
NG1				
NG2				
NG3			✓	✓

☑ official plan ✓ prospect

FIG. VIII.48. Country group classification — official plans and prospects for Thailand.

Figures VIII.50, VIII.51, and VIII.52 represent technology options, collaboration with other countries and collaboration agreements, respectively, for the actual, near, medium and long term periods, according to official plans and prospects. The national technology options include only final geological disposal of all wastes, based on current knowledge and skills of relevant organizations and assumption of their potential competency development and global restriction in fuel cycle related activities. In order to be able to pursue the final geological disposal national programme, Thailand will require access to technology abroad (according to prospects in the 2051–2100 timeframe). The nuclear programme of Thailand will be based on technology abroad regarding the nuclear fuel cycle starting in 2031–2050, and the recycling of spent nuclear fuel for the long term (2051–2100).

In terms of cooperation with other countries, the collaboration strategy according to prospects in the medium (2031–2050) and long (2051–2100) terms include participation in information exchange activities or joint R&D programmes, collaboration on a nuclear fuel cycle international centre, and use of nuclear fuel cycle full services. As for collaboration agreements, Thailand will use spent nuclear fuel storage services, spent nuclear fuel disposal services and HLW disposal services according to prospects in the medium (2031–2050) and long (2051–2100) terms.

National Technology Options

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle				
Recycle of SNF with only physical processing				
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				✓

Access to Technology Options Abroad

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle				
Recycle of SNF with only physical processing				
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				✓

☑ official plan ✓ prospect

FIG. VIII.49. Technology options — official plans and prospects for Thailand. Legend: SNF — spent nuclear fuel; MA — minor actinide; FP — fission product.

Collaboration Strategy

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Participate in information exchange activities			✓	✓
Joint R&D programs			✓	✓
Sharing of R&D facilities				
Collaboration on NFC front end				
NPP selling				
NPP purchasing				
Offer NPP operations services				
Use NPP operations services				
Offer NPP refuelling outage services				
Use NPP refuelling outage services				
Collaboration on NFC international centres			✓	✓
Share an NPP with another country				
Offer NFC back end services				
Use NFC back end services				
Offer NFC full services				
Use NFC full services			✓	✓

☑ official plan ✓ prospect

FIG. VIII.50. Collaboration with other countries — official plans and prospects for Thailand.

2031 – 2050	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium				
Obtain uranium				
Produce/Offer converted uranium				
Obtain converted uranium				
Produce/Offer enriched uranium				
Obtain enriched uranium				
Fabricate/Offer fuel				
Obtain fuel fabrication service				
Produce/Offer NPP design				
Use NPP design service				
Offer NPP operation service				
Use NPP operation service				
National SNF storage/Offer SNF storage service				
Use SNF storage service		✓	✓	✓
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service				
National disposal/Offer SNF disposal service				
Use SNF disposal service		✓	✓	✓
National HLW disposal/Offer HLW disposal service				
Use HLW disposal service		✓	✓	✓
Others				

☑ official plan ✓ prospect

FIG. VIII.51. Collaboration agreements — official plans and prospects for Thailand. Legend: SNF — spent nuclear fuel.

VIII.5.5. Key developments to enhance sustainability

Instead of using the condensed roadmap, a simplified visualization to represent nuclear power planning and scenarios of Thailand is employed. Figure VIII.53 presents a trial roadmap visualization for a Thailand case study as an example of a newcomer country. The dates of NPP commissioning are based on the national energy plan [VIII.41]. All key events related to sociological activities, infrastructure preparation and plant construction after 2016 are accordingly planned to occur at a certain period of time. It is noted again that the nuclear power planning and scenarios presented in this section are based on the judgements of a group of nuclear professionals in Thailand.

Key events	Dates	2000-2016	2016-2036	2037-2056	2057-2100
Sociological monitoring: yes-31%, no-26%	2007				
Sociological monitoring: yes-17%, no-83%	2011				
Legal framework on nuclear liability, safety, radiation & environmental protection, operation, waste management and decommissioning, security & non-proliferation	2016-2018				
The courses on NP in a university; retraining of energy specialist	2016				
Decision on NPP financing	2022				
Establishment of a regulatory & oversight body	2022				
Communication with stakeholders via Information centre near NPP site and Press centre in the Minis try of Information, etc	From 2022				
Directorate for NPP construction is established	2022				
Law on the Use of Atomic Energy	2016				
Start of implementation of nuclear programme	2021				
Receiving licenses for NPP siting	2024				
Country NPP as sessment	2016-2020				
INPRO Assestment	2020-2022				
General Contract & contracts on site investigation, design/working documentation, works at the site	2024-2025				
Completion of construction of manufacturing base at the NPP site	2027				
Receiving licenses for NPP construction	2027				
Start of NPP construction (concrete for Unit 1)	2028				
Signed a construction contract for two units covering fuel supply, training & other service	2029				
Start of the Unit 2 construction	2029				
The unit 1 commissioning	2035				
The Unit 2 commissioning	2036				
Start of construction of the Dry Storage of SNF	2039				
Commissioning of the Dry Storage of SNF	2044				
Start of the Unit 1 decommiss ioning	2095				
Start of the Unit 2 decommiss ioning	2096				
Sociological monitoring on SNF final disposal decision	2040-2045				
Governmental decision on final disposal, licenses on the site and facility construction	N/A				
Governmental decis ion on sending SNF abroad	N/A				
Domestic disposal facilities	N/A				
Disposal facilities abroad	N/A				

FIG. VIII.52. A trial roadmap visualization for Thailand as an example of a newcomer country (colours of the text in the left column correspond to the colours of the visualization lines to the right, different colours in the background have no particular meaning and are used to make the figure look less dull).

VIII.5.6. Nuclear power planning and scenarios

The section of nuclear power planning and scenarios is not applicable owing to limited information.

VIII.5.7. Summary

As a part of the implementation of the ROADMAPS project, the plan for the long term development of a nuclear power programme in Thailand for the period up to 2100 was developed as an example of a newcomer country. Official information and the opinions of a group of nuclear professionals were gathered and used as the basic information to fill in metrics on the nuclear energy position and to develop the roadmap template in this study. The simplified roadmap visualization for the newcomer country was developed to illustrate the example of the nuclear power planning and scenarios of the country up to 2100.

VIII.6. APPLICATION OF THE ROADMAP TEMPLATE TO THE NES OF UKRAINE

VIII.6.1. General country information

VIII.6.1.1. Case study background including strategy and development scenarios in the energy sector

After 2013, the economic stability of Ukraine was disturbed by deep changes to social stability. The industrial sectors have changed correspondingly. The redistribution of the energy resource market can be considered as a main factor in the decreasing electricity consumption. The changes of macroeconomic parameters after 2006 for the energy sector are according to different versions of the national energy strategy of Ukraine for 2030–2035 presented in Refs [VIII.60– VIII.62]. In August 2017, the new energy strategy entitled Safety, Energy Efficiency, Competitiveness was approved by the Ministry Cabinet of Ukraine (Resolution No. 605 of 18 August 2017) [VIII.63]. The prognosis for electricity production is presented in Table VIII.11.

TABLE VIII.10. PROGNOSIS OF ELECTRICITY GENERATION IN THE ENERGY SECTOR OF UKRAINE UP TO 2035

	2015	2020	2025	2030	2035
Total electricity generation (billion kWh)	157	164	178	185	195
NPP	88	85	91	93	94
Thermal power plant	61	60	64	63	63
Hydropower	7	10	12	13	13
Other RESs	2	9	12	18	25

The new energy strategy scenario indicates a slight increase of electricity generation by nuclear power plants in the period from 2025 to 2035 but does not specify the total number of nuclear units. Uncertainty is one of the reasons for the decreased economic attractiveness of nuclear power in Ukraine. It can also be a factor responsible for the absence of financial investments in nuclear power in the near term. At the same time, nuclear is recognized as a low carbon technology and, therefore, will ideally be present in the energy mix based on the Paris Climate Agreement 2015.

According to the State Statistics Service of Ukraine [VIII.47] the demand of primary energy in 2015 was characterized by the following primary source shares: 28.9% (26 million toe) natural gas; 25.5% (23 million toe) nuclear; 30% (27 million toe) coal; 11.6% (10.5 million toe) crude oil and petroleum products; 2.2% (2 million toe) biomass and waste; 1.1% (1 million toe) hydropower; 0.6% (0.5 million toe) thermal energy of the environment and waste resources; and 0.1% (0.1 million toe) windpower. The total share of all RESs was only 4% (3.6 million toe).

VIII.6.1.2. Macroeconomic and motivation conditions for the development and deployment of nuclear power

According to Ref. [VIII.63], Ukraine will have a surplus of generating power until 2025. But after 2025, the national energy system will be confronted with a shortage of electricity and new thermal and nuclear generation will be needed. The main measures for the development of the energy system of Ukraine before 2035 include extending the lifetime of nuclear and thermal generation capacities, increasing power plant economic performance and introducing energy efficient technologies, as presented in Table VIII.12.

TABLE VIII.11. STAGES OF DEVELOPMENT OF THE ENERGY SYSTEM OF UKRAINE TO 2035

Time	Stages
Up to 2020	Realization of efficiency improving programmes for the increasing of NPP capacity factors
	Deployment of electricity grids and decreasing of restrictions on electricity generation
	Lifetime extension of nuclear and thermal generation capacities
	Retirement of 2–6 GW of thermal generation capacities and replacement by highly flexible electricity generation capacities
	Development and approval of roadmap for construction of new NPPs after 2030
	Choosing a new type of NPP (thermal power, thermal efficiency, safety, localization of equipment manufacturing etc.) to be constructed after 2030
	Efforts to raise the funds for the decommissioning of old NPPs
2020 to 2025	Wide deployment of new renewable generation capacities
	Modernization or construction of HPPs
	NPPs lifetime extension according to results of periodic safety assessments
	Construction and connection to the grid of 1 GW generating capacity
2025 to 2035	Increasing the consumption of primary RESs from 20 to 25%
	Commissioning of new hydropower plant
	Replacement of hydrocarbon fuels by other fuel types where it is economically and technically feasible
	Consideration of economic and energy needs for construction of additional 1 GW nuclear generating capacity

Nuclear generation is also an important element of energy security for the energy system of Ukraine in the long term. The share of NPPs in electricity production is expected to be 50% for the period up to 2035. The development of nuclear generation is characterized by:

— The needs of the long term deployment strategy after 2035;
— The extension of the design lifetime of the operating NPPs for 20 years with subsequent decommissioning in the period 2030–2040 of about 11 GW of installed capacity;
— The non-indicated strategy of spent nuclear fuel management with decisions on the final scenarios (reprocessing or disposal in geological formations);
— The need for the identification of reactor design for new nuclear power units expected to be constructed after 2030;
— Expanding international cooperation for the diversification of nuclear fuel supplies, technologies for spent nuclear fuel management and the construction of new NPPs.

VIII.6.1.3. Macroeconomic and motivation conditions for the development and deployment of nuclear power

According to the World Bank [VIII.64], the GDP of Ukraine decreased by 8.2% in 2014 and by 9.9% in 2015 compared with 2013. Electricity consumption decreased by 8.8% in 2014 in comparison with 2013 and amounted to 134 billion kW·h; and electricity consumption decreased by 12% in 2015 in comparison with 2014 and amounted to 118 billion kW·h.

In 2015, the share of NPPs in electricity production in Ukraine was 56% considering the stable nuclear electricity supply in 2014 and 2015 (88 billion kW·h electricity generation) and the decrease in 2015 of the TPPs' share in total electricity production from 42 to 36% (from 75 to 55 billion kW·h [VIII.65]).

According to the State Statistics Service of Ukraine [VIII.65], in 2015 the consumption of natural hydrocarbon energy significantly decreased compared with its level in 2011. This tendency mainly affected coal mining and changed the role of coal in the future electricity generation structure. General information is presented in Table VIII.13.

TABLE VIII.12. CONSUMPTION OF ENERGY IN UKRAINE BY PRIMARY SOURCES FOR THE PERIOD 2011–2015

	2011	2012	2013	2014	2015
Coal (million t)	62.7	65.7	64.4	45.9	29.9
Oil (million t)	2.4	2.3	2.2	2.1	1.9
Natural gas (million t)	0.9	1.1	0.9	0.7	0.7
Liquefied gas (billion m^3)	20.7	20.5	21.3	20.1	19.8

Ukraine ratified the Paris Climate Agreement in July 2016. In December 2016, the Cabinet of the Ministry of Ukraine approved the Concept of Implementing the State Policy in the Sphere of Climate Change for the period until 2030 [VIII.66]. The Ministry of Ecology and Natural Resources of Ukraine developed an action plan for the implementation of the Paris Climate Agreement. One of the actions is the analysis of the possible risks and advantages of developing domestic nuclear power in achieving the state's objectives to reduce anthropogenic emissions of GHGs.

The new energy strategy of Ukraine until 2035 [VIII.63] simultaneously assumes a reduction of hydrocarbon fuel imports to 33% and an increase in the share of RESs to 25% by 2035. At the same time, it is expected to increase the number of suppliers of nuclear fuel, with the share of one supplier reducing from 90% in 2015 to less than 60% in 2035.

The deployment of nuclear generation is considered an essential condition for energy security of supply, decreasing GHG emissions and consumption of natural resources (primarily coal).

VIII.6.1.4. Nuclear energy as part of a national energy mix and the share of nuclear energy in the national energy mix

Currently, there are four NPPs in operation in Ukraine with a total of 15 reactors, of which two units are WWER-440 (B-213) type and 13 units are WWER-1000 (V-320) type. The plants are Zaporizhia NPP (ZpNPP), Rovno NPP (RNPP), Khmelnitsky NPP (KhNPP) and South Ukraine NPP (SUNPP). The total installed nuclear capacity is 13 835 MW. Table VIII.14 contains basic information on the NPPs in Ukraine. The structure of electricity generation in Ukraine and the volume of electricity production is shown in Fig. VIII.54.

TABLE VIII.13. NUCLEAR GENERATION IN UKRAINE

ZpNPP	Number of units:	6
	Electrical power:	6000 MW
	Number of staff:	11 000 persons
	Lifetime of Units 1&2 extended for 10 years	
	On-site dry storage facility for spent nuclear fuel	
RNPP	Number of units:	4
	Electrical power:	2835 MW
	Number of staff:	7800 persons
	Lifetime of Units 1&2 (WWER-440) extended for 20 years	
KhNPP	Number of units:	2
	Electrical power:	2000 MW
	Number of staff:	5100 persons
	The NPP with the most promise for nuclear power facility expansion in Ukraine	
South Ukraine NPP SUNPP	Number of units:	3
	Electrical power:	3000 MW
	Number of staff:	6800 persons
	Lifetime of Units 1&2 extended for 10 years	
	First NPP in Ukraine to diversify nuclear fuel supplies	

The electricity generated by NPPs in 2015 was 87 840.2 million kW·h, i.e. 2052.5 million kW·h more than in 2014.

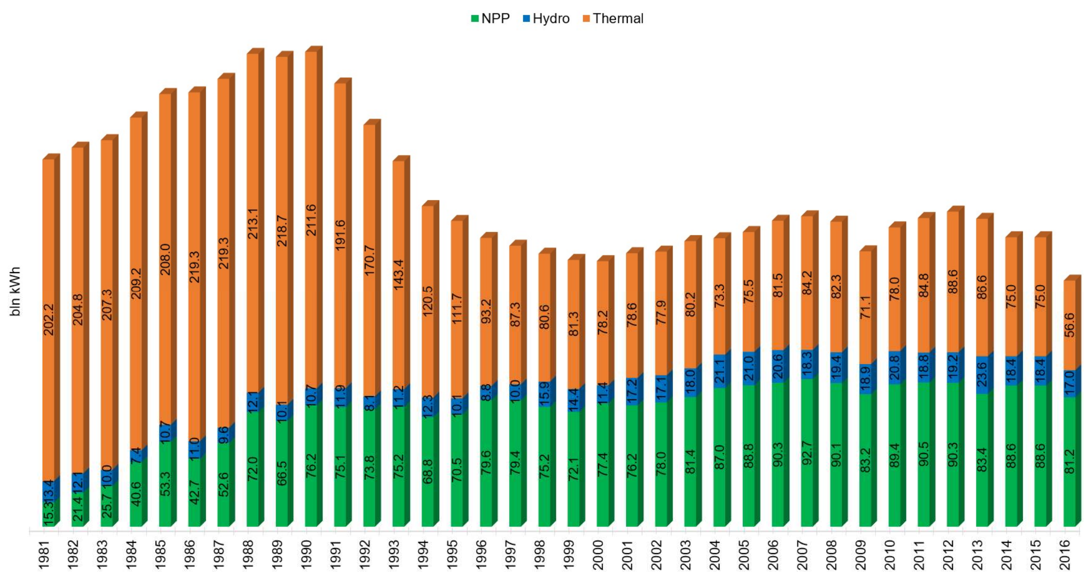


FIG. VIII.53. The structure of electricity generation in Ukraine and the volume of electricity production.

In the first quarter of 2017, the share of NPPs in the production of electricity was 55.6%, with the load factor for the first seven months being 74.2%, which is larger than its value for 2015 (72.3%).

The evolutions of the installed capacity and electricity supply shares by primary sources in Ukraine for the period 2009–2015 are presented in Fig. VIII.55. Although there were no significant changes in the generation structure, a dramatic decrease of electricity supply for all types of generation sources can be noted. The maximum electricity production in this period was 198 GW·h (in 2012) with the minimum electricity generation being 163 GW·h (in 2015). The total decrease in electricity production was 18.5%.

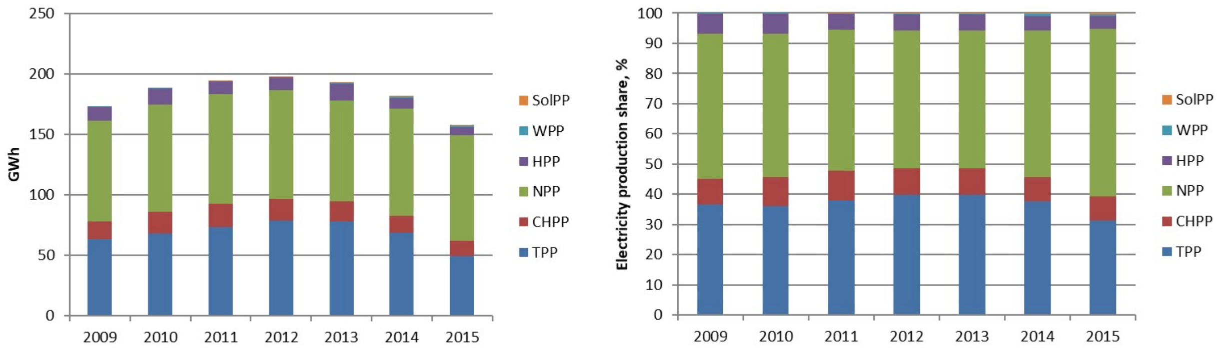


FIG. VIII.54. Electricity generation by primary sources for the period 2009–2015. Legend: SolPP — solar power plant; WPP— windpower plant; HPP— hydropower plant; CHPP— cobined heat and power plant; TPP— thermal power plant.

The most significant activity in the national nuclear programme is the lifetime extension of NPPs, owing to the fact that a significant part of the nuclear fleet was commissioned in the period 1980–1990. Before 2017, a lifetime extension of 20 years for the WWER-440 Units 1 and 2 of the RNPP was realized (the decommissioning of these units will begin in 2030 and 2031, respectively) and the lifetime extension of 10 years for the WWER-1000 Unit 1 of SUNPP and Unit 1 of ZpNPP was also realized. For WWER-1000 units, the service lifetime is extended by 10 years, with a subsequent extension by another 10 years. Currently, work is under way to extend the operational life of the WWER-1000 Unit 2 of SUNPP, Units 2 and 3 of ZpNPP and Unit 3 of RNPP. In the near future, work will begin for the WWER-1000 Units 4 and 5 of ZpNPP, Unit 3 of SUNPP and Unit 1 of KhNPP. After 2020, work will be carried out to extend the lifetime of Unit 6 ZpNPP, Unit 2 of KhNPP and Unit 4 of RNPP. General information on the completion of the design lifetime and service lifetime, taking into account the extension beyond the project, are presented in Table VIII.15.

TABLE VIII.14. COMPLETION OF THE NPP DESIGN LIFETIME ACCORDING TO LIFETIME EXTENSION

NPP	Unit	Reactor type	Completion of the project	Operation extended to:
ZpNPP	1	WWER-1000/B-320	2015-12-23	2025-12-23
	2	WWER-1000/B-320	2016-02-19	2026-12-19
	3	WWER-1000/B-320	2017-03-05	
	4	WWER-1000/B-320	2018-04-04	
	5	WWER-1000/B-320	2020-05-27	
	6	WWER-1000/B-320	2026-10-21	

NPP	Unit	Reactor type	Completion of the project	Operation extended to:
SUNPP	1	WWER-1000/B-302	2013-12-02	2023-12-02
	2	WWER-1000/B-338	2015-05-12	2025-12-31
	3	WWER-1000/B-320	2020-02-10	
RNPP	1	WWER-440/B-213	22-12-2010	2030-12-22
	2	WWER-440/B-213	22-12-2011	2031-12-22
	3	WWER-1000/B-320	2017-12-11	
	4	WWER-1000/B-320	2035-06-07	
KhNPP	1	WWER-1000/B-320	2018-12-13	
	2	WWER-1000/B-320	2035-09-07	

VIII.6.1.5. Historical background of the establishment and development of the NES

Nuclear generation in Ukraine began its development as part of the energy system of the then Soviet Union, taking into account the plans for the development of heavy industry (including metallurgy), the chemical industry and the agricultural sector. The first NPP unit began operation in 1979 (Chornobyl NPP Unit 1). The first plan for nuclear energy deployment included the construction of 16 nuclear units with a total installed capacity of 14 800 MW. Before the accident at the Chornobyl NPP, 10 nuclear power units were in operation, with a total installed capacity of 8.8 GW(e). After the accident at the Chornobyl NPP, six more nuclear reactors with a total capacity of 6 GW(e) were commissioned between 1986 and 1990. In 1990, Ukraine imposed a moratorium on the construction of new NPPs, which was cancelled by Parliament in 1993. Following cancellation of the moratorium, Unit 6 of ZpNPP was completed and connected to the grid in 1995. Unit 4 of RNPP and Unit 2 of KhNPP (WWER-1000 project B-320) were completed and connected to the grid in 2004; these are the newest nuclear power units operating in Ukraine. The national NES also includes:

- The extraction of uranium ore and the production of natural uranium technical concentrate, providing about 30% of the operating NPPs’ needs;
- The extraction of zirconium ore and the production of zirconium concentrate, completely satisfying the NPPs’ needs;
- The pilot industrial production of zirconium dioxide;

— The experimental production of zirconium tubes for nuclear fuel assemblies;
— The manufacturing of stainless steel components for fuel assemblies (top nozzle and bottom nozzle) in accordance with a licence agreement with the TVEL Fuel Company (Russian Federation).

At the same time, Ukraine has no industrial capacities for the conversion and isotopic enrichment of uranium, the production of zirconium tubes and alloys, and nuclear fuel fabrication. According to Ref. [VIII.67], the natural uranium reserves of Ukraine are 117.7 thousand tonnes in the price category below 130 US $/kg U, the confirmed reserves of 84.8 thousand tonnes, which places the country 11th in the world for explored reserves of uranium.

Up to 2019, the need for natural uranium concentrate for the annual reloading of the operating nuclear units was estimated to be 2480 tonnes of uranium per year. At present, the state enterprise VostGok (Ukraine) produces about 800 tonnes of natural uranium concentrate per year, satisfying about 30% of the demand of the domestic NPPs for natural uranium. The purpose of developing uranium mining is to fully satisfy the needs of NPPs for natural uranium for the medium and long term periods. Ukraine has a rich material and production base. Its reconstruction will create an economic cycle of zirconium production.

Ukraine has a developed technology for the production of zirconium dioxide of nuclear purity. It is also necessary to develop a technology for the production of zirconium alloy and tubes. The necessity and expediency of zirconium production development and the organization of the production of components for fuel assemblies are conditioned by the possibility of using its own resources and industrial potentials, by reducing the cost of manufacturing zirconium components and organizing its own production on the available resource base. The plans for the development of zirconium production include increasing zirconium mining to 320 tonnes per year [VIII.68].

Performing nuclear fuel fabrication by using imported components and international cooperation is expected. The design and construction of the fuel fabrication plant will be in accordance with the document The Plant for the Fabrication of Nuclear Fuel for WWER-1000 Reactors, No. 437-r, agreed by the Cabinet of Ministers of Ukraine on June 27 2012 [VIII.69].

VIII.6.2. National decision on and vision for nuclear energy strategy

VIII.6.2.1. Nuclear energy policy and commitment to develop, implement and maintain a sustainable nuclear power programme

The plans for the further development of nuclear generation in Ukraine take into consideration the 13.8 GW fleet of operating WWER nuclear reactors, the expected growth in electricity consumption, the nuclear units' lifetime extension and the assurance of the country's energy security. In this section, several main elements of the plans are briefly mentioned.

In terms of nuclear generation, the continued operation of the fleet of WWER reactors will increase the NPPs' load factor to 80%. A new 1 GW unit at KhNPP will be commissioned in 2025 (with the possibility of constructing an additional 1 GW of capacity) and an LWR NPP will be constructed after 2030 to replace the 11 GW of nuclear capacity that will be decommissioned by 2040. It is assumed that until 2035 the share of the total electricity production by NPPs will be at least 50%.

Regarding spent nuclear fuel, plans include the operation of a long term spent nuclear fuel dry storage facility on the ZpNPP site, and the constructionof the long term spent nuclear fuel Centralized Dry Storage Facility (CDSF) by 2020 in the Chornobyl exclusion zone (the construction of the latter was finished in 2020). Spent nuclear fuel shipping to the Russian Federation will cease a year before CDSF commissioning. The spent nuclear fuel design storage time in CDSF is 100 years.

Plans in the area of fuel fabrication include the manufacturing of the top and bottom nozzles for WWER fuel assemblies.

In terms of radioactive waste, the construction and operation of a facility for the disposal of low level waste and intermediate level waste in the near surface plant VECTORE (located in the Chornobyl NPP exclusion zone) is planned.

VIII.6.2.2. A governmental nuclear energy strategy and industrial institutional infrastructure

The official plans for the deployment of nuclear generation up to 2035 are included in Ref. [VIII.63] and the basic information is presented in Table VIII.16.

TABLE VIII.15. STRATEGIC PLANS FOR THE DEVELOPMENT OF NUCLEAR POWER UNTIL 2035

	2015	2020	2025	2030	2035
Approximate fraction of fuel assembly needs provided by one fuel suppler (%)	>90	<70	<60	<60	<60
Electricity production (billion kW·h)	88	85	91	93	94

VIII.6.2.3. Stakeholder involvement and status of international cooperation in the nuclear sector

International cooperation is related to the lifetime extension of existing NPPs, the construction of KhNPP Unit 3, the possibility to increase the capacity of the power units to 104% (potentially up to 110%), the diversification of nuclear fuel suppliers, spent nuclear fuel management and electricity exports. The main partners and directions for international cooperation are as follows:

— Lifetime extension: SKODA (Czech Republic);
— Unit 3 KhNPP: SKODA (Czech Republic);
— Increase of thermal power of nuclear units up to 104% (potentially up to 110%): TVEL Fuel Company (Russian Federation) and SKODA (Czech Republic);
— Hexagonal fuel assemblies and fuel supply: TVEL Fuel Company (Russian Federation);
— Fuel assemblies: Westinghouse ((United States of America);
— Nuclear fuel supply and fuel assemblies: Westinghouse ((United States of America);
— Long term storage and reprocessing of spent nuclear fuel from the WWER-440 (and reprocessing after 2025): the RT-1 plant (Russian Federation)
— Long term storage of spent nuclear fuel from the WWER-1000 (after 2025): the RT-2 plant (Russian Federation);
— Construction of the dry storage facility at ZpNPP: Duke Engineering & Services ((United States of America);
— Construction of the CDSF in the Chornobyl NPP exclusion zone: Holtec International ((United States of America);
— Research on future spent nuclear fuel management: AREVA (France);
— Electricity export: Polenergia (Poland).

Additional projects according to agreements in the field of nuclear energy are carried out with Nucleoelectrica (Argentina), China National Nuclear Corporation, China National Nuclear Power Company and Dongfang Electric (China), MVM Erbe (Hungary), Nuclear Power Production and Development (Islamic Republic of Iran), Japan Electric Power Information Center and Toshiba (Japan), Korea Hydro & Nuclear Power (the Republic of Korea) and Ingeniería y Dirección de Obras y Montaje (Spain) and others. .

VIII.6.2.4. Possible scenarios and prospects for long term nuclear energy development beyond official plans

There are no official plans for the deployment of nuclear power in the long term. It is assumed that after 2050 the development of nuclear power will take into account the following aspects:

— The operation of LWRs with a total installed capacity of 14.8 GW for the period up to 2050;

— The decommissioning of 2 GW from the KhNPP Unit 2 and the RNPP Unit 4 (2054);
— The availability of long term spent nuclear fuel management systems with a 100 year storage time;
— The lack of identification of the further management of spent nuclear fuel after the completion of the project period for storage of spent nuclear fuel in the spent nuclear fuel storage facility (2051);
— The decommissioning of the KhNPP Unit 3 and Unit 4 in 2090 and 2095, respectively.

VIII.6.3. Purpose of the roadmap

VIII.6.3.1. Purposes of the case study and relevance to the objective of ROADMAPS

A new version of the energy strategy to 2035 was approved in the second quarter of 2017 [VIII.63]. According to this document, the plan for commissioning new NPP capacities was limited by 1 GW, which is expected to be available by 2030. The new nuclear capacities expected after 2030 are to replace capacities that will be decommissioned by 2035. The main goal is to keep electricity production by NPPs at the 2035 level. The purposes of the ROADMAPS project implementation are:

— The evaluation of the need for fuel cycle technology for the period up to 2100 (uranium enrichment, long term spent nuclear fuel storage, fuel fabrication) with the goal of achieving a sustainable NES;
— The identification of a possible deficit in achieving sustainable development of the national NES based on a once-through nuclear fuel cycle and the long term storage of spent nuclear fuel;
— The structured provision of information on the development of the national NES until 2100 on the basis of a new energy strategy until 2035;
— The identification of scenarios of international cooperation taking into account the new strategy for the development of the energy complex of Ukraine until 2035.

VIII.6.3.2. Formulation of targets for moving towards locally and globally sustainable NESs and the identification of prospective partners for cooperation

The evaluation of the development of the NES up to 2035 and 2100 was carried out on the basis of the following assumptions:

- The development of nuclear generation will be based on a once-through nuclear fuel cycle and LWRs.
- Spent nuclear fuel management will be based on a deferred decision strategy until 2035.
- The diversification of nuclear fuel suppliers will increase.
- The diversification of suppliers of reactor technologies for the construction of new NPPs will increase.

VIII.6.4. Metrics on nuclear energy position and development

VIII.6.4.1. NES status indicators including official plans and expert vision and estimates

In accordance with the National Energy Regulatory Committee Resolution No. 294 of 21 March 2017, the tariff for electricity generated by NPPs in Ukraine for the second quarter of 2017 equals US \$ 0.017 kW·h [VIII.70]. At the same time, the electricity tariff for TPPs was US \$ 0.07 /kW·h. According to Decree No. 864 of the National Energy Regulatory Committee of 30 June 2017, the tariff for electricity from wind farms in the period from 2017 to 2019 will be US \$ 0.19 kW·h. The gradual increasing of the nuclear electricity tariff is included in the official plan. But even in this case, nuclear generation remains more economically attractive than other generation sources in Ukraine. Based on non-official assessments, the tariff of nuclear electricity should be at least US $ 0.12 kW·h to ensure new nuclear power construction. The signal status indicator from the roadmap template is presented in Fig. VIII.56.

The construction of the new Unit 3 at KhNPP in 2025 was approved by Ref. [VIII.63]. The construction of this WWER-1000 started in 1986, but after the accident at the Chornobyl NPP and the break-up of the former Soviet Union, construction was frozen for a long period; this particular case cannot be considered characteristic for an average construction time.

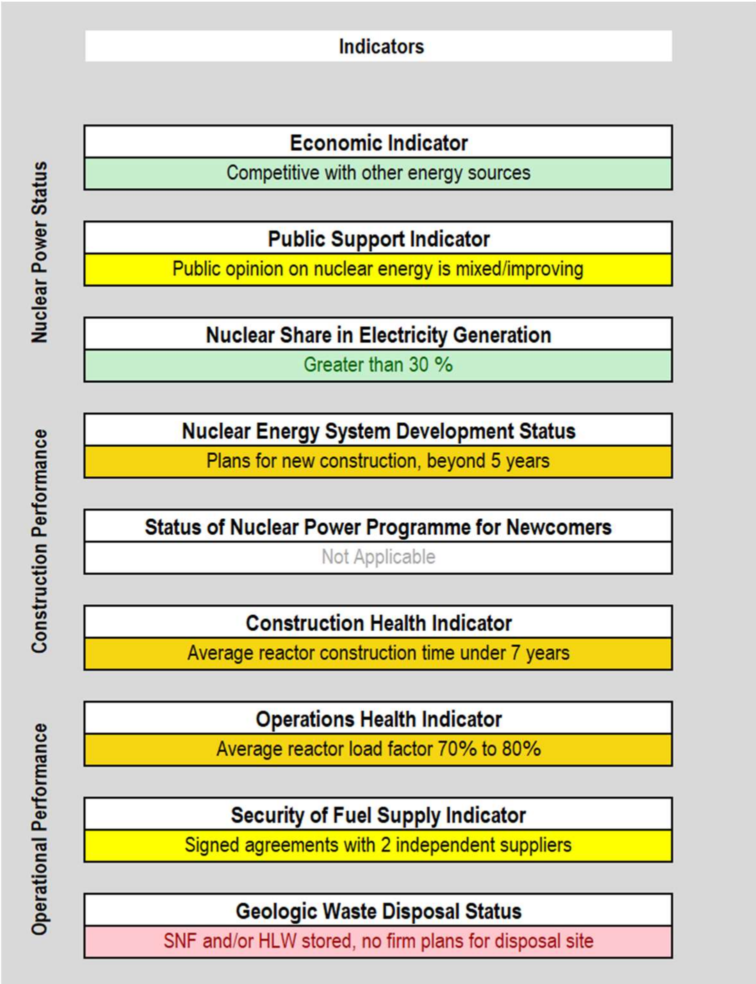


FIG. VIII.55. Signal status indicators for Ukraine.

VIII.6.4.2. Prospects for nuclear energy and country group classification

The total installed capacity of NPPs in Ukraine is 13.8 GW(e). According to the new energy development strategy for the period up to 2035, the commissioning of a new 1 GW power unit in 2025 is planned and, presumably, an additional 1 GW(e) (0.2 GW(e)/year) in the period up to 2030. The construction of new NPP units will be intended to replace the 11 GW(e) of capacity that will be decommissioned during the period 2030–2040 (1.1 GW(e)/year). Thus, the maximum total electrical capacity of nuclear power units in the period 2030–2100 will be 16.2 GW in 2035, with a minimum of 9.6 GW in 2100.

Ukraine is a technology user country and can be included in the NG2 country group according to the GAINS classification. The nuclear programme in Ukraine is based on a once-through nuclear fuel cycle with WWER PWR reactors, the long term storage of spent nuclear fuel and the use of national reserves of natural uranium, which are planned to be further developed. The plans before 2035 do not include the design of a reactor type or nuclear fuel assemblies, the introduction of long term storage technologies, the construction of a uranium enrichment plant or the reprocessing of spent nuclear fuel. Official plans do not imply the construction of a geological repository for spent nuclear fuel and radioactive waste. Spent nuclear fuel was shipped to the Russian Federation for reprocessing until 2018. Taking into account the further development of the once-through nuclear fuel cycle, Ukraine will be a user country of nuclear fuel cycle technologies for the period up to 2100. The prospects for nuclear energy and the country group classification of Ukraine are shown in Fig. VIII.57.

(a)

Nuclear Energy Growth

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Decreasing				
Stabilization	☑			✓
Small growth (below 0.1 GWe/year)				
Medium growth (0.1 - 0.5 GWe/year)		☑	✓	
Significant growth (>0.5 GWe/year)				

Nuclear Energy Size

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
No nuclear				
Small (0-10 GWe)				
Medium (10-50 GWe)	☑	☑	✓	✓
Large(>50 GWe)				

☑ official plan ✓ prospect

(b)

General Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Holder				
User	☑	☑	✓	✓
Newcomer				

GAINS Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
NG1				
NG2	☑	☑	✓	✓
NG3				

☑ official plan ✓ prospect

FIG. VIII.56. (a) Prospects for nuclear energy and (b) country group classification of Ukraine.

(a) Technology options

A once-through fuel cycle with long term storage of spent nuclear fuel in the CDSF in the Chornobyl NPP exclusion zone is envisaged by a new strategy for the development of the energy sector of Ukraine until 2035. There is no long term programme for the development of nuclear power. It is possible to assume a once-through nuclear fuel cycle based on WWER PWR until 2100.

Between 1993 and 2018, the spent nuclear fuel of Ukrainian NPPs has been transported to the Russian Federation for storage and reprocessing. The reprocessed uranium and plutonium will be returned to Ukraine only after WWER-1000 spent nuclear fuel reprocessing. However, this is not the case for the WWER-440 spent nuclear fuel reprocessing. The total volume of spent nuclear fuel up to 2015 is 310 t HM for WWER-440 and 2400 t HM for WWER-1000.

According to Ref. [VIII.67], the total confirmed reserves of natural uranium at a cost of less than 260 US $/kg are 220.7 thousand tonnes. Unconfirmed additional reserves may amount to 277 thousand tonnes.

Until 2020 there was no plant in Ukraine for the fabrication of nuclear fuel. The suppliers of fuel assemblies are the TVEL Fuel Company (Russian Federation) and Westinghouse (United States of America). According to the Concept of the State Targeted Economic Programme for the Development of the Nuclear Industrial Complex of Ukraine of 2016 [VIII.68], the construction of a plant for nuclear fuel fabrication (the annual needs of domestic NPPs are 630 fuel assemblies) is envisaged by 2020.

Since 2001, a long term dry type storage facility has been in operation at the ZpNPP site. The design storage period is 50 years and the capacity is 380 containers. Twenty-four spent fuel assemblies can be loaded into each container. The dry storage facility provides for the storage of spent nuclear fuel of 6 GW capacity for the operation periods of all units with 20 years' lifetime extension.

According to Ref. [VIII.71], it is planned to build and operate a long term dry storage facility in the Chornobyl NPP exclusion zone. The design life of the CDSF is 100 years. The storage facility capacity is for 450 containers. The storage houses 12 010 WWER-1000 fuel assemblies and 4519 WWER-440 fuel assemblies. Commissioning is planned for 2020. The storage of spent nuclear fuel for new power units is under consideration.

Geological disposal is not considered in official documents. According to expert economic estimation, after the completion of the projected storage period of spent nuclear fuel in the ZpNPP spent nuclear fuel storage facility in 2051, it will be possible to consider the placement of spent nuclear fuel in a deep geological repository. This decision may be a consequence of the high cost of the reprocessing of spent nuclear fuel and the development of a once-through nuclear fuel cycle according to the new energy strategy of Ukraine up to 2035 [VIII.63]. Unlike the long term spent nuclear fuel dry storage construction in the Chornobyl exclusion zone, geological disposal was not considered in the roadmap template.

General information about the technology options of Ukraine up to 2100 is presented in Fig. VIII.58.

National Technology Options

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle	☑	☑	✓	✓
Recycle of SNF with only physical processing				
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				

Access to Technology Options Abroad

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle	☑	☑	✓	✓
Recycle of SNF with only physical processing	☑	✓	✓	
Limited recycling of spent fuel				
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geological disposal of all wastes				

☑ official plan ✓ prospect

FIG. VIII.57. Technology nuclear fuel cycle options of Ukraine to 2100.

(b) International collaboration

The directions of international cooperation are determined in accordance with:

- International conventions (for example, the Convention on Nuclear Safety (1994), the Convention on the Physical Protection of Nuclear Material (1980), the Vienna Convention on Civil Liability for Nuclear Damage (1963), the Treaty on the Non-Proliferation of Nuclear Weapons (1968));
- Agreements with international organizations (the Agreement between Ukraine and the IAEA on the Application of Safeguards (1998));
- Agreements between the Governments of Ukraine and Bulgaria, the Czech Republic, Finland, France, the Russian Federation, Sweden, the United States of Americaand other countries.

Ukraine cooperates with the World Association of Nuclear Operators (and has done since 1997), the European Commission, the European Bank of Reconstruction and development (and has done since 2013), the WNA (and has done since 2006), European Nuclear Installations Safety Standards (and has done since 2015), the International Framework for Nuclear Energy Cooperation (and has done since 2007), European Utility Requirements for LWR Nuclear Power Plants (and has done since 2007), FORATOM (and has done since 2011), and the IAEA (and has done so since 1957).

For the construction of new NPP units, the technologies of Generation III+ power units of international suppliers will be used, taking into account the compliance with national regulatory requirements in the field of safety, the recommendations of the IAEA and the Western European Nuclear Regulators‘ Association, European Utility Requirements for LWR Nuclear Power Plants and INPRO Methodology.

Scientific and technical support for NPP operation (normative documentation, fuel use, operating modes, equipment, employee training) is used and is expected to be used in the future.

Since 2010, Ukraine (in the form of the state concern Nuclear Fuel) is a shareholder (with 10% of shares) of the International Uranium Enrichment Center (Russian Federation).

Based on the plans of the Russian Federation for the commissioning of a WWER-1000 reprocessing plant in 2025, it is expected that the total volume of WWER-1000 spent nuclear fuel will be reprocessed there until 2050. The completion of WWER-440 spent nuclear fuel reprocessing is expected by 2025.

VIII.6.5. Key developments to enhance sustainability

VIII.6.5.1. Economics

For 2017 the LCOE for the NPPs in Ukraine is 1.7 c/kW·h, for TPPs US $ 0.07/kW·h and for wind farms US $ 0.19/kW·h. The cost of electricity from the NPPs does not include the capital cost of building new power units. Taking into account the capital costs for new NPPs, LCOE is expected to be at least US $ 0.12/kW·h [VIII.72]. In the period up to 2030 it will be necessary to increase the price of electricity from NPPs in order to raise funds for the construction of new nuclear power units. For the period up to 2050 it is possible to assume a further increase in the price of electricity generated by NPPs for the implementation of the spent nuclear fuel management programme in the long term.

If the refund period of the power units is 10 years, from 2040 it is possible to expect a decrease in LCOE. In the period from 2050 to 2060, it can be assumed that LCOE for NPPs will not exceed LCOE for renewable generation sources. In the period up to 2100, LCOE for NPPs will decrease in the conditions of operation of Generation III+ power units with enhanced economic indicators, lack of construction of new power units and the implementation of strategic decisions of final spent nuclear fuel management.

VIII.6.5.2. Safety

Normative documentation of Ukraine in the field of nuclear energy use fully takes into account IAEA requirements and recommendations in terms of ensuring the safety of NPPs, which has been confirmed by various international missions and the IAEA. The nuclear legislative framework is regulated by a number of laws covering all areas of activity in nuclear energy use. The laws regulate the principles of nuclear safety and radiation protection described in the IAEA Safety Fundamentals. Directive 2013/59/EURATOM has been implemented; it establishes basic safety standards to protect against the danger posed by ionizing radiation. The national report of Ukraine on the updated action plan contains information on the harmonization of the nuclear and radiation safety standards of Ukraine with the reference levels of the Western European Nuclear Regulators' Association. The partnership inspections of the IAEA and the World Association of Nuclear Operators confirmed the safety of operation of the power units of the NPPs in Ukraine. From 2030 it is planned to build and operate Generation III + power units taking into account the new safety requirements.

VIII.6.5.3. Resources

For the period up to 2100 it is planned to deploy a once-through nuclear fuel cycle, which is stipulated by the new energy strategy of Ukraine for the period up to 2035.

VIII.6.5.4. Waste management

Since 2001, a long term dry storage facility for spent nuclear fuel has been in operation at the ZpNPP site. In 2019 a centralized long term storage facility for WWER-440 and WWER-1000 spent nuclear fuel was planned to be put into operation; however, da facto its construction was finished in 2020.

VIII.6.5.5. Non-proliferation

The basic principles of the state system of nuclear non-proliferation guarantees are defined by the Law of Ukraine No. 39 On Nuclear Energy Use and Radiation Safety” dated 8 February 1995 [VIII.73]. The Law of Ukraine No. 3092-IV of 16 November 2005 ratified the Additional Protocol to the Safeguards Agreement. Ukraine fully complies with the Treaty on the Non-Proliferation of Nuclear Weapons of 1968.

VIII.6.5.6. Society

Public support for nuclear generation ensured by the lower cost of electricity from the NPPs of Ukraine compared with other types of generation sources [VIII.74]. Another consideration is the jobs it provides, the development of science it leads to and the possibility of expanding the national production of equipment for NPPs. General information about key developments of the NES of Ukraine up to 2100 to enhance its sustainability are presented in Fig. VIII.59 using the roadmap template.

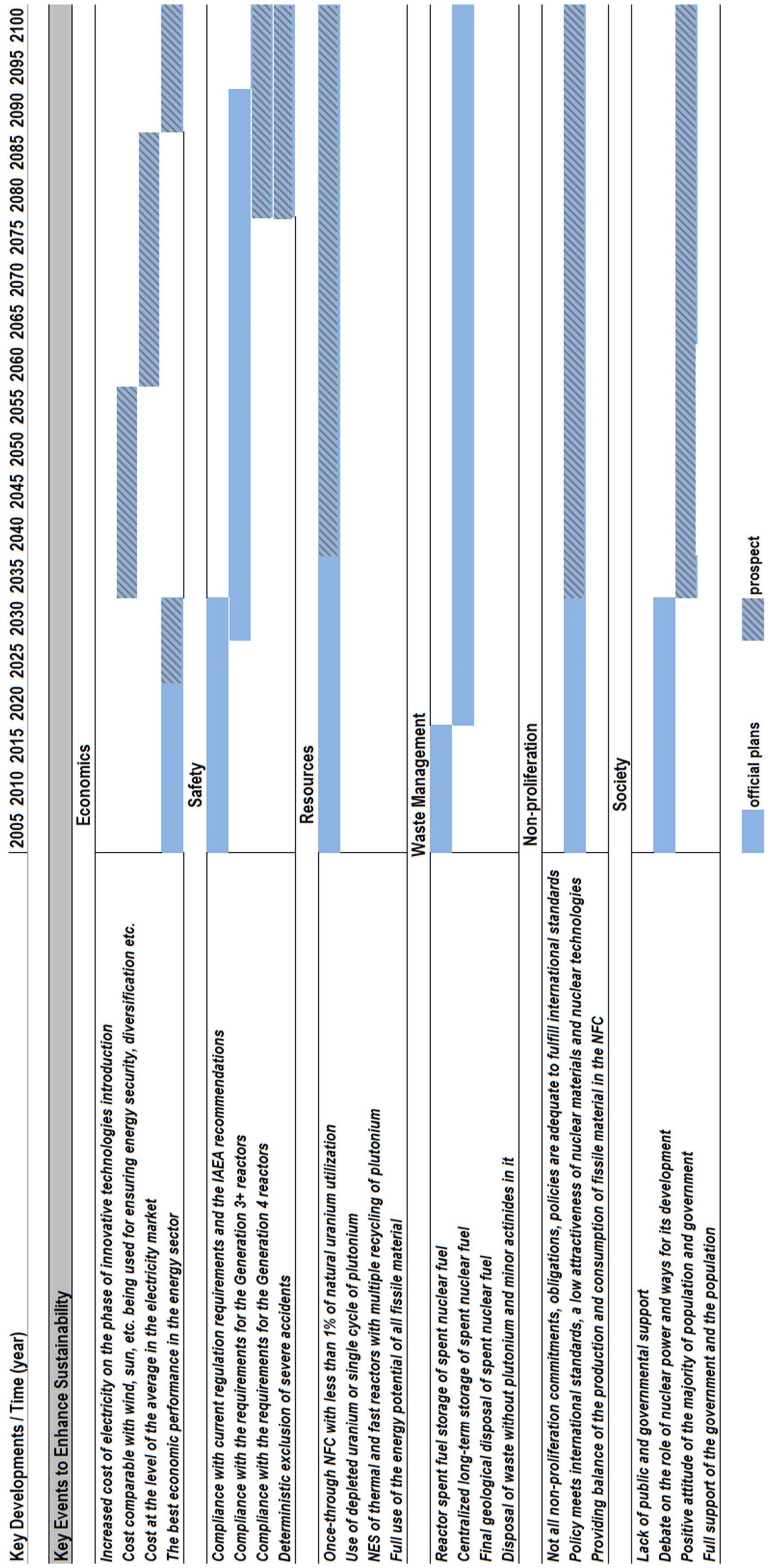


FIG. VIII.58. Key developments to enhance the sustainability of the NES of Ukraine to 2100.

VIII.6.5.7. Key events in the informational support and legal framework

The main directions in the legal framework arising from the implementation of the new energy strategy of Ukraine for the period up to 2035 included the following documents:

- Conception (strategy) of long term spent nuclear fuel management;
- Conception (programme) for the future development of nuclear energy;
- Cadastre of the land for new NPPs (the list of the land areas in Ukraine that have been confirmed by the Government for new NPP construction);
- Safety analysis reports for NPP lifetime extension;
- Choice of reactor types (design) for new NPP;
- Research, design and approval of national geological disposal;
- Diversification of nuclear fuel supply;
- Long term contracts for nuclear fuel supply;
- Implementation and support of regulatory requirements for the Generation III+ reactors.

'Facilities' include activities envisaged by the new energy strategy to have been carried out by 2035, as well as expert evaluations carried out within the framework of other projects:

- The operation of a centralized dry storage spent nuclear fuel facility is approved by the Law of Ukraine [VIII. 75].
- Operation of KhNPP Unit 3 (operation beginning in 2025 is approved by Ref. [VIII.65]).
- Operation of KhNPP Unit 4 (considered in Ref. [VIII.63]).
- Operation of new NPPs with a total installed capacity of 10.8 GW instead of old NPPs, which will be decommissioned in the period 2030–2040).
- Fuel fabrication, with the commissioning of a nuclear fuel factory in 2020, according to Ref. [VIII.63], is considered.
- Increasing of CDSF capacity and the storage of spent fuel from new NPPs after 10 years of storage in the reactor spent fuel pools.
- Reprocessing of spent nuclear fuel from WWER-440 (310 t HM of spent nuclear fuel from WWER-440 were shipped to the Russian Federation before 2016).
- Reprocessing of spent nuclear fuel from WWER-1000 (2400 t HM of WWER-1000 spent nuclear fuel had been shipped to the Russian Federation by 2015).
- Operation of a long term radioactive waste storage facility is planned from 2020.
- Synchronization of national energy system with the European Network of Transmission System Operators (the project is implemented according to the plans of Ukraine for integration into the European Union).

Key developments in the institutions and infrastructure of Ukraine are shown in Fig. VIII.60.

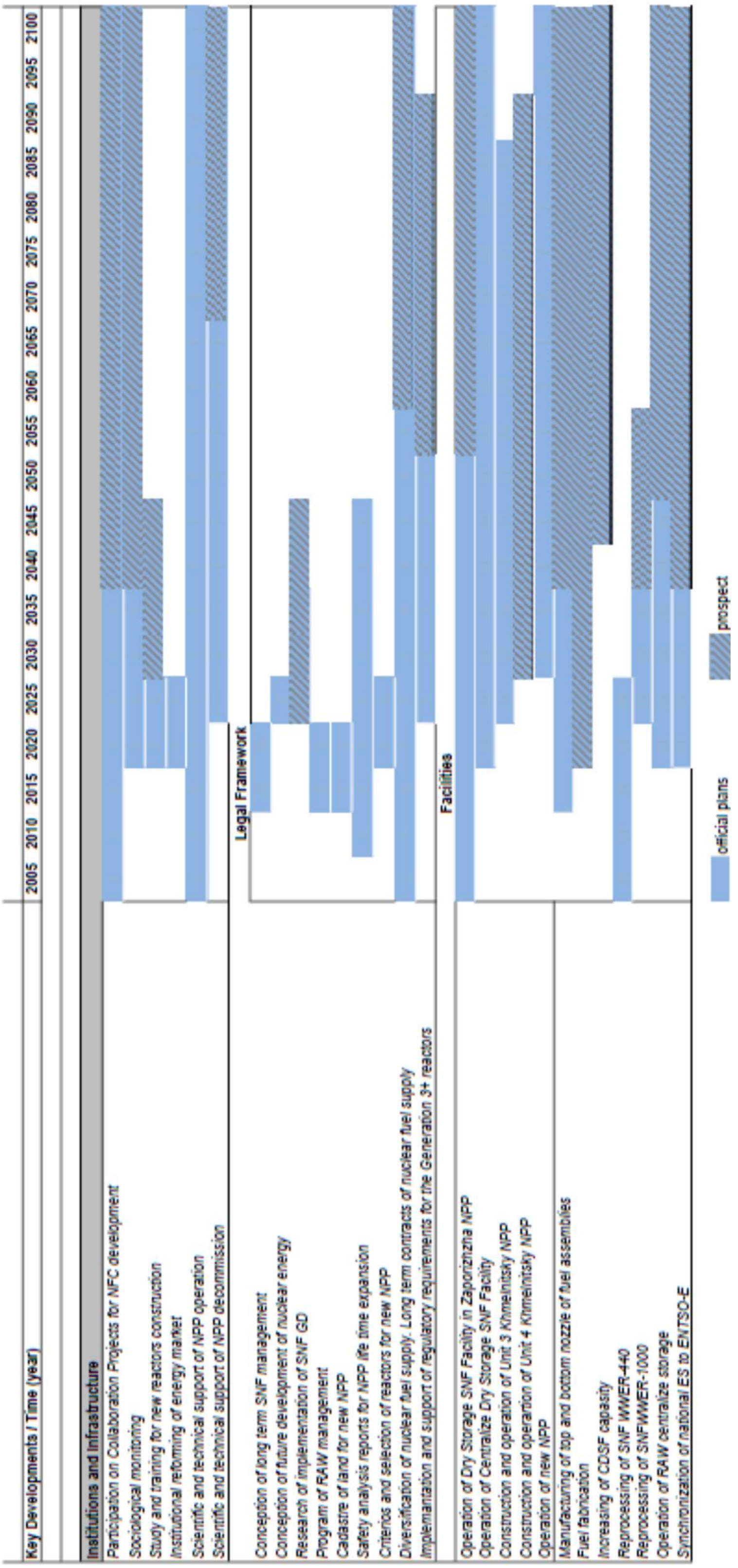


FIG. VIII.59. Key developments in the institutions and infrastructure of Ukraine.

VIII.6.6. Nuclear power planning and scenarios

VIII.6.6.1. NES deployment scenarios including official plans and expert opinions and estimates

To create scenarios for the development of nuclear generation, the following assumptions were made:

- Once-through nuclear fuel cycle based on WWER (1000 MW) and LWR (1200 MW).
- Export of spent nuclear fuel from WWER-440 and WWER-1000 to another country.
- Operation of a centralized spent nuclear fuel repository from 2020. The spent nuclear fuel storage time is 100 years, with a capacity to store spent nuclear fuel from Units 1 and 2 of KhNPP, 1–3 of SUNPP and 1–4 of RNPP with the possibility to store spent nuclear fuel from new NPPs and increase the design capacity of the CSFDSF.
- Operation of a dry type storage facility at the ZpNPP site. Spent nuclear fuel storage time is 50 years. Possibility to extend the storage period by 50 years based on safety analysis reports and long term stabilities of spent nuclear fuel rods.
- Extension of the operational life of old type NPPs for 20 years based on safety analysis reports. Extending the lifetime of new NPPs is not being considered.
- Decommissioning of 10.8 GW in the period from 2030 to 2040.
- Construction and operation of new NPPs with a total capacity of 10.8 GW in the period from 2030 to 2045.

Regarding the reactor fleet, according to the new energy strategy up to 2035, in 2025 it is planned to connect Unit 3 of KhNPP (WWER-1000) to the power system. Unit 4 of KhNPP (WWER-1000) is expected to be commissioned in 2030, based on expert estimates.

The structure of NPP operation until 2100 is presented in Fig. VIII.61. Taking into account the NPPs' lifetime extension for 20 years, in 2030 and 2031 the design lifetime of Units 1 and 2 of RNPP (WWER-440) will be completed. Until 2035, Units 1 and 2 of SUNPP (WWER-1000) will be decommissioned. Thus, the total capacity of NPPs that will be decommissioned before 2035 will be 2.8 GW. Up to 2040, the decommissioning of NPP WWER-1000 units will be realized according to the following sequence: 2036 — Units 1 and 2 of ZpNPP; 2037 — Unit 3 of ZpNNP; 2038 — Unit 4 of ZpNPP and Unit 3 of RNPP; 2039 — Unit 1 of KhNPP; and 2040 — Unit 3 of SUNPP and Unit 5 of ZpNPP. Thus, in the period from 2035 to 2040, the total capacity of decommissioned NPPs will be 8 GW.

After 2040, decommissioning of NPPs will be carried out in the following order: 2046 — Unit 6 of ZpNPP; 2055 — Unit 2 of KhNPP and Unit 4 of RNPP; 2085 — Unit 3 of KhNPP; and 2090 — Unit 4 of KhNPP.

In the framework of this study, the construction of a new LWR with a capacity of 1200 MW is planned. The construction of one power unit of 1.2 GW by 2035 is considered, and in the period 2035–2040 an additional 4.8 GW capacity is projected. Thus, starting from 2030 until 2045 the total capacity of the new NPPs should be 10.8 GW. No new NPP capacity is expected after 2045.

The total installed NPPs capacity is assumed to be 15.835 GW in 2030, 16 GW in 2040 and 14.8 GW in 2050. The total capacity of NPPs will be reduced to 9.6 GW by 2100. The maximum total NPP capacity in this study is expected to be 16.2 GW in 2035.

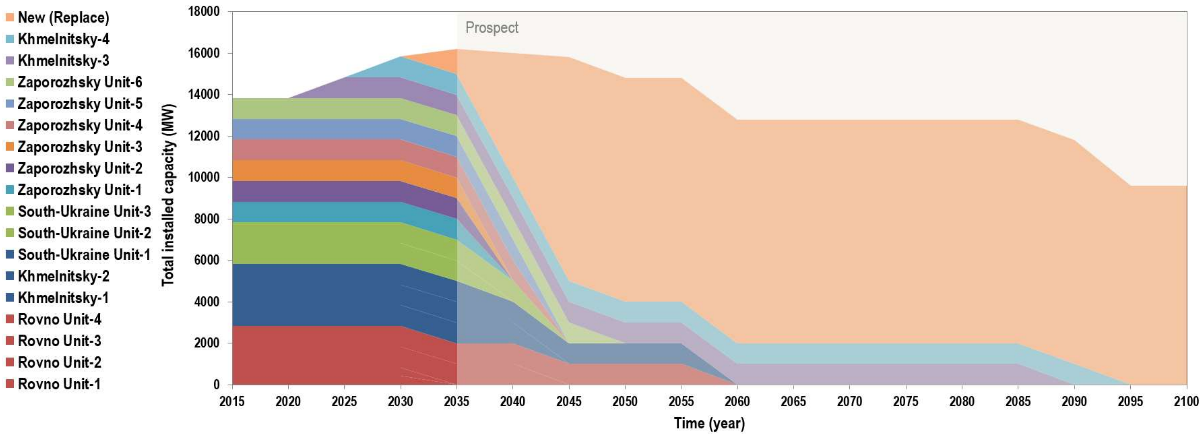


FIG. VIII.60. Reactor fleet of NPPs to 2100.

VIII.6.6.2. Reactor and nuclear fuel cycle data

TABLE VIII.16. THE BASELINE DATA FOR THIS STUDY

	Parameter	Data
Reactors		
WWER-1000	Net electric power output (MW)	1000
	Load factor (%)	75–80
	Thermal efficiency (%)	32
	Mass UO_2 in fuel assembly (kg)	494
	Average burnup ($MW/d^{-1}/kg^{-1}$)	50
	Enrichment (%)	4.4
	Numbers of reloads of fuel assemblies	42
	Numbers of fuel assemblies in core	163
WWER-1000 (Units 3 and 4 KhNPP)	Net electric power output (MW)	1000
	Load factor (%)	82
	Thermal efficiency (%)	32
	Mass UO_2 in fuel assembly (kg)	545
	Average burnup ($MW/d^{-1}/kg^{-1}$)	60
	Enrichment (%)	4.7
	Numbers of reloads of fuel assemblies	36
	Numbers of fuel assemblies in core	163

WWER-1200	Net electric power output (MW)	1200
	Load factor (%)	85
	Thermal efficiency (%)	32
	Mass UO_2 in fuel assembly (kg)	545
	Average burnup ($MW/d^{-1}/kg^{-1}$)	60
	Enrichment (%)	4.95
	Numbers of reloads of fuel assemblies	36
	Numbers of fuel assemblies in core	163
Nuclear fuel cycle		
WWER-1000		18
WWER-1000 Units 3 and 4 KhNPP	Reloads (t HM)	17
WWER-1200		17
Tails	Enrichment (%)	0.25
CDSF	Capacity (t HM)	5650
	Storage period (year)	100
Dry storage facility at ZpNPP	Capacity (t HM)	3800
	Storage period (year)	50

The baseline data for the study is presented in Table VIII. 17. For each examined period, electricity generation is defined by the number of NPP units and by the load factor. According to the plans of the operating company, it is expected to implement measures to increase the load factor up to 2020 from 75% to 78%, and later up to 80% by optimizing repairs, reducing dispatch restrictions and building additional transmission lines. For new NPPs, it is assumed that the load factor will be 85%. Taking in to account a 20 year lifetime extension for existing NPPs, the commissioning of 1 GW of new capacity by 2025 and another 1 GW by 2030, and the construction of 10.8 GW of new NPPs in the period 2030–2040, the assessed electricity production will increase from 12 708 MW/year in 2030 to 13 140 MW/year in 2040. Based on the assumptions made, the production of electricity at NPPs for the entire period of research is given in Fig. VIII.62.

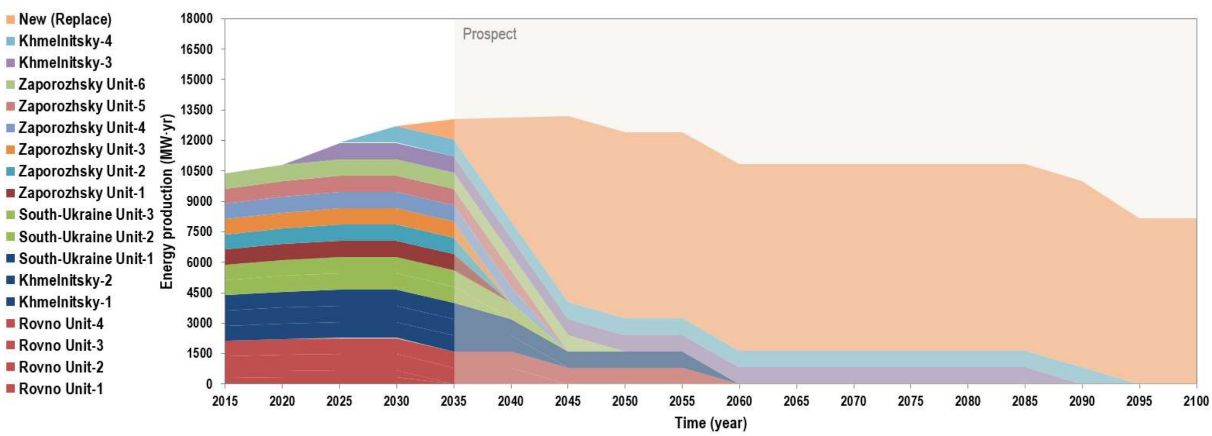


FIG. VIII.61. Electricity production by units of NPP in Ukraine for the period up to 2100.

According to Ref. [VIII.67], the total proven reserves of natural uranium at a cost of less than 260 $/kg are 220.7 thousand tonnes. Unconfirmed additional reserves may amount to 277 thousand tonnes. Currently, uranium production in Ukraine is 800 t/year, which cover about 30% of the demand. The annual demand of the existing fleet of NPPs is 2480 t/year. According to official plans, the uranium production needed to fully satisfy the annual requirement will be provided in 2020.

When determining the demand for natural uranium, the following assumptions are made:

- Uranium mining will produce 2480 t/year from 2020.
- Fuel assemblies produced by TVEL Fuel Company are manufactured using natural uranium from Ukraine.
- Westinghouse's fuel assemblies are manufactured using natural uranium from the world uranium market.

Thus, natural uranium will be purchased on the world market until 2055. From 2020, the need for natural uranium from the Russian Federation has been eliminated. The extraction of natural uranium at a level of 2400 tonnes/year will be sufficient for the production of enriched nuclear fuel. This can be expected after the decommissioning of Unit 2 of KhNPP and Unit 4 of RNPP when utilizing fresh fuel of TVEL Fuel Company in the active core. In Fig. VIII.63, the amount of uranium needed for NPPs in Ukraine is presented.

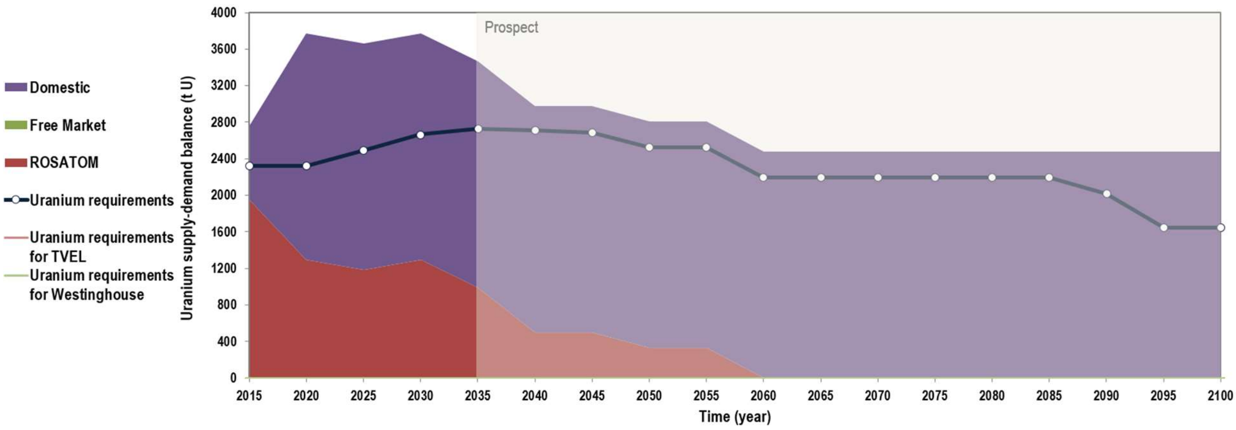


FIG. VIII.62. Uranium consumption by NPPs to 2100.

The need for conversion is determined by the lack of domestic capacity and the presence of two suppliers of fuel assemblies. TVEL Fuel Company (Russian Federation) uses the capacity of Russian Federation conversion plants to produce its fuel. Westinghouse ((United States of America) purchases fuel conversion services on the world market. Information on the need of Ukraine for conversion of natural uranium up to 2055 is presented in Fig. VIII.64.

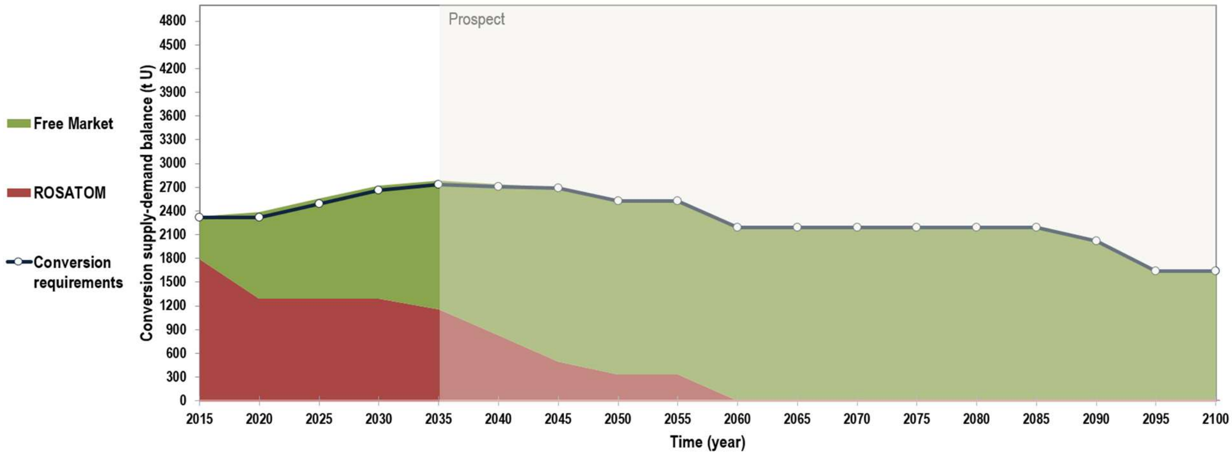


FIG. VIII.63. Conversion of natural uranium to 2100.

The need for enrichment is determined by the lacking domestic facilities and the utilizing of two nuclear fuel assembly designs in the reactor cores. For fuel assemblies of the TVEL type, the enrichment is fully provided by the fuel supplier (Russian Federation). For fuel assemblies of the Westinghouse type, the enrichment services are purchased on the free market. The total volume of enrichment capacity is defined by the volume of the nuclear fuel supply as can be seen in Fig. VIII.65.

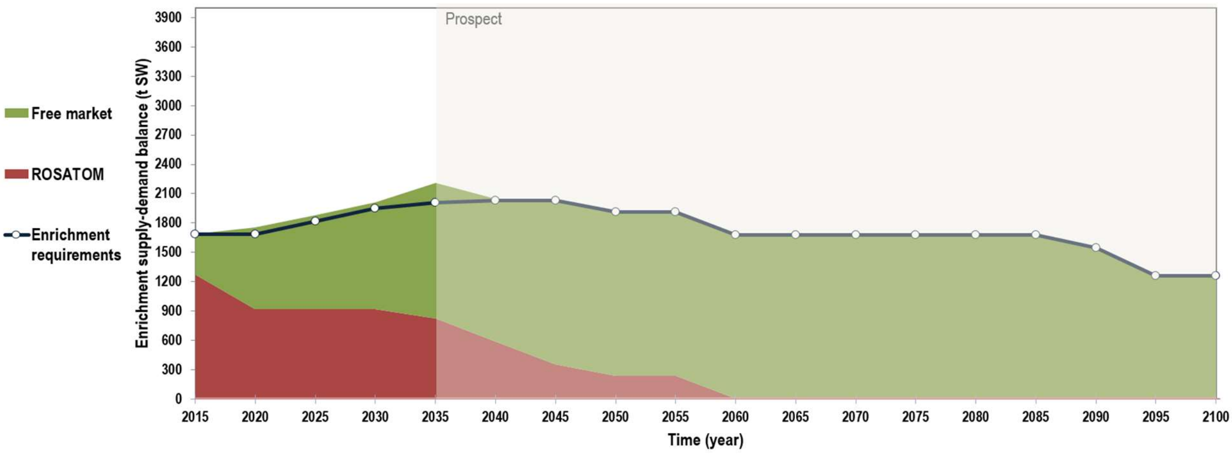


FIG. VIII.64. Enrichment supply–demand balance to 2100.

At the time of this study, Ukraine did not have a domestic nuclear fuel fabrication facility. According to Ref. [VIII.68], a fuel fabrication plant is planned after 2020. As part of this study it is assumed that all fuel assemblies will be supplied by TVEL Fuel Company (who manufacture assemblies in the Russian Federation) and Westinghouse (who manufacture assemblies in Vasteras, Sweden). The total quantity of fuel assemblies used for NPPs in Ukraine in 2015 was 249 t HM.

The operation of Westinghouse nuclear fuel in active cores of WWER-1000 power units is realized in accordance with the nuclear fuel qualification project launched by a bilateral collaboration agreement between the Governments of Ukraine and United States of America in

2000 [VIII.76]. The main goal of the project was to diversify the supply of nuclear fuel to and ensure the energy security of Ukraine.

In 2017, the Westinghouse fuel expansion programme was approved for WWER-1000 power units. It is planned to introduce fuel at Units 2 and 3 of SUNPP and Units 1 and 3–5 of ZpNPP. The volume of implementation is 42 fuel assemblies (18 t HM), which corresponds to an annual reloading. Fuel introduction was implemented in the following order: 2014 — Unit 3 of SUNPP; 2015 — Unit 2 of SUNPP; 2016 — Unit 5 of ZpNPP; 2017 — Unit 1 of ZNPP; and 2018 — Units 3 and 4 of ZpNPP.

To simplify the calculation of the material flows, it is assumed that the fuel assemblies of TVEL and Westinghouse have similar initial enrichment and mass of UO_2 (this assumption does not lead to a significant inaccuracy in the results). The fuel fabrication supply–demand balance to 2100 can be seen in Fig. VIII.66.

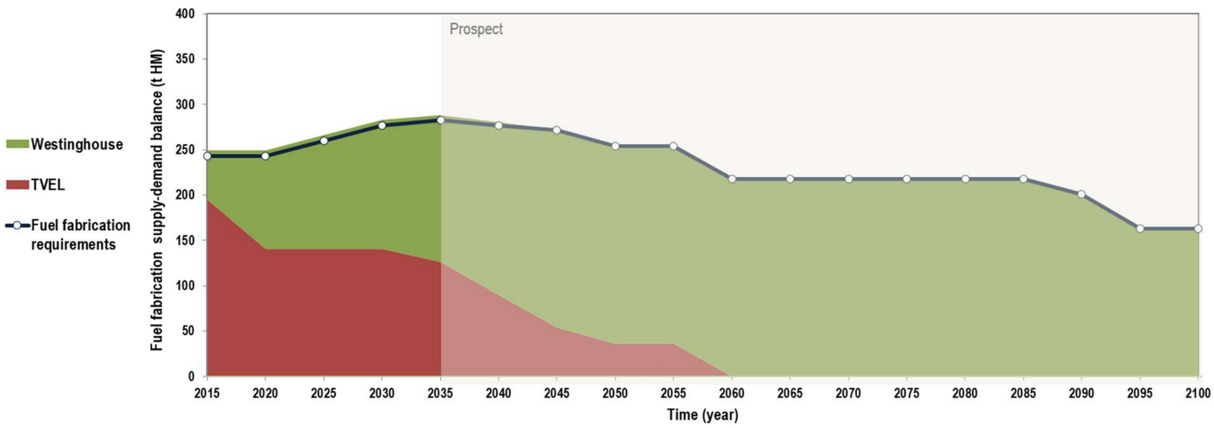


FIG. VIII.65. Fuel fabrication supply–demand balance to 2100.

The annual unloading of nuclear fuel used in nuclear reactors was 249 t HM in 2015 (including 213 t HM fuel assemblies from TVEL Fuel Company and 36 t HM fuel assemblies from Westinghouse). In this analysis, the annual quantity of spent nuclear fuel that is unloaded from the reactor cores is determined by the fuel loading and unloading schemes of Westinghouse and TVEL Fuel Company for the currently operating plants. It is assumed that new NPPs will use Westinghouse fuel, and the quantity of spent nuclear fuel unloaded during the decommissioning of old units is determined by the TVEL Fuel Company fuel management scheme. It is assumed that after unloading, the fuel assemblies will be stored for five years in the reactor pool. After that period of cooling, the spent nuclear fuel from the power units of SUNPP, KhNPP and RNPP is assumed to be shipped for storage and processing in the Russian Federation. The spent nuclear fuel from the power units of ZpNPP is assumed to be sent to a long term dry storage facility located on the site of the ZpNPP.

The following initial data were used for evaluation:

- — The total design volume of the WWER-1000 NPP reactor pools is 3349 t HM (7789 fuel assemblies).
- — The total amount of spent nuclear fuel that at the time of the study was stored in the reactor pools of the WWER-1000 NPPs is 2050 t HM.
- — The total projected capacity of each new WWER-1200 NPP reactor pool is 315 tHM (732 fuel assemblies).
- — The total design capacity of the reactor pool of one WWER-440 is 1200 t HM (1049 fuel assemblies).

— The total quantity of spent nuclear fuel that at the time of this study was stored in the reactor pools of all WWER-440s was 133.87 t HM (615 fuel assemblies).

In the framework of this study the once-through nuclear fuel cycle is considered. The long term storage of spent nuclear fuel in dry type storage facilities in Ukraine without recycling is assumed. It is assumed that spent nuclear fuel will be accumulated in the CDSF and in the dry storage facility in ZpNPP. When the design capacity of CDSF (5560 t HM) is fully reached, the additional capacity for the storage of spent nuclear fuel from the new NPPs is assumed to become available. The spent nuclear fuel storage supply–demand balance up to 2100 is shown in Fig. VIII.67.

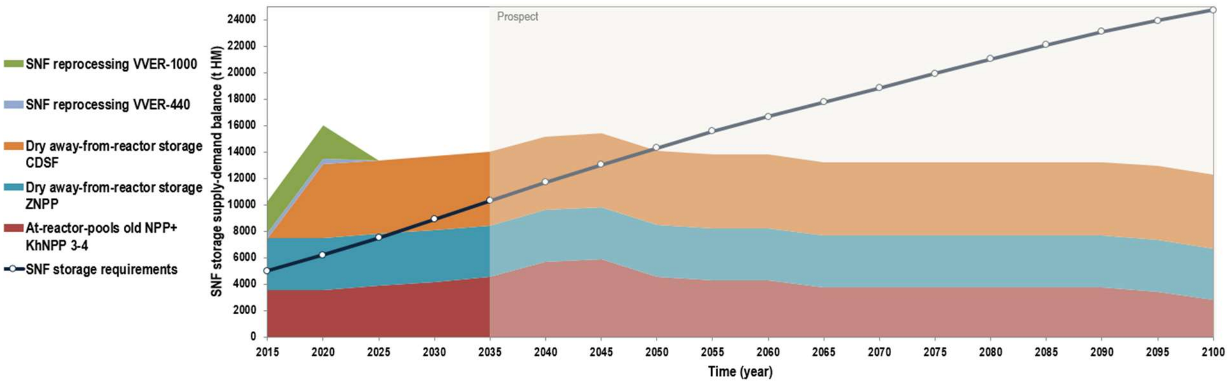


FIG. VIII.66. Spent nuclear fuel storage supply–demand balance up to 2100.

Spent nuclear fuel from NPPs in Ukraine has been shipped for reprocessing in the Russian Federation and will continue to be so until the commissioning of a national CDSF, the construction of which was finished in 2020. The total amount of spent nuclear fuel shipped to the Russian Federation in 2015 was: 380 t HM of spent nuclear fuel from WWER-440 NPPs and 2400 t HM of spent nuclear fuel from WWER-1000 NPPs. The reprocessing of WWER-440 spent nuclear fuel for the period of this study was realized at the Russian Federation reprocessing plant RT-1. The reprocessing of WWER-1000 spent nuclear fuel is expected to start in 2025.

The evaluation of reprocessing facilities for the spent nuclear fuel from the NPPs in Ukraine included the following assumptions:

— The annual spent nuclear fuel reprocessing is equal to the reactor core unloading (7 t HM for WWER-440 and 18 t HM for WWER-1000).
— The total spent nuclear fuel stocks for the reprocessing from one unit is ($A + B$), where A is the spent nuclear fuel amount accumulated before 2015 and B represents the spent nuclear fuel accumulated in the period 2016–2017[3].

The maximum need for reprocessing capacities is 126 t HM/year in the period 2025–2035. Spent nuclear fuel reprocessing will be terminated after 2045. The spent nuclear fuel reprocessing supply–demand balance is shown in Fig. VIII.68.

[3] The spent fuel of WWER-1000 and WWER-440 accumulated before 2015 has been directly transported to Russian Federation for storage and reprocessing. At the time when this study was done (2015), the spent fuel accumulated between 2016 and 2017 was assumed to be transported to Russian Federation for storage and reprocessing. For the spent fuel accumulated in 2018 and later no transportation to Russian Federation was envisaged.

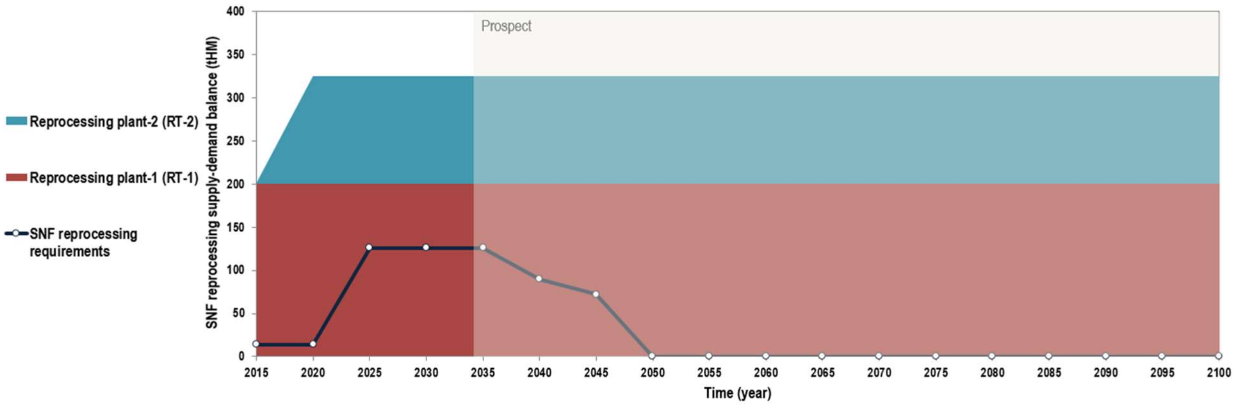


FIG. VIII.67. Spent nuclear fuel reprocessing supply–demand balance.

In the framework of this study, there is no provision for the disposal of spent nuclear fuel in deep geological repositories.

VIII.6.7. Summary

As part of the ROADMAPS project, the long term development of nuclear generation in Ukraine for the period up to 2100 was considered. The once-through nuclear fuel cycle is based on the nuclear power units that were in operation at the time of the analysis, and evolutionary PWR Generation III+ units are assumed to be constructed in the future. The commissioning of new NPPs was determined based on the schedule for decommissioning of old NPPs. It was assumed that there are no plans to commission new NPPs after 2050. Analyses of the fuel supply until 2100, of present spent nuclear fuel storage facilities and the capacities of additional spent nuclear fuel storage facilities, of the capacities of uranium enrichment services and the capacity of natural uranium necessary to ensure the sustainability of the NES of Ukraine have been performed. The fuel fabrication quantities were presented for two different nuclear fuel suppliers up to 2100.

The condensed roadmap for the development of the NES of Ukraine up to 2100 is presented in Fig. VIII.69. The scheme includes existing elements of the nuclear infrastructure in 2017, the time frame for the deployment of nuclear infrastructure elements according to the official strategy [VIII.63] and expert assumptions on the development of nuclear generation beyond 2035.

The spent nuclear fuel deep geological depository is not considered in the present roadmap but is shown as a possible sustainable spent nuclear fuel solution for a user country. Until 2051 the storage of radioactive waste will be realized in a special storage facility which is located in the Chornobyl NPP exclusion zone (in accordance with official statements).

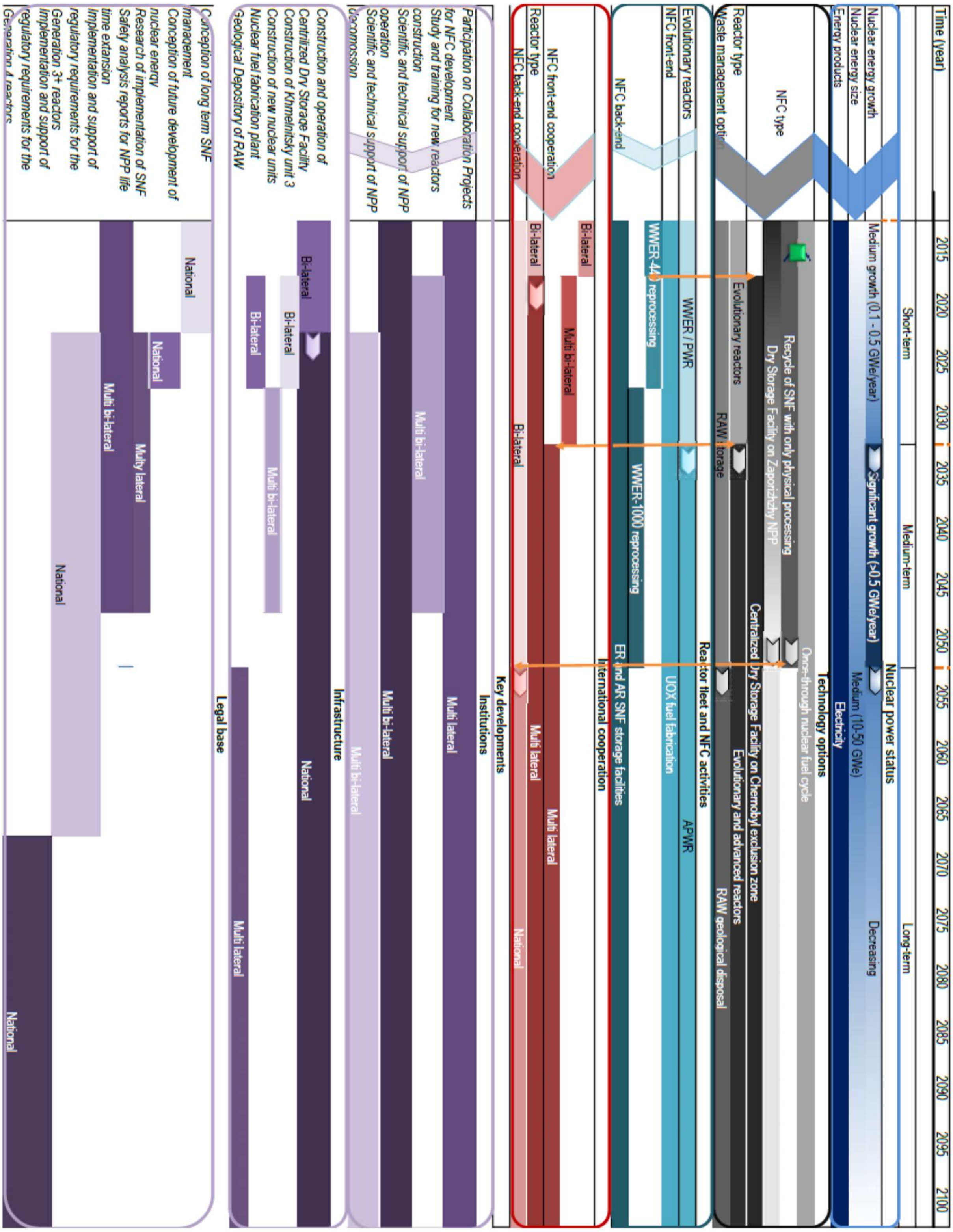


FIG. VIII.68. Condensed roadmap of the NES of Ukraine up to 2100.

Until 2030 it is possible to assume that the construction of new NPPs with evolutionary WWER PWRs will include the construction of Units 3 and 4 of KhNPP. From 2030, the construction of advanced PWR Generation III+ NPPs is being considered. International cooperation is mainly envisaged in three areas: nuclear fuel fabrication and supply; maintenance and operation or construction of new NPPs; and spent nuclear fuel management. Until 2015, the TVEL Fuel Company was the main supplier of fuel assemblies. Since 2015, the NPPs of Ukraine have been diversifying nuclear fuel supplies and are planning to use fuel from TVEL Fuel Company and Westinghouse. The use of nuclear fuel from other suppliers can be assumed after 2030 if new types of NPP are constructed. With regard to spent nuclear fuel management, it is assumed that there will be wide international cooperation for the reprocessing of spent fuel until 2050. After the completion of the reprocessing of the WWER-1000 spent nuclear fuel sent to the Russian Federation before 2017, spent nuclear fuel management will be implemented at the national level. Broad cooperation in the field of scientific and technical support for spent nuclear fuel management can also be considered.

Participating in international projects on research in development of the nuclear fuel cycle, the implementation of new reactors and support for scientific advancement is interesting throughout the period considered in this study. In the period from 2020 to 2050, deep cooperation with various technology suppliers is expected, taking into account plans for the construction of new power units. A cooperation with HOLTEC ((United States of America)for the construction of the CDSF was considered. The start of operation for the first complex (four containers) is currently considered for 2021. The operation of CDSF and container manufacturing will be realized in Ukraine.

The construction of Unit 3 of KhNPP will be realized by the selected supplier of the WWER-1000. The type of reactor has been determined according to the feasibility study, which was completed in 2017. The construction of other new replacement NPPs will be implemented in accordance with contracts with technology suppliers.

The consideration of the construction of a nuclear fuel fabrication plant in the period 2020–2030 is presented based on The Concept of the State Targeted Economic Program for the Development of the Nuclear Industrial Complex of Ukraine (approved by the Cabinet Ministry of Ukraine in 2016) [VIII.68] and will be implemented in accordance with the contract with the technology supplier and taking into account the types of NPP that will be used after 2030.

For the period of this study, in Ukraine the concept of spent nuclear fuel management for a long term period is being developed at the national level. The study includes a comparative analysis of different nuclear fuel cycles with the choice of the optimal spent nuclear fuel management scenario. The results of the roadmap template application show possible directions for sustainability enhancements of the national NES based on a once-through nuclear fuel cycle (considering uranium resources, enrichment requirements and nuclear fuel supply) up to 2100. Meanwhile, the limited spent nuclear fuel reprocessing related to the external fuel cycle implemented abroad is the reason for the accumulation of spent nuclear fuel and has resulted in expenses for additional capacities of long term spent nuclear fuel storage.

VIII.7. APPLICATION OF THE ROADMAP TEMPLATE TO THE NES OF THE RUSSIAN FEDERATION, INCLUDING COOPERATION

VIII.7.1. General country information

As stated in the guidance on the roadmap template application, its first section ,'Country profile', is intended to provide general information on a country's macroeconomics and its energy sector. The brief outline of the Russian Federation's energy sector and nuclear power presented below is an excerpt from the materials available on the first Excel page of ROADMAPS-ET.

The Russian Federation is a country with a growing economy, industry and energy sector. The population of the Russian Federation is 146.3 million [VIII.77], and the annual GDP at purchasing power parity for 2015 was US $3796 billion [VIII.78]. The consumption of primary energy resources is about 688 million toe, which puts it in third place after China and the United States of America. Export is 640 million toe and imports are almost absent. The Russian Federation is in fourth place on GHG emissions with 2300 million tonnes/year [VIII.79]. The largest share of emissions comes from the energy sector — 82%, followed by industry and agriculture with 8% and 6%, respectively.

The total installed capacity of power plants in the Russian Federation is 235.3 GW(e). During 2015, 1049.9 TW·h of electricity were generated in the Russian Federation. The major share of electricity was generated by fossil fuel power plants (65%) while NPPs generated about 18% and hydroelectric power stations generated approximately 16%. Data on the amount of electricity generated from RESs are absent. Most of the generated electricity is supplied to domestic consumers. Export supply makes up 17.5 TW·h representing 1.7% of the total generated electricity [VIII.80]. The share of installed capacity of nuclear power is 11.5% while, due to the high load factor, it produces about 18% of all generated electricity.

VIII.7.1.1. Historical background

The development of nuclear energy in the Russian Federation began in the first half of the twentieth century. Active research in nuclear physics leading to the discovery of the fission chain reaction was carried out in the Leningrad Radium Institute in the second half of the 1930s. The first controlled nuclear fission chain reaction was achieved in 1946, and the first industrial nuclear reactor was commissioned in 1948. The first commercial NPP in the world with a water cooled uranium-graphite reactor started up in Obninsk in 1954. The Ministry of Medium Machine Building responsible for nuclear science and technology was established in 1953. The Soviet Union ratified the statute of the IAEA as one of its founders in 1957. The first commercial PWR, the WWER-210, was commissioned at the Novovoronezh NPP in 1964. In the same year, the first commercial graphite moderated nuclear power reactor with water coolant and nuclear steam superheating, the AMB-100, was commissioned at the Beloyarsk NPP. The first light water cooled graphite moderated (LWGR) reactor RBMK-1000 at the Leningrad NPP and the world's first prototype sodium cooled fast reactor BN-350 (built in Kazahkstan) were commissioned in 1973. BN-350 was designed for power generation and water desalination. The first plant for reprocessing, RT-1, began to operate in 1977. The first reactor WWER-1000 and the first commercial fast neutron power reactor, BN-600, were commissioned in 1980. In 1986, an accident occurred at the Chornobyl NPP, which had catastrophic consequences and affected the development of nuclear energy throughout the world.

The Ministry of Medium Machine Building was merged with the Ministry of Atomic Energy into the united Ministry of Atomic Energy and Industry of the then USSR by a decree of the Council of Ministers of the USSR in 1989. Since 2007, the state corporation Rosatom manages the development of nuclear power and is responsible for all aspects of its use [VIII.81].

As can be seen from the above, the development of nuclear power and the nuclear industry in the Russian Federation has a long history, and considerable experience has been accumulated in the field of design, construction and operation of various types of nuclear reactors, including FRs, and in various areas of the nuclear fuel cycle front end and back end.

VIII.7.1.2. Current state and prospects of the NES and its contribution to assure long term energy needs

The status iondicators of the Russian NES are presented in Fig. VIII.70.

Today, Rosatom is a global company with many years of experience in the different markets of nuclear technologies and services. It implements programmes in practically all nuclear energy segments: nuclear medicine, applied and fundamental science, nuclear power complex, nuclear icebreaker fleet, composite materials and nuclear and radiation safety.

Rosatom incorporates companies from all stages of the technological chain, such as uranium mining, conversion and enrichment, nuclear fuel fabrication, equipment manufacture and engineering, NPP operation, and the management of spent nuclear fuel and nuclear waste. Nowadays, Rosatom encompasses more than 350 enterprises and organizations with a workforce of more than 250 000 In addition, the federal state unitary enterprise Atomflot, which operates the world's only nuclear powered icebreaker fleet, is a part of Rosatom [VIII.82].

Nuclear power is one of the most important sectors of the Russian Federation economy. The dynamic development of the nuclear industry is one of the basic conditions for ensuring the energy independence of the state and the stable growth of the economy. Today, 10 NPPs are in operation in the country (35 units with an installed capacity of 27.89 GW). The operator of all Russian Federation NPPs is Rosenergoatom, which showed a record generation of electricity of 195.2 billion kW·h in the year 2015.

Currently, 8 new nuclear power units are under construction in the Russian Federation, 33 nuclear power units are at the implementation stage abroad, including units at the NPPs Ostrovets (Belarus), Tianwan (China), Kudankulam (India) and Akkuyu (Turkey) [VIII.83].

VIII.7.2. National decision on and vision for nuclear energy strategy

The Energy Development Strategy of the Russian Federation until 2035 is the basic document indicating the direction of energy development of the country, and of nuclear energy in particular [VIII.84]. The goals and objectives of the country's power industry development in the period up to 2035 include:

- 30–40% increase of electricity generation by 2035 with an increase of 21–28% in the installed capacity of power plants and decommissioning of economically inefficient and obsolete power equipment;
- Reduction by 13% in specific fuel consumption for electricity generation by 2035;
- Optimization of the structure and the load of electricity and heat generation capacities by type and kinds of energy used.

The main directions of nuclear energy development [VIII.85] are the following:

- Improving the efficiency and competitiveness of nuclear energy as a whole, achieving the economic competitiveness of new NPPs by reducing the unit cost of their construction, while maintaining safety and security as a priority;
- The creation of a competitive technological base of nuclear energy on the basis of FRs with inherent safety that operate in a closed nuclear fuel cycle, the preservation of the natural balance of the radioactivity of waste disposal and the prevention of the proliferation of nuclear weapons material;
- Development of production capacities, nuclear machine building and construction organizations to provide the required pace of unit commissioning in the country and for increasing export deliveries;
- The formation of the second phase of a new nuclear energy technological platform based on NPPs with improved water cooled reactors and FRs operating in a closed nuclear fuel cycle;
- Increase the export potential of Russian Federation nuclear technologies, the further development of the export of NPPs, products and technologies of the nuclear fuel cycle and electricity.

The nuclear industry is able to perform the role of driver for the development of other sectors of the economy. It provides orders for machine building, metallurgy, construction and other sectors. It is planned to reach a level of 36 GW(e) for the total installed capacity of nuclear power units, and to increase electricity generation from 18% to 21% of the total production in the country by 2035, according to the plans of developing Russian Federation nuclear energy described in Refs [VIII.84, VIII.85]. It is possible to complete the establishment of the industrial energy complex with a closed nuclear fuel cycle based on a small series of FRs, which will provide the basis for further full scale close of the nuclear fuel cycle. It is also possible to meet the fuel needs of the domestic reactor fleet and the export commitments for fuel supply, increasing the attractiveness of NPP domestic projects in the international market [VIII.86]. All this will determine the future development of the whole NES for the long term, up to the end of the century, and nuclear energy itself will play a significant role in the country's economy.

VIII.7.3. Purpose of the roadmap

The trial roadmap of the Russian Federation NES was developed using the roadmap template and ROADMAPS-ET (see Section 3). It provides structured information and a visual demonstration of the state of the country's energy system and the status, prospects and options for the development of nuclear energy. The roadmap in particular addresses:

- The existing reactor fleet and installations of the nuclear fuel cycle;
- Demands for the new reactor units and installations of the nuclear fuel cycle over time and plans for their commissioning and decommissioning;
- The current quantity of accumulated spent nuclear fuel and the rate of its increase over time;
- The need for plutonium for achieving the closure of the nuclear fuel cycle.

The elaboration of the trial Russian Federation roadmap has confirmed the utility of the roadmap template for planning the strategic development of the NES, for assistance in analytical studies and for identifying possible gaps in meeting requirements of enhanced NES sustainability. The roadmap template was also useful for the evaluation of ways for enhancing the bilateral and multilateral cooperation of the Russian Federation as a technology holder country. It helped to examine the need to purchase some products or services from abroad and, on the other hand, to expand the volume of services to be provided to foreign customers. The portion of the roadmap template addressing the nuclear fuel cycle back end has been especially valuable for the tasks of long term planning. It provides a framework on the development of options that promise mutual benefits for country partners and for global NES sustainability.

VIII.7.4. Metrics on nuclear energy position and development

The roadmap contains the section 'Metrics' with a specified set of 'Health' indicators aimed to reflect the current state of a country's NES, and prospects for the expansion of the installed capacity of nuclear reactors, for the development of reactor and nuclear fuel cycle technologies, and for enhancing international cooperation.

VIII.7.4.1. NES status indicators

At present, the cost of electricity generated by Russian Federation NPPs is competitive compared with most other energy plants, while public opinion on nuclear power is generally positive. New nuclear power units are under construction with a construction time of below six years and existing NPPs produce about 18% of all generated electricity. The average load factor for all NPPs has reached 86%. All the needs of NPPs (natural uranium, conversion and enrichment etc.) are covered by domestic facilities.

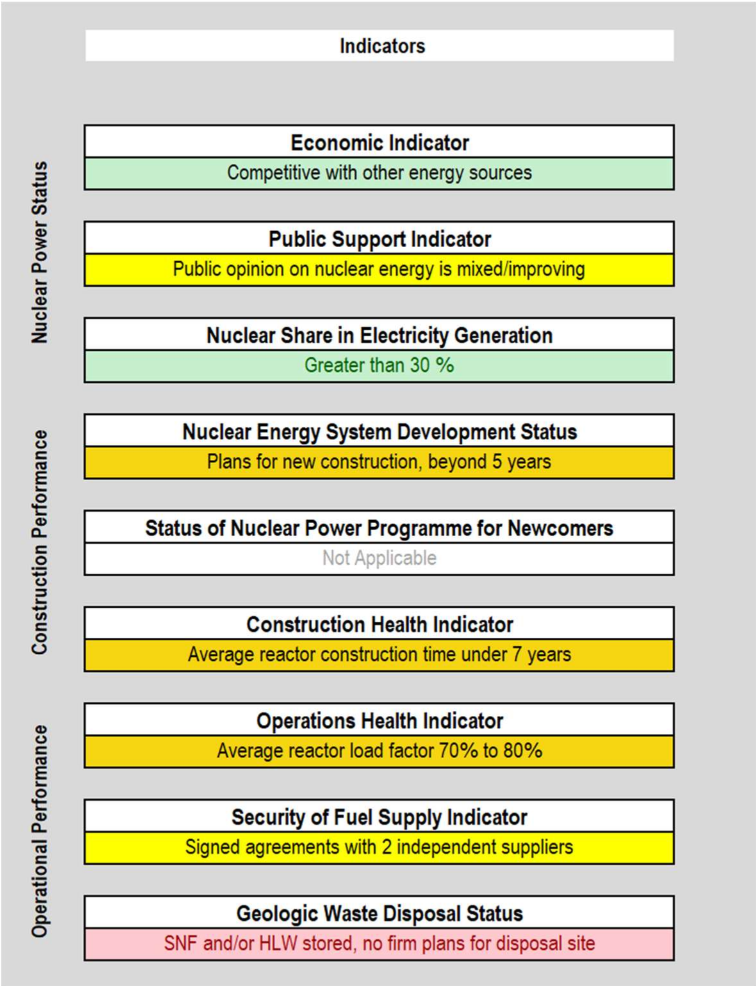


FIG. VIII.69. The status indicators for the NES of the Russian Federation.

The problem of a final geological disposal of radioactive waste has not been solved, but active research work and construction of an underground laboratory for the geological isolation of radioactive waste are in progress at the Kansk granite massif in Siberia.

VIII.7.4.2. Prospects for nuclear energy and country group classification

The rate of the national total installed capacity growth of NPPs in the near term (until 2035) will be about 0.5 GW(e) per year. The expected rate of growth of installed capacity in the medium and long term will be about 0.9 GW(e) and 0.8 GW(e) each year, respectively, taking into account the decommissioning of old reactors.

The total installed capacity of the domestic NES should reach 35 GW(e) by 2035, and is estimated to reach 50 GW(e) and ~90 GW(e) by 2050 and 2100, respectively. The Russian Federation also has contracts for the construction of 33 nuclear power units abroad before 2030. More information on the growth of installed capacity of NPPs is presented in the section ‘Reactor fleet’ of the template.

At present, the Russian Federation is actively developing nuclear power. It has facilities at all nuclear fuel cycle stages, carries out deep scientific research in the field of nuclear technology, and works on the commercialization of the closed nuclear fuel cycle with thermal and FRs. It is also one of the leaders in providing a wide spectrum of services to the international nuclear power market. The Russian Federation is a recognized technology holder country and is assigned to the NG1 (nuclear group 1) country group according to the GAINS classification.

This technological status is expected to be maintained during the whole time interval under consideration in the template.

VIII.7.4.3. Technology options

The current domestic technology status is presented in Fig. VIII.71.

At present, the basis of the Russian Federation’s nuclear reactor fleet are LWRs — WWERs and LWGRs with uranium oxide fuel, and two sodium FRs: BN-600 with uranium oxide fuel and BN-800 with uranium oxide fuel and a partial MOX fuel load. The BN-800 reactor is planned to be fully loaded with MOX fuel in the coming years. The designs and technologies for small and medium sized reactors, HTGRs, molten salt reactor types and accelerator driven systems are now under research. The Russian Federation has facilities for natural uranium mining and milling, conversion, enrichment and UOX fuel fabrication, a small scale MOX fuel fabrication for the BN-800 reactor and a research programme of nitride fuel for the BREST reactor. The reprocessing of spent nuclear fuel from WWER and BN-600 reactors has been partially implemented. The reprocessed uranium is used in LWGRs and WWERs while reprocessed plutonium has been temporarily stored. The HLW arising from reprocessing is vitrified.

c.y.	Research	Prototype	Demonstration	Operating
LWR				☑
HWR				
HTGR	☑			
SMR	☑			
FR				☑
ADS	☑			
MSR	☑			
Uranium mining and milling				☑
Conversion				☑
Enrichment				☑
Uranium fuel fabrication				☑
Mixed uranium-plutonium fuel fabrication			☑	
Advanced fuel fabrication		☑		
Wet SNF storage				☑
Dry SNF storage				☑
Aqueous SNF reprocessing				☑
Advanced SNF reprocessing		☑		
HLW forms				☑
Geological disposal	☑			
Related industrial activities				☑
Others				☑

☑ official plan ✓ prospect

FIG. VIII.70. Current domestic technology status.

The large scale reprocessing of spent nuclear fuel from WWER-1000/1200s (and probably from LWGRs) is planned to be deployed in the near future The deployment of the full scale fabrication of MOX fuel for FRs is expected from 2024, and commissioning of a small series of BN-1200 reactors is expected from 2027.

The domestic technology status in long term is presented in Fig. VIII.72. Facilities for the reprocessing of spent nuclear fuel from FRs and MOX spent nuclear fuel from WWERs are supposed to be commissioned after accumulating a sufficient amount of sodium cooled fast reactor and WWER MOX spent nuclear fuel in storage in order to optimally use the capacity of the reprocessing facilities. HTGRs and molten salt reactors are under research and development. The prototypes may appear in the medium term. In the long term, reactors of those types could take part in minor actinide burning

2051 – 2100	Research	Prototype	Demonstration	Operating
LWR				✓
HWR				
HTGR			✓	✓
SMR				✓
FR				✓
ADS			✓	✓
MSR			✓	✓
Uranium mining and milling				✓
Conversion				✓
Enrichment				✓
Uranium fuel fabrication				✓
Mixed uranium-plutonium fuel fabrication				✓
Advanced fuel fabrication				✓
Wet SNF storage				✓
Dry SNF storage				✓
Aqueous SNF reprocessing				✓
Advanced SNF reprocessing				✓
HLW forms				✓
Geological disposal				✓
Related industrial activities				✓
Others				✓

☑ official plan ✓ prospect

FIG. VIII.71. Domestic technology status in the long term. Legend: SMR — small and medium reactors; ADS — accelerator driven system; MSR — molten salt reactors; SNF — spent nuclear fuel.

According to the Federal Programme [VIII.88], an experimental laboratory for the final geological disposal of radioactive waste is expected to be commissioned after 2030.

VIII.7.4.4. Collaboration with other countries

At present, the state corporation Rosatom implements different options of collaboration with other countries, including (Fig. VIII.73):

- Information exchange, joint scientific research and providing consultation and support in the establishment of institutional infrastructure for nuclear power in partner countries;
- Providing a full package of front end services of the nuclear fuel cycle;
- Selling of NPPs;
- Offering services in the field of NPP operation;
- Bilateral agreements with some countries on the return of spent nuclear fuel to the Russian Federation for further processing.

Also, the international centre for uranium enrichment is located in the Russian Federation.

Collaboration Strategy	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Participate in information exchange activities	☑	☑	✓	✓
Joint R&D programs	☑	☑	✓	✓
Sharing of R&D facilities	☑	☑	✓	✓
Collaboration on NFC front end	☑	☑	✓	✓
NPP selling	☑	☑	✓	✓
NPP purchasing				
Offer NPP operations services	☑	☑	✓	✓
Use NPP operations services				
Offer NPP refuelling outage services	☑	☑	✓	✓
Use NPP refuelling outage services				
Collaboration on NFC international centres	☑	☑	✓	✓
Share an NPP with another country				
Offer NFC back end services	☑	✓	✓	✓
Use NFC back end services				
Offer NFC full services			✓	✓
Use NFC full services				

☑ official plan ✓ prospect

FIG. VIII.72. Collaboration strategy of the Russian Federation.

An important direction of the further development of cooperation with other countries is the expansion of the range of services at the nuclear fuel cycle back end. In particular, the ‘take back’ option for the spent fuel of Russian Federation origin implies the reprocessing of foreign spent nuclear fuel, the fabrication of new fuel using fissile materials (plutonium and reprocessed uranium) separated from spent nuclear fuel, and the use of these materials in thermal and FRs.

VIII.7.5. Key developments to enhance sustainability

The development of nuclear power technologies and infrastructure is at varying levels around the world. In some countries the implementation of nuclear power programmes is at the initial stage, which assumes that the first NPPs are being constructed and operated and the nuclear fuel cycle infrastructure that meets current regulation requirements for nuclear power is being created. Other countries have already passed this stage and have begun the research and development of innovative components of NESs within the evolutionary approach. There are also countries that are creating a radically new technological and institutional platform for future nuclear power. The Russian Federation falls into the third group of countries mentioned above.

The strategic concept of the Russian Federation consists in reaching enhanced NES sustainability through developing a commercial closed nuclear fuel cycle. There are some important intermediate tasks that need to be solved before the final goal can be reached. These tasks are considered key developments typical for strategies oriented towards the creation of a closed nuclear fuel cycle.

Key developments in the Russian Federation case study were considered across six areas in accordance with INPRO methodology [VIII.89]: economics, safety, resources, waste management, non-proliferation and infrastructure, including public and governmental attitudes towards nuclear power. The key developments specific to the Russian Federation NES were defined for time intervals from 2015 to 2100 and are shown in Fig. VIII.74.

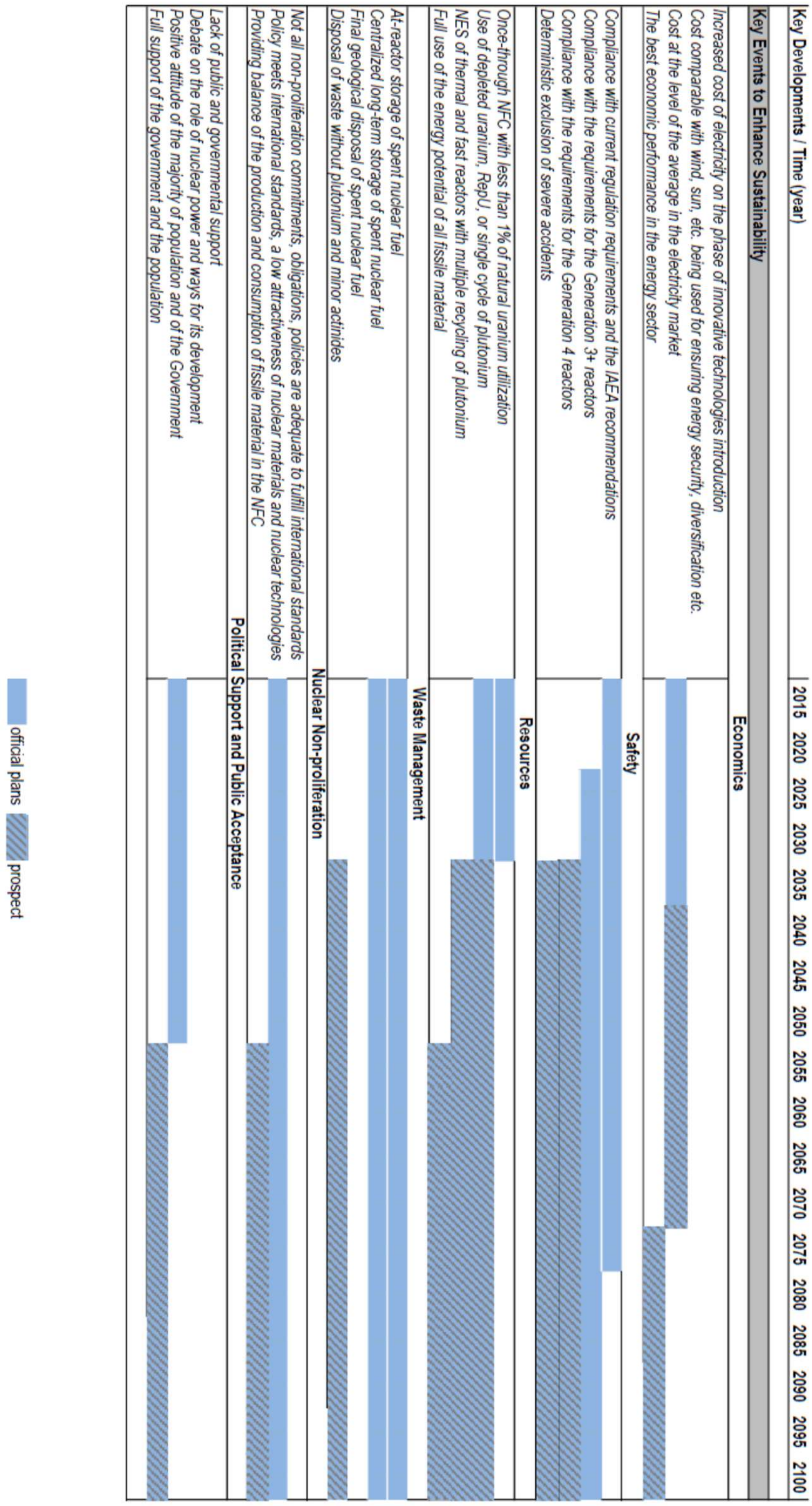


FIG. VIII.73. Key developments for the Russian Federation case study (shaded areas indicate prospects).

A brief explanation of the key developments and events reached and expected to be reached is given below.

— Economics:
  - The increased cost of electricity during the introductory phase of innovative technologies relates to the cost of electricity generation by the innovative FRs BN-600 and BN-800, which is higher than average cost generated by WWER based on mastered PWR technology.
  - That the cost of nuclear power is comparable with wind, sun, etc. being used for ensuring energy security, the diversification of energy sources and decreasing environmental impact is true for NPPs in general.
  - The cost of nuclear power is at the level of the average in the electricity market as at the moment, the cost of one kW·h from NPPs in the Russian Federation is comparable to the cost of one kW·h from the main sources of electricity on the market. A requirement for the BN-1200, which is currently in the design stage, is to provide electricity at a cost comparable with the cost for electricity generated by the WWER-1200.
  - Nuclear power may one day offer the best economic performance in the energy sector as in the long term (after 2050), when the nuclear fuel cycle is closed and the cost of fossil fuels has increased, the cost of one kW·h from NPPs with a reduced period of construction and decreased capital cost could become the lowest in the electricity market.

— Safety:
  - The key development of compliance with current regulatory requirements and IAEA recommendations has been reached for Russian Federation Generation II reactors, the latter of which will be decommissioned by 2070.
  - Compliance with the requirements for Generation *III/III+* reactors involves the use of passive safety systems, the presence of containment and a melt trap, an increased grace period until human intervention is necessary relative to existing facilities and the calculated frequency of a major release of radioactivity being $<10^{-6}$ per unit-year and so on. The first Generation *III+* reactor is to be commissioned in the Russian Federation at the Novovoronezh NPP. Generation *III+* reactors will operate until the end of the century.
  - Compliance with the requirements for Generation IV reactors involves passive automatic reactor shutdown systems, a lower probability of core damage than for the Generation III+ reactors and no need for relocation or evacuation measures outside the plant site and so on. The first reactors corresponding to these requirements will be commissioned after 2025 and will operate until the end of the century.
  - The deterministic exclusion of severe accidents corresponds to the next generation nuclear reactors, which could be commissioned in the mid or long term.

— Resources:
  - A once-through nuclear fuel cycle with less than 1% of natural uranium utilization is the mode in which most Russian Federation thermal reactors are currently operated.
  - Depleted uranium or a single recycle of plutonium are used. At present, some types of reactors use reprocessed uranium fuel, and Remix fuel for WWER reactors is under research.

- The NES of thermal and FRs with multiple recycling of plutonium can be considered after the middle of the century, when the share of FRs is expected to be large enough to consider a full scale closure of the nuclear fuel cycle and multiple recycling of plutonium.
- A full use of the energy potential of all fissile material in reactors and installations that can burn long lived radiotoxic isotopes are under research and development with no definite plans for their introduction to the NES.

— Waste management:
  - Reactor spent nuclear fuel storage is a current feature of the NES as now a part of the spent nuclear fuel from LWGR reactors is stored at the NPP sites in at-reactor pools. After storage in the at-reactor pools, all spent nuclear fuel is to be taken out by 2030 according to the Federal Target Programme "Ensuring nuclear and radiation safety for 2016–2020 and for the period up to 2030" [VIII.89].
  - The centralized long term storage of spent nuclear fuel is planned and spent nuclear fuel, after cooling down at the reactor sites, will be moved to centralized storage.
  - The final geological disposal of spent nuclear fuel does not currently feature in official plans.
  - The disposal of waste without plutonium and minor actinides in it is planned for the medium term and industrial facilities for reprocessing all types of spent nuclear fuel from thermal reactors, and the first part of the geological disposal facility for radioactive waste final isolation, should be put into operation by 2030 in accordance with the Federal Target Programme Nuclear Radiation Safety – 2 [VIII.89].

— Proliferation resistance:
  - Not all States' commitments, obligations and policies regarding non-proliferation and its implementation are adequate to fulfil international standards, but this is not applicable to the Russian Federation.
  - Russian Federation policy fully meets international standards, provides a low attractiveness of nuclear materials and nuclear technologies, ensures the difficulty of carrying out acts of sabotage and creates conditions for its concurrent detection.
  - Providing a balance of the production and consumption of fissile material in the nuclear fuel cycle will be achieved from the middle of the century.

— Public and governmental attitude:
  - A lack of public and governmental support is not found in the Russian Federation.
  - Debates on the role of nuclear power and prospects for its development in the Russian Federation are constructive.
  - A positive attitude of the majority of the population and Government is currently found.
  - The full support of the Government and the population will probably be reached after the demonstration of the economic advantages of nuclear power and the solution of the problem of the rational use of fissile materials from spent nuclear fuel and the safe disposal of radioactive waste.

In the Russian Federation, as well as in other technology holder countries, the institutional infrastructure has been comprehensively developed. It often serves as a reference point for the partners of the Russian Federation who are beginning with the use of nuclear power. An example of some basic legislative acts adopted by the Russian Federation Government in the field of nuclear energy is provided in Fig. VIII.75.

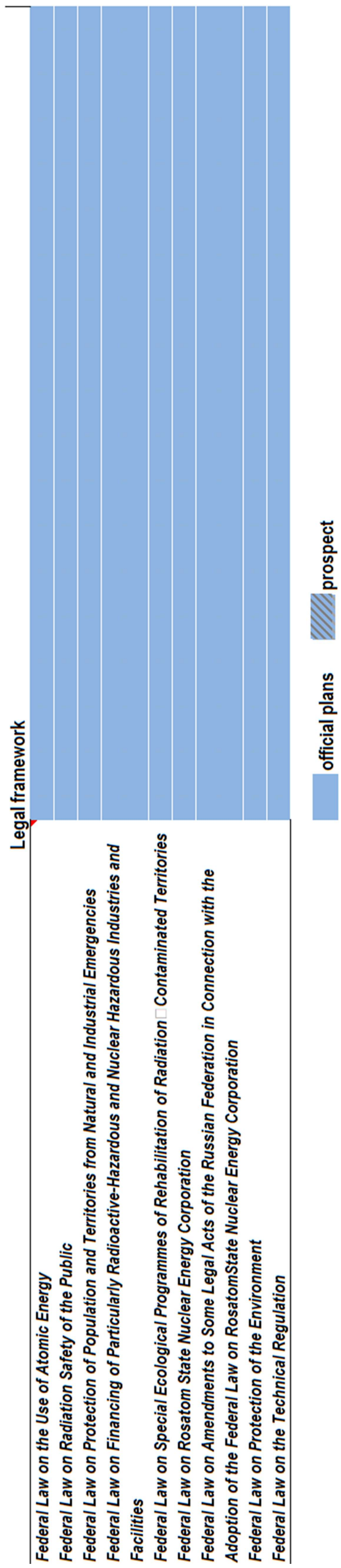


FIG. VIII.74. Basic legislative acts in the field of nuclear energy.

VIII.7.6. Nuclear power planning

The roadmap provides basic information on the status and plans for development and deployment of Russian Federation nuclear power and for providing services for the foreign reactor fleet of Russian Federation design. It describes the evolution of reactors and installations of the nuclear fuel cycle by types and capacities at time intervals of five years until the year 2100. The information includes data from recent publications on the issue. The roadmap provides data on demand and supply for natural uranium, industrial capacities for conversion, enrichment, fuel fabrication, reprocessing, spent nuclear fuel and plutonium storage.

VIII.7.6.1. Reactor fleet

The data on the commissioning and decommissioning of nuclear reactors presented in the section ‘Reactor fleet’ of the case study is based on the materials detailed in Ref. [VIII.90]. The current official strategy for the development of nuclear energy in the Russian Federation and the reactor fleet of Russian Federation design abroad is considered for the period up to 2035. After 2035, the development of the NES in this case study is aimed at closing the nuclear fuel cycle and reducing the amount of spent nuclear fuel (including spent nuclear fuel from abroad) and stored plutonium. The commissioning of HTGRs for the production of synthetic liquid fuels will also be possible after 2035.

In 2015, the total installed capacity of the reactor fleet was 25.4 GW(e), of which 11 GW(e) corresponds to RBMK-1000 reactors, 13.8 GW(e) to various modifications of WWER reactors and 0.6 GW(e) to BN-600 reactors (Fig. VIII.76).

Ten RBMK-1000 reactors and four WWER-440 reactors will be decommissioned by 2035; LWGR reactors will be replaced by WWER-1200 or VBER-TOI reactors and WWER-440 reactors will be replaced by WWER-600 or VBER-600 reactors. The decommissioning of all RBMK-1000 and WWER-400 reactors will be completed during the period from 2035 to 2050. The reactor BN-800 was commissioned in 2016. There are plans to commission from 2027 a series of three BN-1200 reactors and to implement the partial closure of the nuclear fuel cycle using civilian and weapons grade plutonium in MOX fuel.

National total installed capacity, MW(e)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
RBMK-1000	11000	10400	7200	3200	800													
VVER-440	2640	2200	2200	2200	1408	264												
VVER-1000	11400	12800	13000	13000	13000	12400	11400	7600	6400	6000	4600	3800	1600	200				
VVER-1200		3120	7200	12960	16200	20880	21600	21600	21600	22320	22800	22800	22800	19680	15600	9840	7680	4080
VVER-TOI (MOX)						1200	3840	8400	11760	13440	16560	20400	23760	27840	31680	37680	42240	48240
BN-600	600	600	600															
BN-800	160	800	800	800	800	800	800	800	800	640								
BN-1200				1200	3120	4080	7440	10560	13440	16320	18240	20400	23040	26160	29040	30720	32880	34320
HTGR					9	55	92	92	185	222	268	342	416	508	545	554	554	554
BREST-1200																		
Total, MW(e)	25800	29920	31000	33360	35337	39679	45172	49053	54185	58942	62468	67742	71616	74388	76865	78795	83355	87195

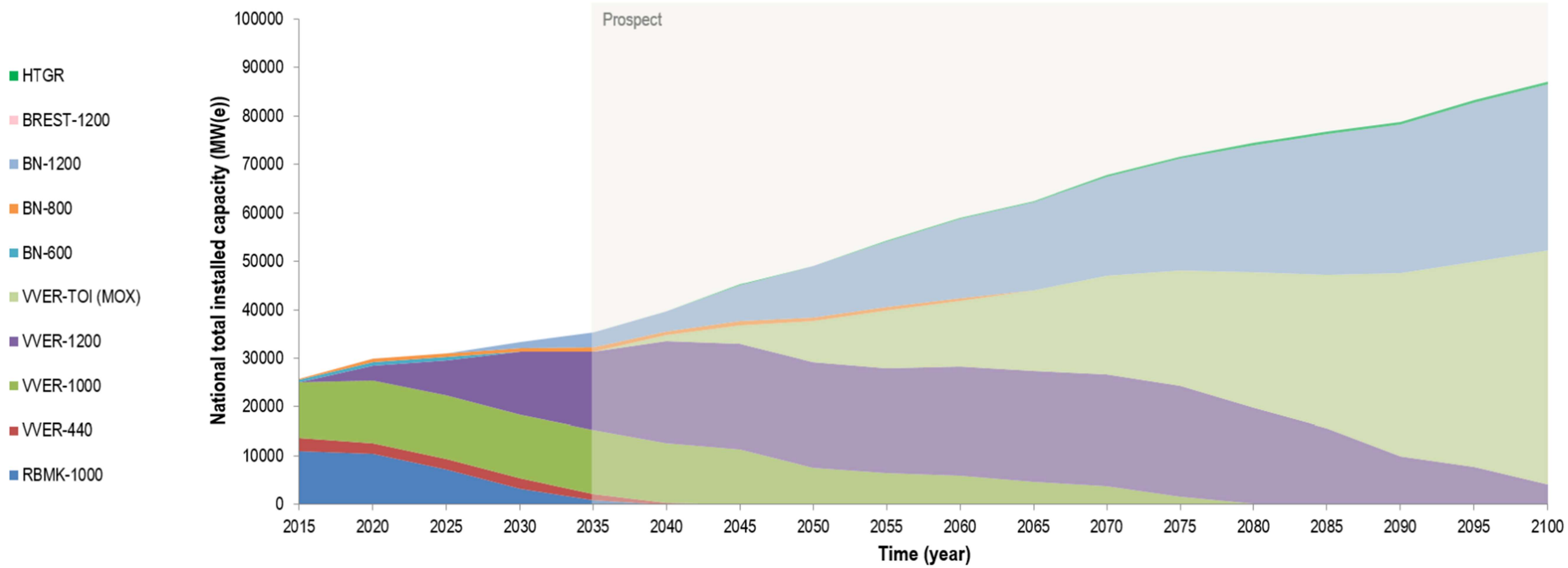


FIG. VIII.75. Programme for the development of national reactor fleet up to 2100.

The conducted studies show that, in order to fully close the nuclear fuel cycle and reduce plutonium reserves, it will be necessary to commission a large series of BN-1200 and VBER-TOI reactors with partial loading of MOX fuel after 2035.

The rate of capacity growth will be 0.4 GW(e) per year for WWER-1200/TOI, 0.6 GW(e) per year for VBER-TOI reactors with partial load of MOX fuel and 0.5 GW(e) per year for BN-1200 for the time period from 2035 to 2050. After 2050, most of the WWER-1200/TOI reactors with UOX fuel will be undergoing decommissioning and the rate of capacity growth of VBER-TOI reactors with partial load of MOX fuel and BN-1200 will be 0.8 and 0.5 GW(e) per year, respectively. Twelve high temperature GCRs can be commissioned after 2035.

Currently, 40 reactors of Russian Federation design (WWER-440s and WWER-1000s) are under operation abroad, with total installed capacities of about 30 GW(e), and the Russian Federation has a contract for the construction of 34 reactors abroad until 2030 (Fig. VIII.77).

Total installed capacity of Russian design reactors fleet abroad, MW(e)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Armenia	440	440	1000	1000	1300	1300	1600	1600	1900	1900	2200	2200	2500	2500	2500	2500	2500	2500
Belarus		1194	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388	2388
Ukraine	13835	13835	14835	15835	15000	10000	5000	4000	4000	2000	2000	2000	2000	2000	2000	1000		
Other																		
-VVER (UOX)	13760	16246	24884	37972	39108	42532	45212	46852	49492	52892	54892	55052	56132	56052	53292	50532	50432	53492
-VVER (MOX)						240	2160	3840	5280	7920	9360	11760	14640	16080	19200	22800	24960	25440
Total, MW(e)	28035	31715	43107	57195	57796	56460	56360	58680	63060	67100	70840	73400	77660	79020	79380	79220	80280	83820

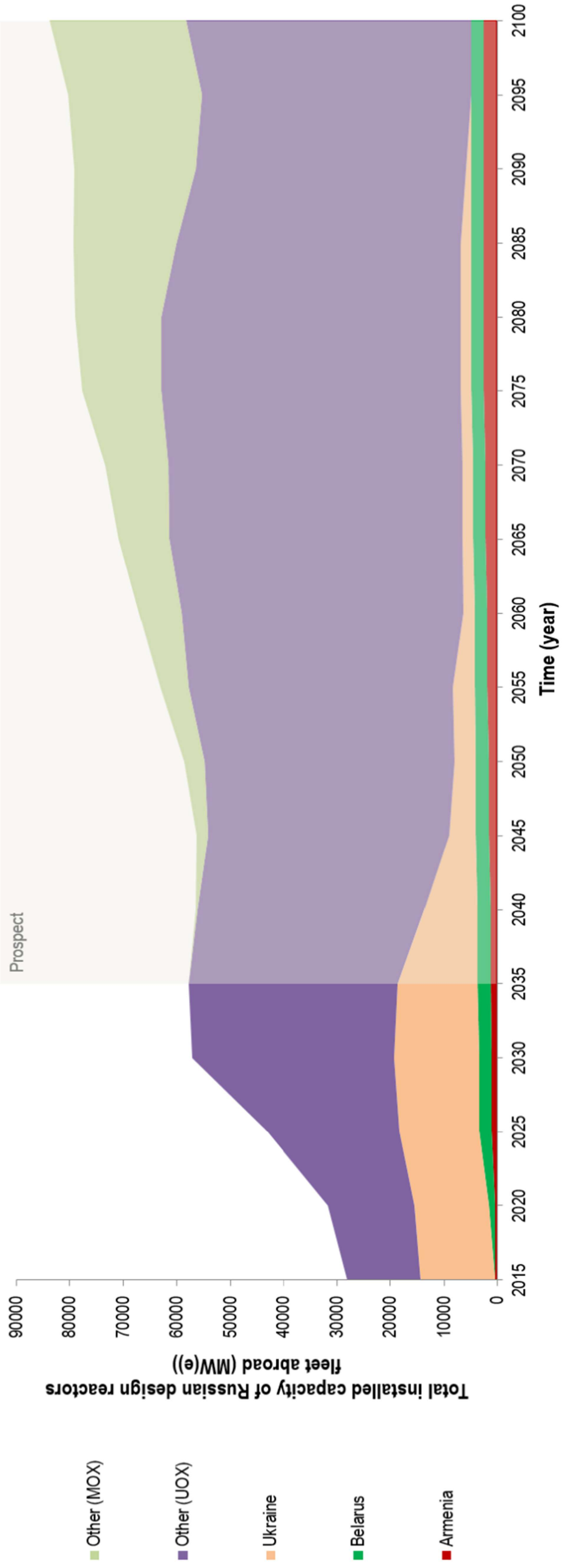


FIG. VIII.76. Programme for the development of Russian Federation design reactor fleet abroad up to 2100.

Most of the reactors planned for construction before 2035 will be WWER-1200 with UOX fuel. After 2035, in order to balance the amount of plutonium in the system, a number of VBER-TOI reactors with a partial load of MOX fuel will be commissioned abroad. It is estimated that the rate of commissioning new reactors of Russian Federation design abroad will be comparable to the rate of commissioning new reactors in the Russian Federation. By 2035, the total installed capacity of Russian Federation design reactors abroad will be 59 GW(e), of which WWER-440 will account for 0.9 GW(e), WWER-1000 will account for 31 GW(e) and WWER-1200/TOI will account for 27 GW(e). In 2050, the total installed capacity of reactors outside the Russian Federation will be similar owing to the decommissioning of a large number of previously built reactors. The total installed capacity will include 15 GW(e) of WWER-1000 reactors, 37 GW(e) of WWER-1200/TOI reactors and 5 GW(e) of VBER-TOI reactors with a partial load of MOX fuel. By 2100, the total installed capacity of Russian Federation design reactors abroad will be 84 GW(e) and will include 59 GW(e) of WWER-1200/TOI reactors and 25 GW(e) of VBER-TOI reactors with a partial load of MOX fuel.

VIII.7.6.2. Reactors and nuclear fuel cycle data

Currently, six types of reactors are in operation in the Russian Federation as presented in Table VIII.18.

TABLE VIII.18 Technical data of existing reactors

Item	RBMK-1000	WWER-440	WWER-1000	WWER-1200/TOI	BN-600	BN-800
Nuclear capacity (MW(e))	1000	440	1000	1200	600	800
Load factor	0.75	0.75	0.85	0.94	0.8	0.85
Thermal efficiency	0.31	0.32	0.33	0.38	0.40	0.38
Fresh fuel annual (t HM)	40	16	17	16	10	11
Fresh fuel first load (t HM)	198	41	86	87	11	15
Plutonium breeding ratio	n.a.[a]	n.a.	n.a.	n.a.	n.a.	~1.0
Enrichment of fresh fuel	0.028	0.049	0.049	0.049/0.063[b]	0.214	n.a.
Lifetime (years)	45	45	60	60	45	45

[a] n.a.: not applicable.
[b] In this case study, the enrichment of fresh UOX fuel for WWER-1200/TOI reactors is projected to increase to 6.3% owing to the introduction of new high enrichment fuel after 2035.

In the future, new types of reactors such as the VBER-TOI with partial loading of MOX fuel, BN-1200, BREST-300 and high temperature GCRs can be commissioned, but this case study details only the VBER-TOI reactors with partial loading of MOX fuel and the BN-1200 (Table VIII.19). High temperature GCRs are considered in a separate case study devoted to the non-electric application of nuclear reactors.

TABLE VIII.19 Technical data of new type reactors

Item	VBER-TOI MOX		BN-1200
Nuclear capacity (MW(e))	1200		1200
Load factor	0.94		0.9
Thermal efficiency	0.38		0.43
	UOX	MOX	
Fresh fuel annual (t HM)	9	7	6.4[a]
Fresh fuel first load (t HM)	48.4	23.6	41.6[a]
Plutonium breeding ratio	n.a.[b]	0.77	1.18
Enrichment of fresh fuel	0.063	0.114[c]	0.197[c]
Lifetime (years)	60	60	

[a] Without considering axial and radial blankets.
[b] n.a.: not applicable.
[c] Plutonium content.

At present, most Russian Federation reactors are operated in a once-through nuclear fuel cycle. However, four options are used for the recycling of reprocessed uranium:

- The blending of reprocessed uranium with higher enriched uranium without its conversion to UF_6;
- The blending of reprocessed uranium converted to UF_6 with highly enriched uranium and low enriched uranium up to 17%;
- The 'mixed route' which involves both enrichment and blending;
- Re-enriching of reprocessed uranium converted to U_3O_8 and blending with highly enriched uranium and low enriched uranium up to 17%.

The reprocessed uranium is used in the fresh fuels of LWGRs, WWERs and PWRs. The extracted plutonium is stored at the RT-1 plant.

The Russian Federation plans a partial closure of the nuclear fuel cycle in the near term and a full closure of the nuclear fuel cycle in the medium or long term with the multirecycling of plutonium. The first stage is the commissioning of a small series of BN-1200 reactors by 2035 to reduce the amount of spent nuclear fuel from thermal reactors, and the use of plutonium extracted from this spent nuclear fuel (Fig. VIII.78 (a)). In this case, the BN-1200 reactors will operate to utilize plutonium.

FIG. VIII.78 Possible plutonium flows in nuclear fuel cycles.

In this roadmap, after 2035 consideration is given to the commissioning of WWERs with partial loading of MOX fuel and an increased installed capacity of BN-1200 reactors to organize a fully closed nuclear fuel cycle (Fig. VIII.78 (b)). This scheme of nuclear fuel cycle organization is optimal for achieving a low balance of plutonium in the NES and takes into account various options for the growth rate of installed capacities [VIII.89].

VIII.7.6.3 Energy production

The average load factor, which currently is about 82%, is planned to be raised to 90% by 2035. In the medium and long term it is expected to remain at the level of 90% or more (Fig. VIII.79).

Energy production, MW(e)·year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
RBMK-1000	8250	7800	5400	2400	600													
VVER-440	1980	1650	1650	1650	1056	198												
VVER-1000	9690	10880	11050	11050	11050	10540	9690	6460	5440	5100	3910	3230	1360	170				
VVER-1200		2933	6768	12182	15228	19627	20304	20304	20304	20981	21432	21432	21432	18499	14664	9250	7219	3835
VVER-TOI (MOX)						1128	3610	7896	11054	12634	15566	19176	22334	26170	29779	35419	39706	45346
BN-600	480	480	480															
BN-800	136	680	680	680	680	680	680	680	680	544								
BN-1200				1080	2808	3672	6696	9504	12096	14688	16416	18360	20736	23544	26136	27648	29592	30888
HTGR					8	50	83	83	166	200	241	308	374	457	491	499	499	499
BREST-1200																		
Total, MW(e)·year	20536	24423	26028	29042	31430	35895	41063	44927	49741	54146	57566	62506	66237	68840	71070	72816	77016	80568

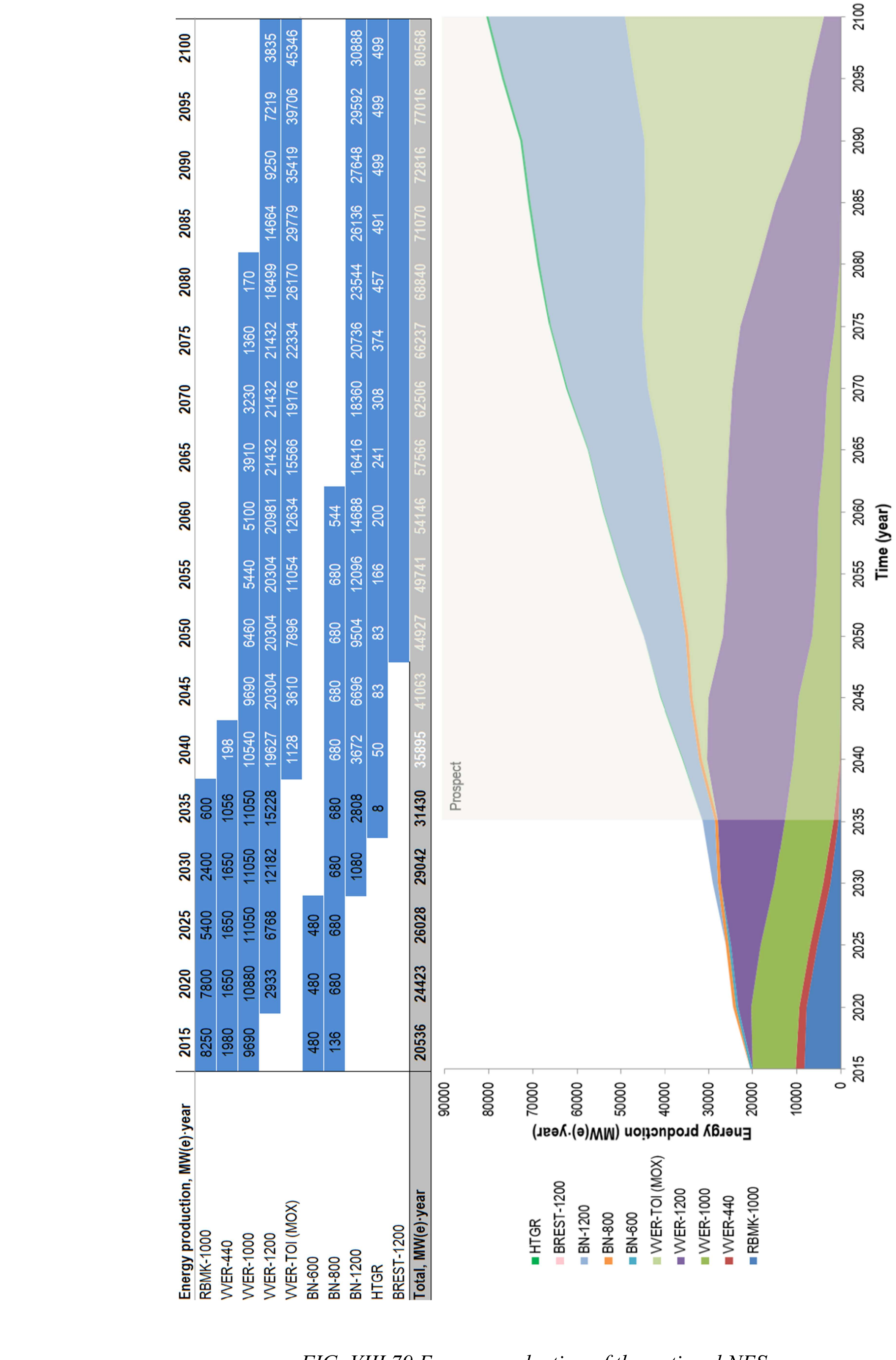


FIG. VIII.79 Energy production of the national NES.

VIII.7.6.4 Uranium mining

Domestic uranium mining in the Russian Federation is carried out on three deposits (Delur, Khiagda, Priargunsky) with a total capacity about 3055 tonnes of natural uranium per year [VIII.90]. The supply from foreign deposits provides about 4794 tons of natural uranium per year [VIII.91]. Reserves of these three indigenous deposits are sufficient to 2036, 2055 and 2070, respectively, if the current rate of uranium mining remains constant. At present AtomRedMetZoloto and UraniumOne are conducting work on the exploration and development of promising new deposits of uranium and the total amount of the natural uranium resource base is estimated to be 521 000 MT U for domestic deposits and about 213 000 MT U for UraniumOne [VIII.91].

Uranium requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium requirements for RBMK-1000	1704	1611	1116	496	124													
Uranium requirements for VVER-440	377	314	314	314	201	38												
Uranium requirements for VVER-1000	1979	2064	1968	1968	1968	1877	1726	1151	969	908	696	575	242	30				
Uranium requirements for VVER-1200		944	1543	2389	3730	3954	3811	3811	3811	4180	4035	4035	4035	3452	2690	1614	1603	919
Uranium requirements for VVER-TOI (MOX):																		
-UOX						531	818	1315	1681	1684	2203	2621	2987	3431	3939	4682	5179	5870
-MOX																		
Uranium requirements for BN-600	253	253	253															
Uranium requirements for BN-800																		
Uranium requirements for BN-1200																		
Uranium requirements for HTGR					20	54	66	66	160	173	220	273	298	392	422	414	398	398
Uranium requirements for BREST-1200																		
Total, t U	**4313**	**5186**	**5194**	**5167**	**6044**	**6453**	**6421**	**6342**	**6620**	**6945**	**7154**	**7504**	**7563**	**7306**	**7051**	**6711**	**7179**	**7187**
Provide services																		
Provide services, t U	**4301**	**4553**	**7204**	**8402**	**8740**	**9131**	**9957**	**10214**	**11240**	**11725**	**12156**	**12657**	**13407**	**13533**	**15268**	**14161**	**13837**	**14673**
Armenia	69	69	235	141	212	184	254	226	297	268	339	311	381	353	353	447	381	353
Belarus		131	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262
Ukraine	1955	1294	1184	1294	991	496	496	330	330									
Other																		
-UOX fuel	2276	3059	5523	6705	7275	8190	8945	9396	10352	11195	11555	12084	12763	12918	14653	13452	13193	14058
-MOX fuel																		
Supply																		
Primary supply, t U	**3055**	**3377**	**3677**	**3677**	**9990**	**10790**	**11584**	**11762**	**13067**	**13876**	**19310**	**20161**	**20969**	**20839**	**22319**	**20872**	**21016**	**21860**
Delur (ARMZ)	590	650	700	700	700	140												
Khiagda (ARMZ)	488	750	1000	1000	1000	1000	1000	1000	1000									
Priargunsky (ARMZ)	1977	1977	1977	1977	1977	1977	1977	1977	1977	1977	1977	1977						
Mineral resources and reserves of U					6313	7673	8607	8785	10090	11899	17333	18184	20969	20839	22319	20872	21016	21860
Secondary supply, t U	**765**	**1569**	**3926**	**5097**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Uranium stocks (experts assessment)	765	1569	3926	5097														
Transfer in materials, t U	**4794**	**4794**	**4794**	**4794**	**4794**	**4794**	**4794**	**4794**	**4794**	**4794**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
UraniumOne	4794	4794	4794	4794	4794	4794	4794	4794	4794	4794								
Total supply, t U	**8614**	**9740**	**12397**	**13568**	**14784**	**15584**	**16378**	**16556**	**17861**	**18670**	**19310**	**20161**	**20969**	**20839**	**22319**	**20872**	**21016**	**21860**
Surplus (supply - demand)																		
Surplus, t U	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

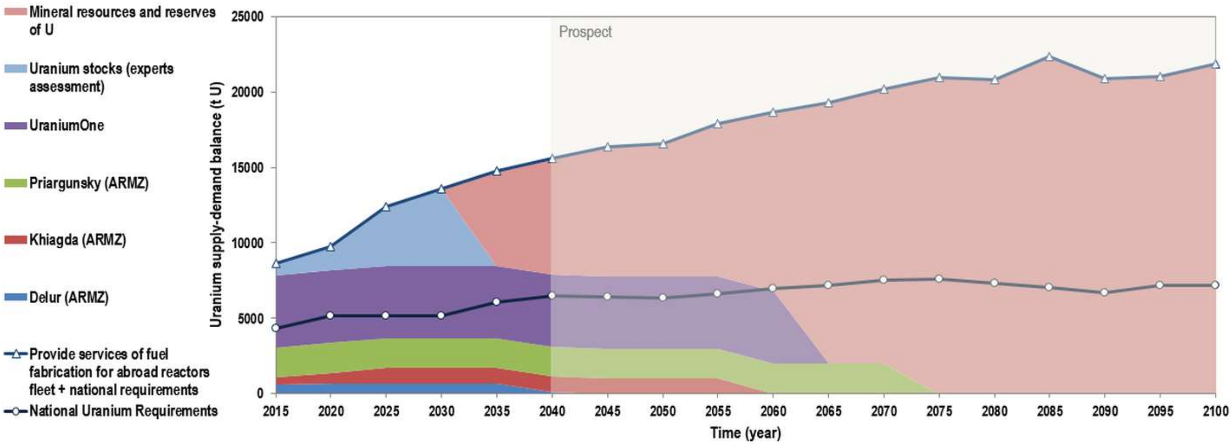


FIG. VIII.80 Demand, supply and surplus for uranium mining and milling.

The estimated annual demand for natural uranium was about 8600 Mt U in 2015 for the fabrication of fuel for the domestic fleet of reactors and for the fleet of Russian Federation design reactors abroad (Fig. VIII.80). This annual demand will increase to about 15 000 Mt U by 2035. In this case study, the increase of the average annual demand for natural uranium will be insignificant (16 500 t U) by the middle of the century owing to the commissioning of significant capacities of the BN-1200 and VBER-TOI reactors with partial loading of MOX fuel in the national NES and with the beginning of commissioning of VBER-TOI reactors with partial loading of MOX fuel abroad. The total annual demand for natural uranium is expected to be about 22 000 Mt U by the end of the century for the given rate of capacity growth and its configuration.

The supply of the mineral resource base is under control and management is being carried out by Government structures to ensure that all demands of the domestic reactor fleet and the export commitments can be met until 2075 if new deposits of uranium are not found, taking into account the growth of demands. But the purchase of uranium in foreign markets, the use of recycled uranium and the enrichment of depleted uranium will allow this problem to be addressed.

VIII.7.6.5 Conversion

For the time being, the conversion capacity of the Russian Federation is located at one site — the Siberian Chemical Combine, Seversk. The total annual conversion capacity of the plant was 12 500 Mt U in 2015 and will be 20 000 Mt U by 2018 (Fig. VIII.81) of which 18 000 Mt U will converted from natural uranium and 2000 Mt U from regenerated uranium. These capacities will be sufficient to cover demands for conversion for the national reactor fleet and for export commitments until 2070. The conversion facility capacity will ideally be sufficient to ensure fabrication fuel for the domestic reactor fleet and for the fleet of Russian Federation design reactors abroad. This capacity is currently 8500 Mt U and will be about 15 000 Mt U by 2035, increasing to 16 500 Mt U by 2050 and to 22 000 Mt U by 2100.

Conversion requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Conversion requirements for RBMK-1000	1704	1611	1116	496	124													
Conversion requirements for VVER-440	377	314	314	314	201	38												
Conversion requirements for VVER-1000	1979	2064	1968	1968	1968	1877	1726	1151	969	908	696	575	242	30				
Conversion requirements for VVER-1200		944	1543	2389	3730	3954	3811	3811	3811	4180	4035	4035	4035	3452	2690	1614	1603	919
Conversion requirements for VVER-TOI (MOX):																		
-UOX						531	818	1315	1681	1684	2203	2621	2987	3431	3939	4682	5179	5870
-MOX																		
Conversion requirements for BN-600	253	253	253															
Conversion requirements for BN-800																		
Conversion requirements for BN-1200																		
Conversion requirements for HTGR					20	54	66	66	160	173	220	273	298	392	422	414	398	398
Conversion requirements for BREST-1200																		
Total, t U	4313	5186	5194	5167	6044	6453	6421	6342	6620	6945	7154	7504	7563	7306	7051	6711	7179	7187
Provide services																		
Provide services, t U	4136	4553	7314	8402	8905	9461	9957	10214	11240	11725	12156	12657	13407	13533	15268	14161	13837	14673
Armenia	69	69	235	141	212	184	254	226	297	268	339	311	381	353	353	447	381	353
Belarus		131	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262
Ukraine	1790	1294	1294	1294	1156	826	496	330	330									
Other																		
- UOX fuel	2276	3059	5523	6705	7275	8190	8945	9396	10352	11195	11555	12084	12763	12918	14653	13452	13193	14058
- MOX fuel																		
Supply																		
Primary supply, t U	12500	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
SCC (Siberian Chemical Combine, Seversk)	12500	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
Secondary supply, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total supply, t U	12500	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
Surplus (supply - demand)																		
Surplus, t U	4051	10260	7493	6432	5051	4086	3622	3444	2139	1330	690	-161	-969	-839	-2319	-872	-1016	-1860

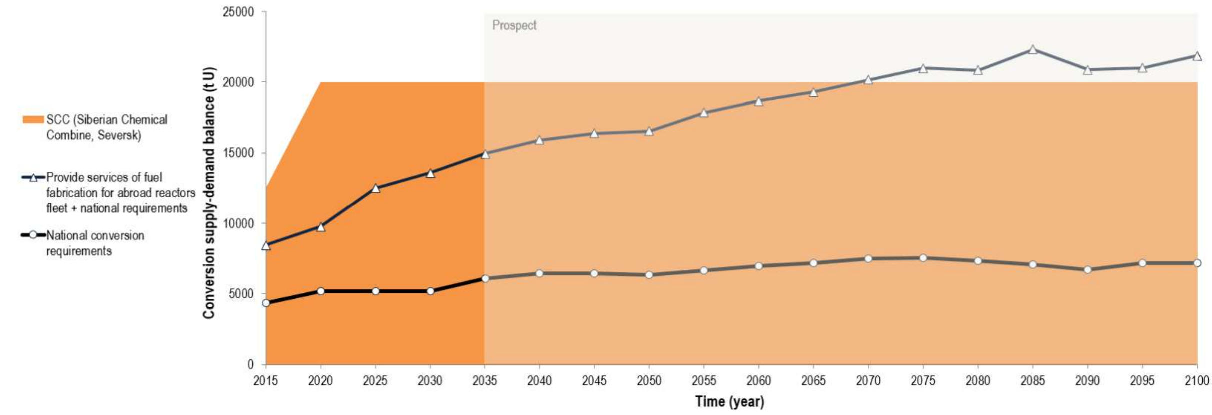


FIG. VIII.81 Demand and supply for and surplus of uranium conversion services.

VIII.7.6.6 Enrichment

Currently, uranium enrichment takes place at four facilities: Ural Electrochemical Integrated Plant (10 000 t SW), Zelenogorsk Electrochemical Plant (8700 t SW), Seversk Siberian Chemical Combine (2600 t SW) and Angarsk Electrolysis & Chemical Combine (3000 t SW).

The total enrichment capacities of these facilities are 24 300 t SW per year (Fig. VIII.82). The Ural Electrochemical Integrated Plant, which can enrich uranium up to 30%, and Zelenogorsk Electrochemical Plant provide enrichment services for needs abroad. Seversk Siberian Chemical Combine specializes in enriching reprocessed uranium, including that from western Europe. Angarsk Electrolysis & Chemical Combine specializes in tails enrichment and it has become the site for the new International Uranium Enrichment Centre and fuel bank. In the near term, the enrichment capacities of Zelenogorsk Electrochemical Plant will be increased to 12 000 t SW with a view to exporting its services [VIII.92].

Enrichment requirements, t SW	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Enrichment requirements for RBMK-1000	1297	1226	849	377	94													
Enrichment requirements for VVER-440	353	294	294	294	188	35												
Enrichment requirements for VVER-1000	1852	1932	1842	1842	1842	1757	1615	1077	907	850	652	538	227	28				
Enrichment requirements for VVER-1200		879	1437	2225	3726	4370	4030	4030	4030	4403	4254	4254	4254	3672	2911	1836	1831	918
Enrichment requirements for VVER-TOI (MOX):																		
-UOX						310	687	1183	1548	1551	2070	2488	2853	3297	3804	4547	5043	5837
-MOX																		
Enrichment requirements for BN-600	301	301	301															
Enrichment requirements for BN-800																		
Enrichment requirements for BN-1200																		
Enrichment requirements for HTGR					26	69	86	86	208	224	285	353	386	508	546	537	515	515
Enrichment requirements for BREST-1200																		
Total, t SW	**3802**	**4631**	**4722**	**4738**	**5877**	6542	6418	6376	6693	7029	7261	7634	7721	7506	7262	6920	7389	7271
Provide services																		
Provide services, t SW	**3468**	**3967**	**6541**	**7555**	**8401**	9053	9647	9963	11000	11581	12026	12545	13311	13457	15207	14142	13821	14657
Armenia	55	55	197	118	177	153	212	189	248	224	283	260	319	295	295	374	319	295
Belarus		131	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262	262
Ukraine	1273	920	920	920	822	588	353	235	235									
Others																		
-UOX fuel	2140	2861	5162	6255	7139	8050	8820	9277	10255	11094	11481	12024	12731	12900	14650	13506	13241	14099
-MOX fuel																		
Supply																		
Primary supply, t SW	**24300**	**24300**	**24300**	**27600**	**27600**	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600
UEIP (Ural Electrochemical Integrated Plant)	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
ECP (Zelenogorsk ElectroChemical Plant)	8700	8700	8700	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000
SCC (Seversk Siberian Chemical Combine)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
AECC (Angarsk Electrolysis & Chemical Combi	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600
Secondary supply, t SW	**0**	**0**	**0**	**0**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)																		
Total supply, t SW	**24300**	**24300**	**24300**	**27600**	**27600**	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600	27600
Surplus (supply - demand)																		
Surplus, t SW	17030	15701	13037	15307	13323	12005	11535	11261	9907	8991	8313	7420	6568	6637	5131	6538	6390	5673

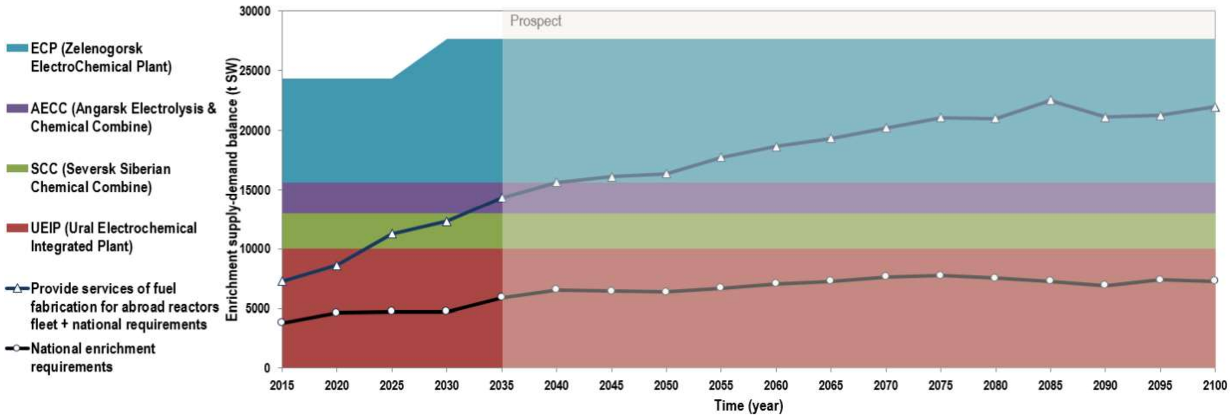


FIG. VIII.82 Demand, supply and surplus for uranium enrichment services.

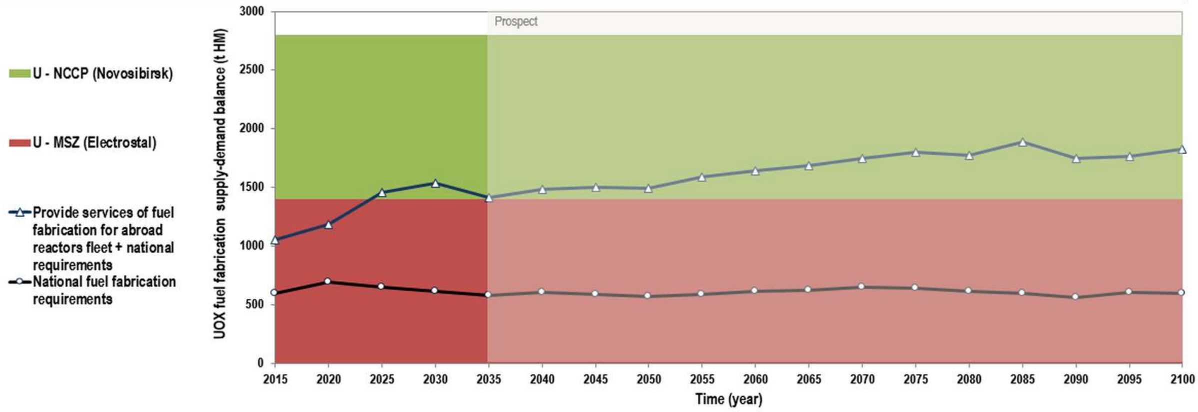
At present, enrichment facilities are using centrifuges of the sixth to ninth generations and testing centrifuges of the tenth generation. The re-equipment of enrichment facilities on ninth generation centrifuges are planned to be completed by 2020.

The demand for enrichment capacities for the national reactor fleet and the reactor fleet abroad is now about 7000 t SW. The demand for enrichment will increase to about 14 000 t SW per year by 2035, up to 16 000 t SW per year by 2050 and to about 22 000 t SW per year by 2100. These capacities will be sufficient to meet the demand for uranium enrichment services to the end of the century.

VIII.7.6.7 Fuel fabrication

Two types of nuclear fuel are industrially fabricated in the Russian Federation: UOX fuel at Mashinostroitelny Zavod (TVEL Fuel Company's subsidiary Mashinostroitelny Zavod, Electrostal) and at Novosibirsk Chemical Concentrates Plant (Novosibirsk) and MOX fuel at the Mining and Chemical Combine (Zheleznogorsk). A pilot facility for vibropac MOX fuel production operates at the site of the Research Institute of Atomic Reactors (Dmitrovgrad) [VIII.92]. The total capacity of the facilities for fabrication of UOX fuel is 2800 t HM per year and capacities for the fabrication of MOX fuel are 60 t HM at present and will be 74 t HM by 2030 (Fig. VIII.83).

Fuel fabrication requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Fuel fabrication requirements for RBMK-1000	335	317	219	97	24													
Fuel fabrication requirements for VVER-440	41	34	34	34	22	4												
Fuel fabrication requirements for VVER-1000	216	225	215	215	215	205	188	126	106	99	76	63	26	3				
Fuel fabrication requirements for VVER-1200		105	171	265	311	365	337	337	337	368	356	356	356	307	243	153	153	77
Fuel fabrication requirements for VVER-TOI (MOX):																		
						26	57	99	129	130	173	208	239	276	318	380	422	488
						14	36	67	90	96	123	150	173	201	231	275	306	354
Fuel fabrication requirements for BN-600	6	6	6															
Fuel fabrication requirements for BN-800	3	8	8	8	8	8	8	8	8	7								
Fuel fabrication requirements for BN-1200				21	27	33	68	88	99	118	130	144	160	187	199	209	237	232
Fuel fabrication requirements for HTGR					1	4	5	5	11	12	16	19	21	28	30	30	28	28
Fuel fabrication requirements for BREST-1200																		
Total (UOX fuel), t HM	598	687	646	612	574	604	587	566	584	609	620	646	642	614	591	563	603	593
Total (MOX fuel), t HM	3	8	8	30	35	56	112	163	198	220	253	293	333	388	429	484	543	586
Provide services																		
Provide services (UOX Fuel), t HM	451	498	804	925	839	877	908	920	1001	1033	1062	1096	1152	1159	1293	1184	1155	1225
Provide services (MOX Fuel), t HM	0	0	0	0	0	5	18	33	39	61	68	90	107	114	145	163	175	178
Armenia	10	10	28	17	25	22	30	27	35	32	40	37	45	41	41	53	45	41
Belarus		19	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38
Ukraine	195	141	141	141	126	90	54	36	36									
Other																		
-UOX fuel	247	329	597	729	650	727	786	820	892	963	984	1022	1069	1079	1213	1093	1072	1145
-MOX fuel						5	18	33	39	61	68	90	107	114	145	163	175	178
Supply																		
Primary supply/Utilize services (UOX fuel), t HM	2800	2800	2800	2800	2801	2804	2805	2805	2811	2812	2816	2819	2821	2828	2830	2830	2828	2828
U - MSZ (Electrostal)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
U-NPO LUCH (Podolsk)					1	4	5	5	11	12	16	19	21	28	30	30	28	28
U - NCCP (Novosibirsk)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
Primary supply/Utilize services (MOX fuel), t HM	60	60	60	74	74	74	74	74	74	74	74	74	74	74	74	74	74	74
MOX - MCC (Zheleznogorsk)	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Vibropaked MOX - RIAR (Dmitrovgrad)				14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Nitride Fule																		
Secondary supply/Transfer in materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)																		
Total supply (UOX fuel), t HM	2800	2800	2800	2800	2801	2804	2805	2805	2811	2812	2816	2819	2821	2828	2830	2830	2828	2828
Total supply (MOX fuel), t HM	60	60	60	74	74	74	74	74	74	74	74	74	74	74	74	74	74	74
Surplus (supply - demand)																		
Surplus (UOX fuel), t HM	1750	1614	1350	1263	1388	1323	1309	1318	1226	1170	1133	1077	1027	1055	946	1082	1070	1010
Surplus (MOX fuel), t HM	57	52	52	44	39	14	-56	-122	-163	-207	-247	-309	-366	-428	-500	-573	-644	-691



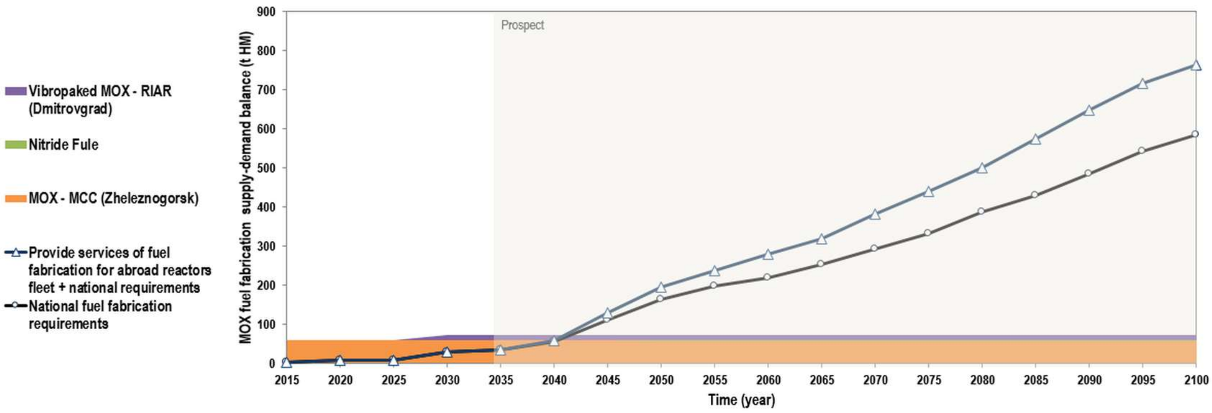


FIG. VIII.83 Demand, supply and surplus for UOX and MOX fuel fabrication.

The UOX fuel fabrication capacity demand for the national reactor fleet and for the fleet of Russian Federation design reactors abroad is now about 1000 t HM. The demand for UOX fuel fabrication will increase to about 1400 t HM per year by 2035, up to 1500 t HM per year by 2050 and to about 1800 t HM per year by 2100. The existing capacities for the fabrication of UOX nuclear fuel are commissioned with an essential reserve and they are sufficient for meeting the demand of the domestic reactor fleet and export commitments until 2100. At present, the existing capacities for MOX nuclear fuel fabrication are capable of providing the fuel needs of the BN-800. The roadmap shows the demand for MOX for BN-1200 and VBER-TOI rectors with a partial load of MOX fuel and nitride fuels for the domestic reactor fleet up to 2050 and beyond. The plans for construction of the fabrication plants to cover the demand are not yet accepted since the dates for the BN-1200 and VBER-TOI reactors with partial load of MOX fuel commissioning are not officially defined. The required capacity of MOX fuel fabrication facility for the domestic reactor fleet and for the fleet of Russian Federation design reactors abroad will be about 35 t HM by 2035, 200 t HM by 2050 and 800 t HM by 2100.

VIII.7.6.8 Spent nuclear fuel storage

According to estimates, the total amount of spent nuclear fuel accumulated by the end of 2015 in the Russian Federation was 33 000 t HM. The main share of it is spent nuclear fuel from LWGR reactors — 20 000 t HM. The amount of spent nuclear fuel from WWER-440/1000 reactors is 9000 t HM and the amount of spent fuel from BN-600 is 222 t HM. It is supposed that the Russian Federation will take back about 50% of foreign spent nuclear fuel resulting from fresh fuel exported from the Russian Federation. This was about 3200 t HM of UOX spent nuclear fuel in 2015. By 2035, the total volume of accumulated UOX spent nuclear fuel including spent nuclear fuel from abroad is estimated to be 46 000 t HM, by 2050 60 000 t HM and by 2100 115 000 t HM.

Existing at-reactor and centralized spent nuclear fuel storage allows the storage of about 36 000 t HM. Commissioning at the Mining and Chemical Combine the second part of the dry storage for spent nuclear fuel from WWER-1000s with a capacity of 8600 t HM and the third part of the dry storage for spent nuclear fuel from LWGRs with a capacity of 15 870 t HM will increase the total amount of spent nuclear fuel storage capacity up to 60 000 t HM by 2020 (Fig. VIII.84) [VIII.93].

These storage capacities are sufficient for storing all spent nuclear fuel from LWGR and WWER reactors now accumulated. The storage will be completely filled by 2045 if large scale spent nuclear fuel reprocessing has not been started by that time.

SNF storage requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SNF storage requirements for RBMK-1000	19185	21164	22855	24332	24652	24652	24652	24652	24652	24652	24652	24652	24652	24652	24652	24652	24652	24652
SNF storage requirements for VVER-440	3922	4135	4307	4479	4713	4816	4816	4816	4816	4816	4816	4816	4816	4816	4816	4816	4816	4816
SNF storage requirements for VVER-1000	4796	5838	6912	7987	9061	10172	11285	12170	12784	13280	13832	14231	14535	14637	14637	14637	14637	14637
SNF storage requirements for VVER-1200		176	685	1664	2917	4498	6183	7867	9552	11274	13052	14830	16608	18491	20056	21171	22075	22610
SNF storage requirements for VVER-TOI (MOX):																		
-UOX						33	175	524	1026	1626	2346	3240	4288	5520	6917	8575	10441	12698
-MOX						25	132	397	777	1232	1778	2456	3250	4185	5244	6501	7915	9600
SNF storage requirements for BN-600	222	253	283	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301
SNF storage requirements for BN-800		42	85	127	169	211	254	296	338	401	401	401	401	401	401	401	401	401
SNF storage requirements for BN-1200				23	115	237	451	764	1177	1682	2247	2882	3600	4411	5320	6496	7619	8803
SNF storage requirements for HTGR						1	13	35	57	98	149	210	289	386	504	636	772	902
SNF storage requirements for BREST-1200																		
Total (UOX fuel), t HM	28126	31566	35042	38763	41644	44473	47425	50365	53188	56047	59148	62281	65488	68804	71882	74789	77693	80617
Total (MOX fuel), t HM	0	42	85	150	284	473	837	1457	2293	3315	4426	5739	7251	8996	10965	13397	15934	18803
Provide services/Transfer in materials																		
Transfer in materials (UOX SNF), t HM	3175	3387	3406	3792	4914	6400	8008	9742	11644	13682	15892	18277	20773	23412	26361	29576	32329	34759
Transfer in materials (MOX SNF), t HM	0	0	0	0	0	0	0	66	182	356	612	926	1307	1795	2341	2969	3738	4590
Armenia								220	440	660	880	1100	1320	1540	1760	2430	2880	3430
Belarus					97	288	479	670	861	1052	1243	1434	1625	1816	2007	2198	2389	2580
Ukraine	2780	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992	2992
Other																		
-UOX fuel	395	395	414	800	1826	3120	4537	5860	7352	8978	10778	12751	14837	17064	19602	21957	24068	25757
-MOX fuel								66	182	356	612	926	1307	1795	2341	2969	3738	4590
Supply																		
Primary supply (UOX fuel), t HM	41584	67122	68115	68377	64005	58743	55221	42908	43037	42483	42707	43114	43209	43548	43509	42826	42155	41275
At-reactor-pools of UOX reactors	21184	22252	23245	23507	19135	13873	10351	9238	9367	8813	9037	9444	9539	9878	9839	9156	8485	7605
Wet AFR storage (PA Mayak, VVER SNF)	2600	2600	2600	2600	2600	2600	2600											
Wet AFR storage (MCC, VVER SNF)	8600	8600	8600	8600	8600	8600	8600											
Dry AFR storage-1 (MCC, RBMK SNF)	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200	9200
Dry AFR storage-2 (MCC, VVER SNF)		8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600	8600
Dry AFR storage-3 (MCC, RBMK SNF)		15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870	15870
Transfer out materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transfer out materials (all)																		
Total supply, t HM	41584	67122	68115	68377	64005	58743	55221	42908	43037	42483	42707	43114	43209	43548	43509	42826	42155	41275
Primary supply (MOX fuel), t HM	21	106	106	169	271	442	882	1501	1988	2308	2719	3195	3584	4155	4690	5134	5404	5620
At-reactor-pools of MOX reactors	21	106	106	169	271	442	882	1501	1988	2308	2719	3195	3584	4155	4690	5134	5404	5620
Surplus (supply - demand)																		
Surplus (UOX fuel), t HM	10284	32170	29667	25822	17448	7871	-212	-17199	-21795	-27246	-32333	-37444	-43052	-48667	-54735	-61538	-67867	-74100
Surplus (MOX fuel), t HM	21	63	21	20	-12	-32	45	44	-305	-1007	-1707	-2544	-3667	-4841	-6275	-8264	-10530	-13183

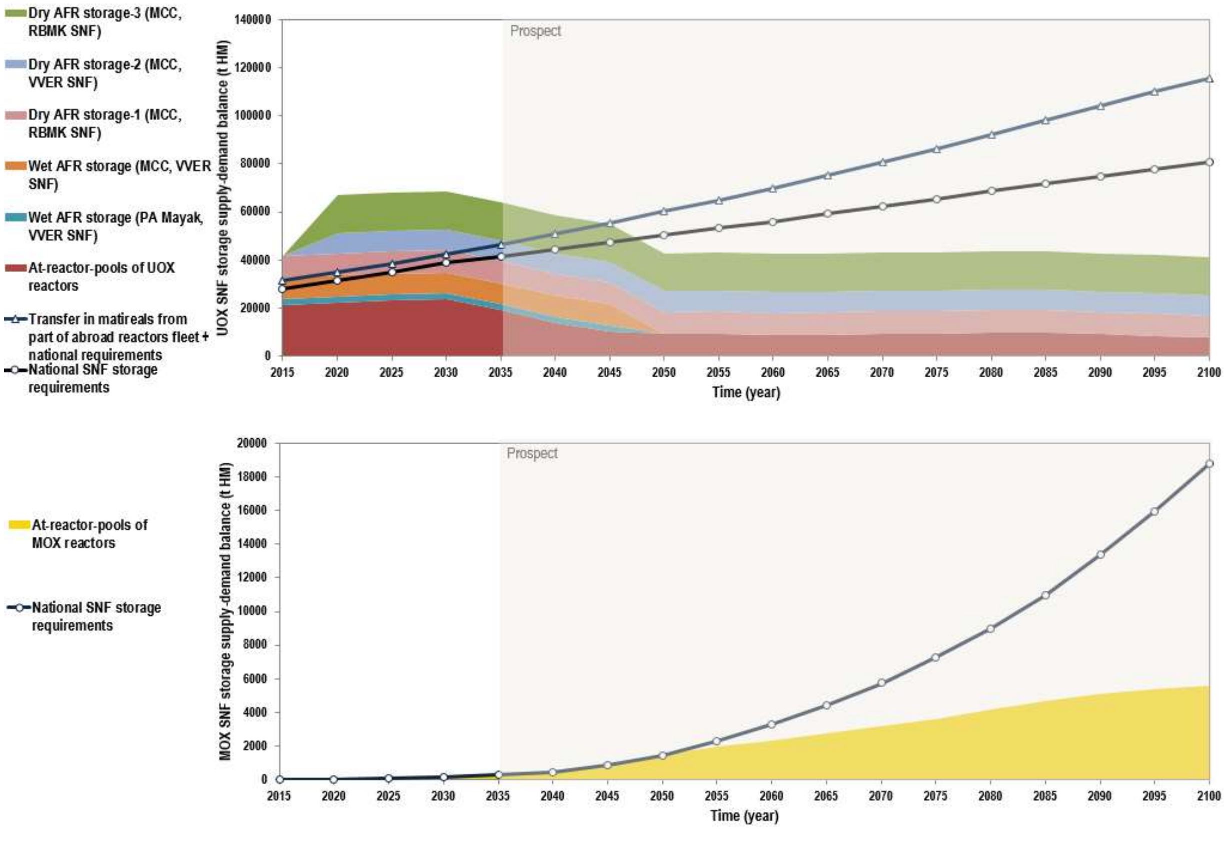


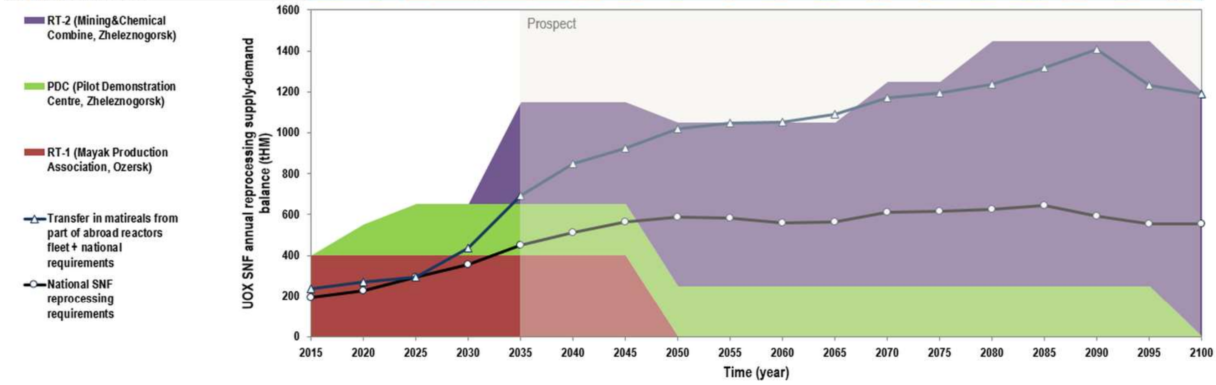
FIG. VIII.84 Demand, supply and surplus for UOX and MOX spent nuclear fuel storage.

Currently there is no centralized storage facility for MOX spent nuclear fuel from the FRs nor for MOX spent nuclear fuel from WWERs. By 2035, the total volume of accumulated MOX spent nuclear fuel is estimated to be 300 t HM, by 2050 to be 1500 t HM and by 2100 to be 23 400 t HM.

VIII.7.6.9 Reprocessing of spent nuclear fuel

To date, only one facility for reprocessing — RT-1 with a capacity of 400 t HM/year (Fig. VIII.85) — is in commercial operation. In accordance with the project lifetime, it will be decommissioned by 2045. In 2018, the Pilot Demonstration Centre is planned to be commissioned with a reprocessing capacity of spent nuclear fuel of up to 250 t HM per year. In 2024, based on experience from the Pilot Demonstration Centre, a large scale plant for spent nuclear fuel reprocessing, RT-2, is to be built with a capacity of 800 t HM per year [VIII.93], but in this study the date of commissioning of RT-2 and its capacity is selected on the basis of the BN's and WWER's requirements for plutonium.

SNF reprocessing requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SNF reprocessing requirements for RBMK-1000																		
SNF reprocessing requirements for VVER-440	41	41	43	34	34	47	21											
SNF reprocessing requirements for VVER-1000	149	182	208	215	215	215	222	223	177	123	99	110	80	61	20			
SNF reprocessing requirements for VVER-1200			35	102	196	251	316	337	337	337	344	356	356	356	377	313	223	181
SNF reprocessing requirements for VVER-TOI (MOX):																		
- UOX fuel							7	28	70	100	120	144	179	209	247	279	332	373
- MOX fuel							5	22	53	76	91	109	136	159	187	212	251	283
SNF reprocessing requirements for BN-600	6	6	6	6	4													
SNF reprocessing requirements for BN-800			8	8	8	8	8	8	8	8	13							
SNF reprocessing requirements for BN-1200					5	18	24	43	63	83	101	113	127	144	162	182	235	225
SNF reprocessing requirements for BREST-1200																		
Total (UOX fuel), t HM	196	229	292	357	449	512	566	588	584	560	564	610	614	626	644	592	555	554
Total (MOX fuel), t HM	0	0	8	8	13	27	38	73	124	167	204	222	263	303	349	394	487	507
Provide services/Transfer in materials																		
Transfer in materials (UOX SNF), t HM	42	42	0	77	244	335	360	429	463	490	524	559	581	610	672	815	679	634
Transfer in materials (MOX SNF), t HM	0	0	0	0	0	0	0	13	23	35	51	63	76	98	109	126	154	170
Armenia								44	44	44	44	44	44	44	44	134	90	110
Belarus					19	38	38	38	38	38	38	38	38	38	38	38	38	38
Ukraine	42	42																
Other																		
- UOX fuel				77	225	297	322	347	381	408	442	477	499	528	590	643	551	486
- MOX fuel								13	23	35	51	63	76	98	109	126	154	170
Supply																		
Primary supply (UOX fuel), t HM	400	550	650	650	1150	1150	1150	1050	1050	1050	1050	1250	1250	1450	1450	1450	1450	1200
RT-1 (Mayak Production Association, Ozersk)	400	400	400	400	400	400	400											
PDC (Pilot Demonstration Centre, Zheleznogorsk)		150	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	
RT-2 (Mining&Chemical Combine, Zheleznogorsk)					500	500	500	800	800	800	800	1000	1000	1200	1200	1200	1200	1200
Primary supply (MOX fuel), t HM	0	0	0	0	0	0	150	150	200	200	300	350	350	450	500	600	650	750
RT-2 (Mining&Chemical Combine, Zheleznogorsk)							50	50	100	100	200	200	200	300	300	400	400	500
RT-2 (Mining&Chemical Combine, Zheleznogorsk)							100	100	100	100	100	150	150	150	200	200	250	250
Transfer out materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transfer out materials (all)																		
Surplus (supply - demand)																		
Surplus (UOX fuel), t HM	161	278	358	216	457	302	225	33	4	0	-38	81	54	214	134	43	216	12
Surplus (MOX fuel), t HM	0	0	-8	-8	-13	-27	112	77	76	33	96	128	87	147	151	206	163	243



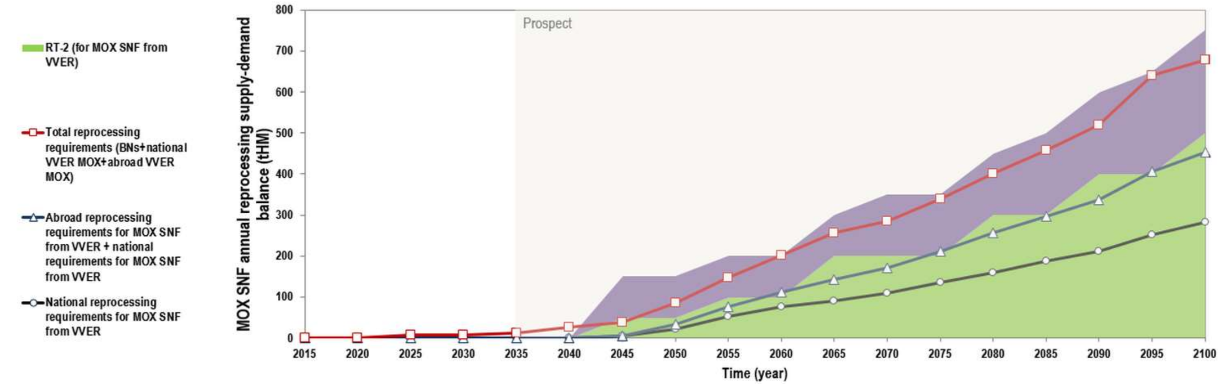


FIG. VIII.85 Demand, supply and surplus for UOX and MOX spent nuclear fuel reprocessing services. Legend: SNF— spent nuclear fuel.

The required capacities for spent nuclear fuel reprocessing will be 700 t HM/year by 2035 for UOX and 13 t HM/year for MOX, 1000 t HM/year for UOX and 86 t HM/year for MOX by 2050 and 1200 t HM/year and 680 t HM/year for UOX and MOX spent nuclear fuel by 2100, respectively, assuming that all discharged spent nuclear fuel is reprocessed.

As can be seen from Fig. VIII.86, the planned capacities could provide the reprocessing of all UOX spent nuclear fuel discharged and spent nuclear fuel previously accumulated, excluding spent nuclear fuel from LWGR and spent nuclear fuel that is being cooled in spent fuel pools.

Cumulative amount of reprocessed SNF	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
RT-1 (Mayak Production Association, Ozersk)																		
Reprocessed SNF from VVER-440	4135	4300	4513	4685	4857	5091	5194	5194	5194	5194	5194	5194	5194	5194	5194	5194	5194	5194
Reprocessed SNF from BN-600	187	222	253	283	301	301	301	301	301	301	301	301	301	301	301	301	301	301
Reprocessed SNF from VVER-1000		200	700	1200	1700	2200	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700
PDC (Pilot Demonstration Centre, Zheleznogorsk)																		
Reprocessed SNF from VVER-1000		750	2000	3250	4500	5750	7000	8250	9500	10750	12000	13250	14500	15750	17000	18250	18777	18777
RT-2 (Mining&Chemical Combine, Zheleznogorsk)																		
Reprocessed UOX SNF from VVER-1200/TOI					2500	5000	7500	11407	15013	18906	22906	27660	32498	37631	43366	49037	54445	59644
Reprocessed MOX SNF from VVER-TOI							25	198	579	1079	1844	2704	3704	5045	6526	8213	10213	12505
Reprocessed SNF from BN-800/1200							448	705	1060	1515	2015	2648	3283	4001	4811	5721	6897	8019
Total reprocessed UOX, tHM	4322	5472	7466	9418	13858	18342	22695	27852	32708	37851	43101	49105	55193	61576	68561	75482	81417	86616
Total reprocessed MOX, tHM	0	0	0	0	0	0	448	705	1060	1515	2015	2648	3283	4001	4811	5721	6897	8019

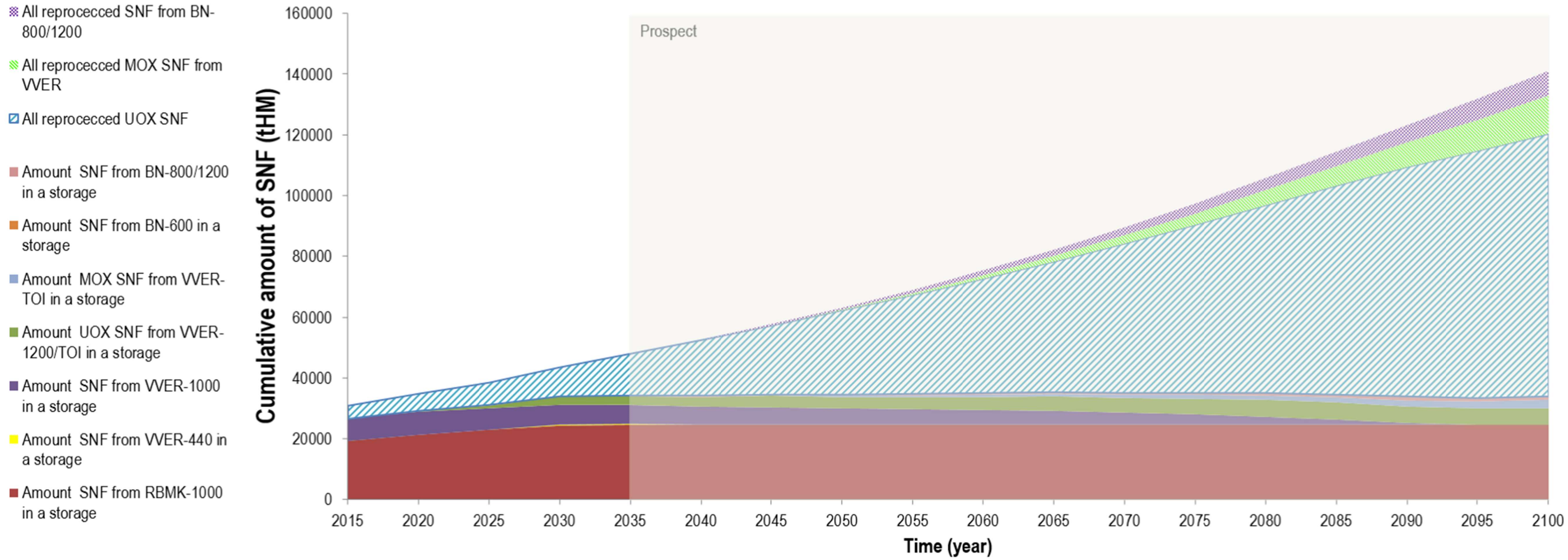


FIG. VIII.86 Cumulative amount of reprocessed spent nuclear fuel and spent nuclear fuel in storage. Legend: SNF— spent nuclear fuel.

According to the evaluation, the reprocessing of BN spent nuclear fuel and MOX spent nuclear fuel from the WWERs has to start after 2045, when separated plutonium from the spent uranium fuel of WWERs will not be sufficient for implementing the national nuclear power deployment programme and for supplying MOX fuel for reactors abroad. At the same time, the amount of accumulated MOX spent nuclear fuel will be sufficient for the operation of the MOX spent nuclear fuel reprocessing plant in a commercial regime.

VIII.7.6.10 Handling of plutonium

For the Russian Federation case study, the issue of plutonium balance in the system (Fig. VIII.87) is important as a part of the strategy aimed at the closure of the nuclear fuel cycle.

Average annual Pu requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Average annual Pu requirements for VVER-440																		
Average annual Pu requirements for VVER-1000																		
Average annual Pu requirements for VVER-1200																		
Average annual Pu requirements for VVER-TOI (MOX)						1.6	4.1	7.7	10.3	10.9	14.1	17.1	19.7	22.9	26.3	31.4	34.9	40.4
Average annual Pu requirements for BN-600																		
Average annual Pu requirements for BN-800	0.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.3								
Average annual Pu requirements for BN-1200				4.2	5.3	6.5	13.4	17.3	19.6	23.2	25.6	28.3	31.6	36.9	39.2	41.3	46.7	45.8
Average annual Pu requirements for HTGR																		
Total, t HM	0.6	1.6	1.6	5.8	6.9	9.7	19.1	26.6	31.5	35.4	39.7	45.4	51.3	59.8	65.5	72.6	81.6	86.2
Provide services																		
Provide services, t HM	0	0	0	0	0	1	2	4	5	7	8	10	12	13	17	19	20	20
Average annual Pu requirements for VVER-TOI (MOX)						1	2	4	5	7	8	10	12	13	17	19	20	20
Supply																		
Primary supply/Utilize services, t HM	4.0	5.5	6.5	6.5	11.5	11.5	37.1	36.3	40.8	40.9	49.6	62.8	62.8	73.6	84.5	93.3	104.2	110.4
RT-1 (Mayak Production Association, Ozersk)	4.0	4.0	4.0	4.0	4.0	4.0	4.0											
PDC (Pilot Demonstration Centre, Zheleznogorsk)		1.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	
RT-2 (Zheleznogorsk), from VVER-1000/1200/TOI UOX SNF					5.0	5.0	5.0	8.0	8.0	8.0	8.0	10.0	10.0	12.0	12.0	12.0	12.0	12.0
RT-2 (Zheleznogorsk), from VVER-TOI MOX SNF							4.4	4.4	8.7	8.7	17.5	17.5	17.5	26.2	26.2	35.0	35.0	43.7
RT-2 (Zheleznogorsk), from BN-800/1200 SNF							21.2	21.5	21.6	21.7	21.6	32.8	32.8	32.8	43.8	43.8	54.7	54.7
Secondary supply/Transfer in materials, t HM	0.0	1.8	1.6	1.6	3.2	4.2	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ex-weapons Pu		1.8	1.6	1.6	0.8													
Reactor-grade plutonium (most of it on RT-1)					2.3	4.2	4.5											
Total supply, t HM	4.0	7.3	8.1	8.1	14.7	15.7	41.6	36.3	40.8	40.9	49.6	62.8	62.8	73.6	84.5	93.3	104.2	110.4
Surplus (supply - demand)																		
Surplus, t HM	3.4	5.7	6.5	2.3	7.8	5.5	20.6	6.1	4.8	-1.4	2.2	7.1	-0.7	0.8	2.6	2.0	2.6	4.0

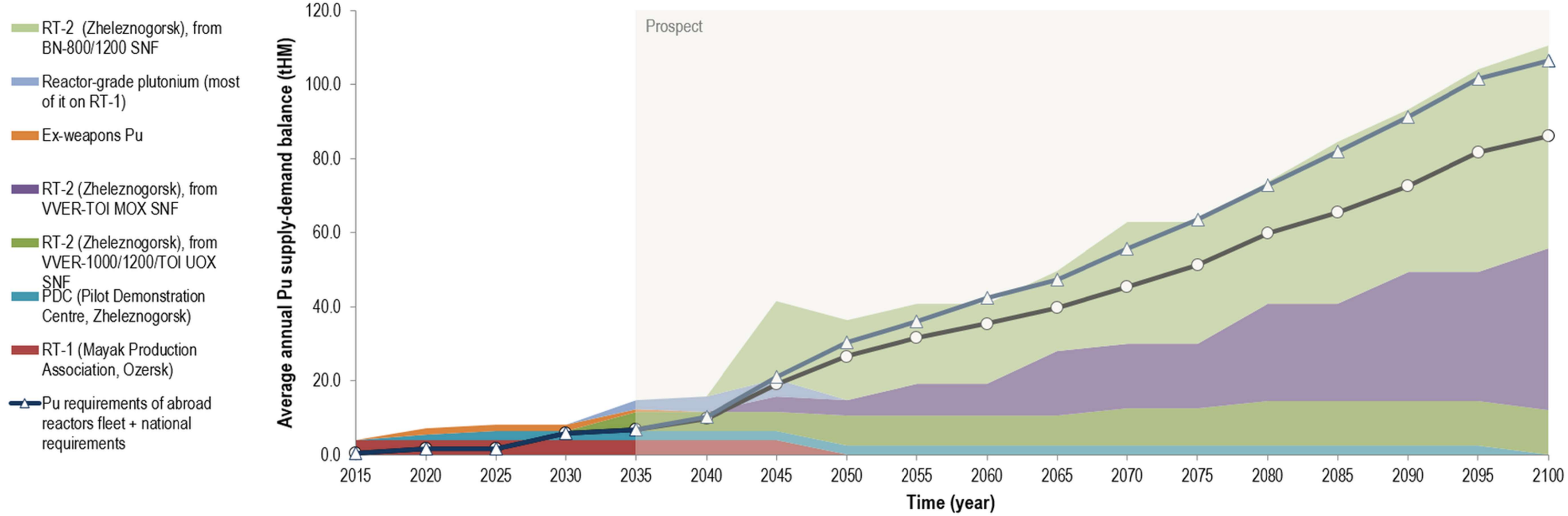


FIG. VIII.87 Annual average surplus of and demand for plutonium.

Available literature sources indicate that at present the Russian Federation stocks of weapons grade plutonium are 34 tonnes, stocks of reactor grade plutonium are 53 tonnes, and stocks of about 4 tonnes of plutonium are held at the site of RT-1 [VIII.94].

It is assumed that a part of this plutonium could be used for reload fuel for the BN-800 reactor, for the BN-1200 reactor and for VBER-TOI reactors with partial MOX fuel loading. The estimated annual average demand for plutonium will reach 6.9, 30.6 and 106.2 t per year by 2035, 2050 and 2100, respectively.

Cumulative Pu amount in the NFC	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Pu charged in the VVER-MOX core						4.6	19.0	38.8	54.0	67.6	82.1	101.8	121.6	139.1	161.1	191.5	212.8	233.3
Pu charged in the BNs core	0.6	2.9	2.9	10.3	22.1	28.1	48.8	68.0	85.8	103.0	112.5	125.8	142.1	161.3	179.1	189.4	202.8	211.6
Extracted Pu in storage	98.7	102.0	113.8	104.2	121.6	122.5	168.3	151.5	142.0	136.8	140.9	150.6	134.7	124.4	108.6	85.4	85.5	66.5
Pu amount in not reprocessed SNF	76.8	91.4	105.2	138.0	161.7	200.5	176.9	212.6	250.1	292.9	319.1	332.6	373.6	405.3	437.0	510.1	513.8	554.8

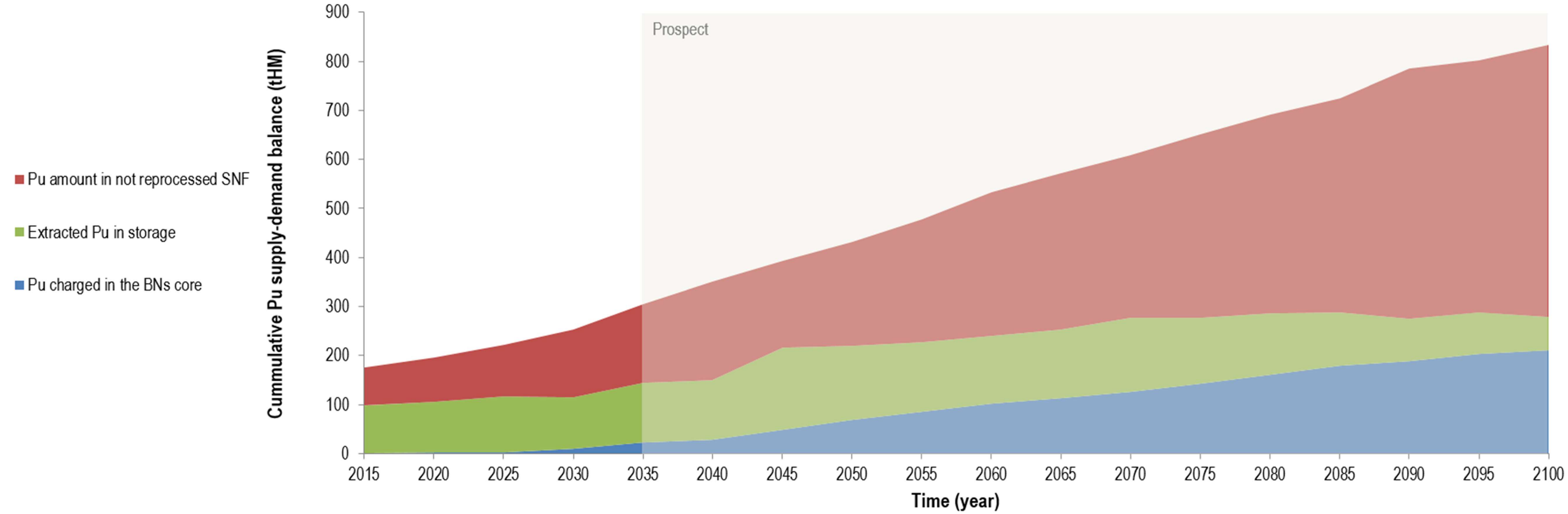


FIG. VIII.88 Cumulative amount of plutonium in the nuclear fuel cycle. Legend: SNF — spent nuclear fuel.

The scenario with a closure of the nuclear fuel cycle considered in this study is characterized by a reduction of the amount of recovered plutonium to the required level (Fig. VIII.88) but an increase of the total amount of plutonium in the nuclear fuel cycle, most of which would be cooling in reactor pools in the form of MOX spent nuclear fuel from WWER and BN reactors before being sent for reprocessing.

VIII.7.7 Summary

This case study considers not only the national reactor fleet and nuclear fuel cycle, but also the perspective of the further development of the fleet of Russian Federation design reactors abroad and the corresponding potential of the national nuclear infrastructure to meet the associated demand for nuclear fuel cycle services. Data provided by Armenia, Belarus and Ukraine and expert assessments were used in assessing prospects for the development of international cooperation. This study considered that the installed capacity of the reactor fleet of Russian Federation design outside the Russian Federation is approximately equal to the national reactor fleet, and includes WWER reactors with UOX and MOX fuel. The share of WWER reactors with a partial load of MOX fuel in the reactor park outside the Russian Federation will depend on the amount of plutonium (Fig. VIII.77). It is assumed that the Russian Federation will provide fresh fuel services to all WWER reactors that have been and will be built abroad, excluding Ukraine (see more details in Annex VIII Section VIII.6). As for spent nuclear fuel, it is supposed that after 2035 half the countries with Russian Federation WWERs will select the option of spent nuclear fuel return to the country of origin, including all MOX fuel from WWERs built abroad.

On account of the commissioning of BN reactors and WWER MOX, the demand for nuclear fuel cycle front end services for the national NES is approximately half the demand for nuclear fuel cycle front end services for the reactor fleet outside the Russian Federation, and the capacities of existing nuclear fuel cycle front end facilities are sufficient to meet all long term demands (see Fig. VIII.80– VIII.83). At the same time, the existing capacities of the nuclear fuel cycle back end facilities are not sufficient to reprocess all incoming national and foreign spent nuclear fuel, and they require further expansion (in this case study, the reprocessing capacity is automatically increasing according to the amount of the spent nuclear fuel for balancing plutonium; see Fig. VIII.84– VIII.86). The amount of extracted plutonium from spent nuclear fuel (see Figs VIII.87 and VIII.88) will allow the commissioning of only BN reactors and WWER MOX with partial loading of MOX fuel in the national NES after 2035, and an increase in the share of WWER with partial loading of MOX fuel up to 30% in the reactor fleet outside the Russian Federation by 2100.

Status Monitoring (Quantitative Indicators)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium utilization	1.00	1.03	1.09	0.97	1.02	1.01	0.97	0.92	0.91	0.89	0.87	0.86	0.84	0.81	0.85	0.78	0.76	0.75
Geologic waste production	1.00	1.04	1.05	0.92	0.82	0.82	0.79	0.77	0.76	0.75	0.74	0.74	0.73	0.73	0.77	0.74	0.73	0.73
Enrichment utilization	1.00	1.08	1.17	1.04	1.17	1.20	1.13	1.08	1.07	1.05	1.03	1.01	1.00	0.97	1.02	0.94	0.91	0.90
Pu amount on NFC	1.00	0.97	1.14	1.03	0.99	0.99	1.03	1.07	1.09	1.13	1.14	1.14	1.16	1.19	1.22	1.34	1.35	1.36

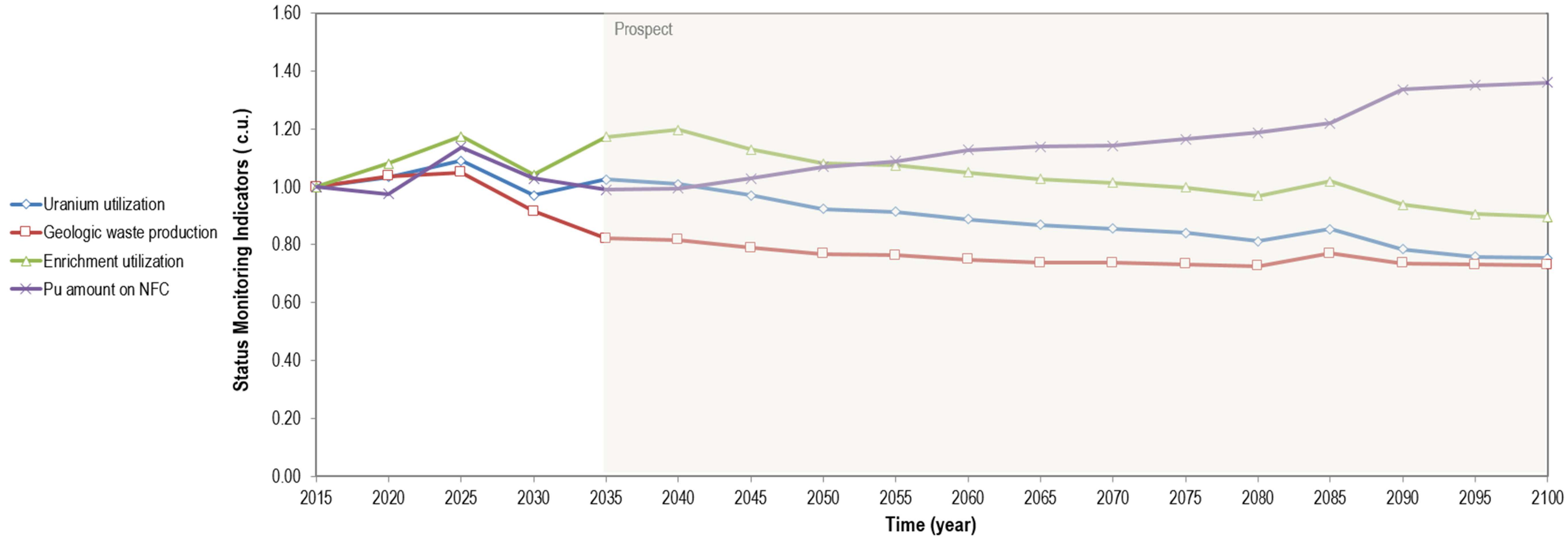


FIG. VIII.89 Set of indicators characterizing NES strategy performance.

The commissioning of a certain number of BNs and VBER-TOI reactors with partial loading of MOX fuel allowed a reduction of the consumption of natural uranium, of the demand for enrichment capacities and of the specific amount of spent nuclear fuel, even taking into account the fleet of nuclear reactors outside the Russian Federation (Fig. VIII.89). However, the specific amount of plutonium in the NES has increased.

The roadmap of Russian Federation nuclear energy development until the end of the century with consideration of possible transition points, which depend on the introduction of certain technologies, is shown in Fig. VIII.90. The evolvement of the Russian Federation NES is considered in several related areas that reflect its general characteristics, the development of technologies in the field of nuclear reactor design and the nuclear fuel cycle, and international cooperation indicating key phases of NES development (Fig. VIII.90).

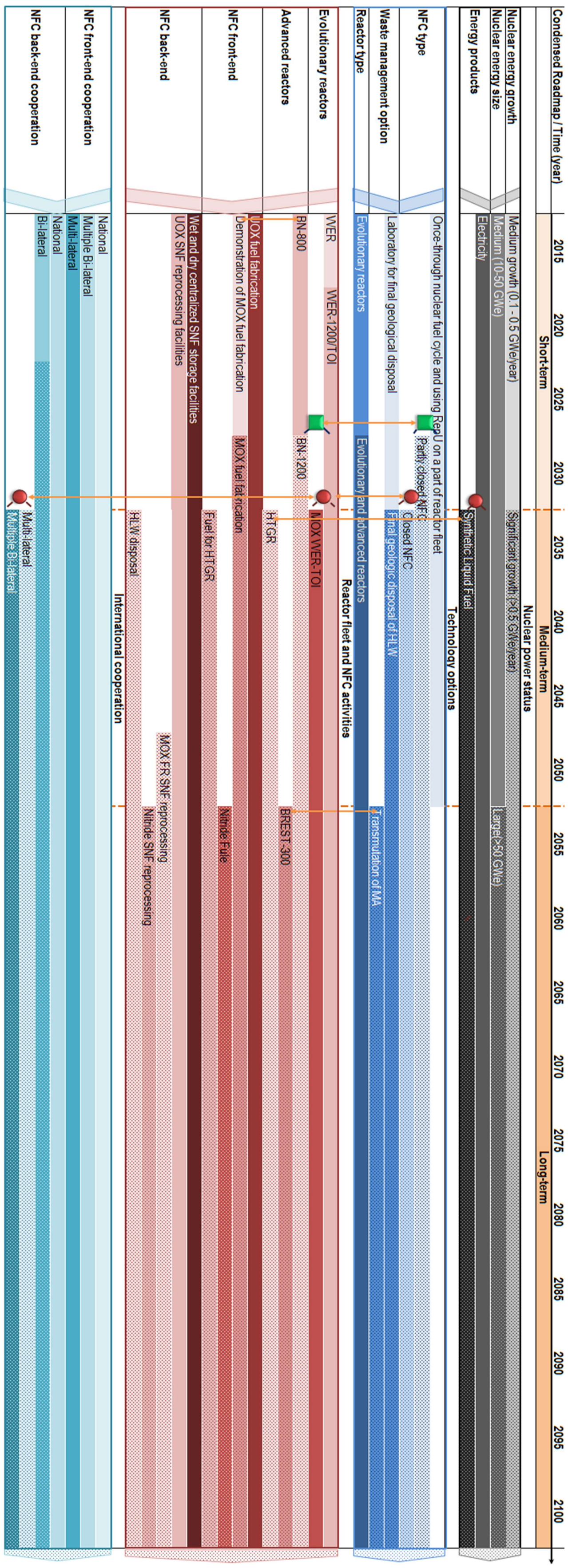


FIG. VIII.90 Condensed roadmap of Russian Federation NES development. Legend: MA — minor actinides; SNF — spent nuclear fuel.

The first transition point is related to the commissioning of a small series of BN reactors after 2025 and the organization of a partial closed nuclear fuel cycle. The next transition point is the possible commissioning of WWER reactors with a partial load of MOX fuel and a fully closed nuclear fuel cycle. A closed nuclear fuel cycle and the reprocessing of UOX and MOX fuel will allow the rational use of plutonium from spent nuclear fuel returned from abroad and facilitate the opening of an international centre of nuclear fuel cycle back end services.

The commissioning of high temperature GCRs in the medium term will allow the use of nuclear energy for the production of synthetic liquid fuel. The commissioning of BREST reactors with nitride fuel and capability for minor actinide burning presents another way of closing the nuclear fuel cycle.

An analysis of the data presented in the roadmap shows the status and prospects for and some impediments to the development and deployment of nuclear power in the Russian Federation and opportunities to further the development of international cooperation in nearly all areas of the nuclear fuel cycle. The case study provides a database helpful in activities on enhancing Russian Federation NES sustainability and indicating some areas of concern to be addressed by decision making.

As follows from the roadmap, the Russian Federation has a great potential for international collaboration and collaboration with other countries. The roadmap applies the model of cooperation with both user and newcomer countries. This cooperation is mainly related to the provision of services to country partners. It is shown that in spite of the active participation of the country in the world market in the nuclear fuel cycle front end, some reserves of uranium conversion, enrichment and fabrication capacities will still remain. Taking back spent nuclear fuel from abroad for reprocessing and the subsequent use of separated plutonium and reprocessed uranium in FRs and thermal reactors provides a good perspective towards ensuring the global sustainability of nuclear power. This activity assumes the use of an instrument, such as the roadmap template, for projecting and monitoring the material flows. It follows from the Russian Federation roadmap that currently the programmes for plutonium separation are far ahead of the programmes for the deployment of reactors capable of effectively using that plutonium.

The roadmap also demonstrates that in some areas of international cooperation the Russian Federation is a consumer of certain services from abroad rather than a supplier of these services. For instance, deposits of natural uranium ore explored to date on the territory of the Russian Federation do not have a rich content of natural uranium in ore. Therefore, purchasing national uranium on the international markets or the organization of joint ventures with foreign companies are practical alternatives to the exploring and mining of indigenous deposits.

It could be noted that the roadmaps allow existing and future problems to be addressed in a structured manner and support identifying solutions on an integrated basis.

REFERENCES TO ANNEX VIII

[VIII.1] STATISTICAL COMMITTEE OF THE REPUBLIC OF ARMENIA, Statistical yearbook of Armenia 2015, Yerevan (2015), https://www.armstat.am/en/?nid=586&year=2015

[VIII.2] PUBLIC SERVICES REGULATORY COMMISSION OF THE REPUBLIC OF ARMENIA, Legal Entities Licensed in the Field of Energy, PSRC, Yerevan (2021) (in Armenian), https://psrc.am/uploads/files/%D4%B7%D5%AC%D5%A5%D5%AF%D5%BF%D6%80%D5%A1%D5%AF%D5%A1%D5%B6%20%D4%B7%D5%B6%D5%A5%D6%80%D5%A3%D5%AB%D5%A1/%D4%BC%D5%AB%D6%81%D5%A5%D5%B6%D5%A6%D5%A1%D5%BE%D5%B8%D6%80%D5%BE%D5%A1%D5%AE%20%D5%A8%D5

%B6%D5%AF%D5%A5%D6%80%D5%B8%D6%82%D5%A9%D5%B5%D5%B8%D6%82%D5%B6%D5%B6%D5%A5%D6%80/KAYQVERJN%2003-06-21.pdf

[VIII.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Power Profiles. 2016 Edition. Armenia (Updated 2016), IAEA, Vienna (2016), https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2016/countryprofiles/Armenia/Armenia.htm

[VIII.4] PUBLIC SERVICES REGULATORY COMMISSION OF THE REPUBLIC OF ARMENIA, Reports 2016, PSRC, Yerevan (2021), https://psrc.am/uploads/files/%D4%B7%D5%AC%D5%A5%D5%AF%D5%BF%D6%80%D5%A1%D5%AF%D5%A1%D5%B6%20%D4%B7%D5%B6%D5%A5%D6%80%D5%A3%D5%AB%D5%A1/%D5%80%D5%A1%D5%B7%D5%BE%D5%A5%D5%BF%D5%BE%D5%B8%D6%82%D5%A9%D5%B5%D5%B8%D6%82%D5%B6%D5%B6%D5%A5%D6%80/2016/2%E2%80%A4%20%D5%80%D5%AB%D5%B4%D5%B6%D5%A1%D5%AF%D5%A1%D5%B6%20%D5%A2%D5%B6%D5%B8%D6%82%D5%A9%D5%A1%D5%A3%D6%80%D5%A5%D6%80/4%20Eramsyak.pdf

[VIII.5] MINISTRY OF ENERGY INFRASTRUCTURES AND NATURAL RESOURCES, ”Long term development of the energy system of the Republic of Armenia (till 2036)", Yerevan (2015), http://www.minenergy.am/page/493 (in Armenian).

[VIII.6] ARMENIAN LEGAL INFORMATION SYSTEM (ARLIS), “Concept of the Energy Security of the Republic of Armenia”, ARLIS, Yerevan (2013), https://policy.asiapacificenergy.org/sites/default/files/Concept%20of%20the%20Energy%20Security%20of%20the%20Republic%20of%20Armenia_2013%20%28ARM%29%20.pdf (in Armenian)

[VIII.7] GOVERNMENT OF THE REPUBLIC OF ARMENIA, Energy Sector Development Strategies in the Context of Economic Development in Armenia, Approved by the Government of Republic of Armenia at June 23, 2005 session, No. 1 resolution of No. 24 protocol, Yerevan (2005), http://www.nature-ic.am/wp-content/uploads/2013/10/Energy-Strategy-Final-_Eng_.pdf

[VIII.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Information System, IAEA-TECDOC-1613, IAEA, Vienna (2009).

[VIII.9] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy and Nuclear Power Planning Study for Armenia, IAEA-TECDOC-1404, IAEA, Vienna (2004).

[VIII.10] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Human Resource Needs for a New Nuclear Power Plant: Armenian Case Study, IAEA-TECDOC-1656, IAEA, Vienna (2011).

[VIII.11] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology, A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1636, IAEA, Vienna (2009).

[VIII.12] KAROPA, G.N., Physical Geography of Belarus: Course of Lectures for Students шт ерy Specialty 1-31 02 01 02 "Geography (Scientific and Pedagogical activity)", Ministry of Education of the Republic of Belarus; Gomel State University named after F. Skaryna. - 2nd ed., Revised and Amended, Gomel: GSU named after F. Skaryna (2010), 164 p.

[VIII.13] NATIONAL STATISTICAL COMMITTEE OF THE REPUBLIC OF BELARUS, Statistical Yearbook 2016, Belstat, Minsk (2017).

[VIII.14] MIHALEVICH, A.A., MYASNIKOVICH, M.V., Nuclear Energy: Status, Problems and Prospects, Belarusian Navuka, Minsk (2009), 189 pp.

[VIII.15] NATIONAL STATISTICAL COMMITTEE OF THE REPUBLIC OF BELARUS, Energy Balance of the Republic of Belarus, Statistical Book, Belstat, Minsk (2018).

[VIII.16] GRANTHAM RESEARCH INSTITUTE ON CLIMATE CHANGE AND ENVIRONMENT (LSE), “Concept of Energy Security of the Republic of Belarus”, Decree of the President of the Republic of Belarus No. 433 from17 September 2007, LSE (2007), https://www.climate-laws.org/geographies/belarus/policies/concept-of-energy-security-of-the-republic-of-belarus-decree-of-the-president-of-the-republic-of-belarus-no-433

[VIII.17] CIS LEGISLATION DATABASE, Resolution of the Council of Ministers of the Republic of Belarus No. 1084 from 23 December 2015 “About approval of the Concept of energy security in the Republic of Belarus”, SojuzPravoInform, Moscow (2015), https://cis-legislation.com/document.fwx?rgn=81997 .

[VIII.18] Указ Президента Республики Беларусь
№ 565 от 12.11.2007 “О некоторых мерах по строительству атомной электростанции”, дополненный указами Президента Республики Беларусь № 47 от 31.01.2013 и № 168 от 12.04.2013 (in Russian),
https://belzakon.net/%D0%97%D0%B0%D0%BA%D0%BE%D0%BD%D0%BE%D0%B4%D0%B0%D1%82%D0%B5%D0%BB%D1%8C%D1%81%D1%82%D0%B2%D0%BE/%D0%A3%D0%BA%D0%B0%D0%B7_%D0%9F%D1%80%D0%B5%D0%B7%D0%B8%D0%B4%D0%B5%D0%BD%D1%82%D0%B0_%D0%A0%D0%91/2007/4042/%D1%81%D0%BA%D0%B0%D1%87%D0%B0%D1%82%D1%8C

[VIII.19] Постановление Совета Министров Республики Беларусь № 1330 от 10.09.2008 “О некоторых вопросах Министерства энергетики” (in Russian),
https://belzakon.net/Законодательство/Постановление_Совета_Министров_РБ/2008/67571#:~:text=Постановление%20Совета%20Министров%20РБ%20№,Совет%20Министров%20Республики%20Беларусь%20ПОСТАНОВЛЯЕТ%3A

[VIII.20] Постановление Совета Министров Республики Беларусь № 1330 от 10.09.2008 “О некоторых вопросах Министерства энергетики” (in Russian),
https://belzakon.net/%D0%97%D0%B0%D0%BA%D0%BE%D0%BD%D0%BE%D0%B4%D0%B0%D1%82%D0%B5%D0%BB%D1%8C%D1%81%D1%82%D0%B2%D0%BE/%D0%9F%D0%BE%D1%81%D1%82%D0%B0%D0%BD%D0%BE%D0%B2%D0%BB%D0%B5%D0%BD%D0%B8%D0%B5_%D0%A1%D0%BE%D0%B2%D0%B5%D1%82%D0%B0

%B0_%D0%9C%D0%B8%D0%BD%D0%B8%D1%81%D1%82%D1%80%D0%BE%D0%B2_%D0%A0%D0%91/2008/67571

[VIII.21] Указ Президента Республики Беларусь № 418 от 15 сентября 2011 г. "О размещении и проектировании атомной электростанции в Республике Беларусь" (in Russian), https://gosatomnadzor.mchs.gov.by/upload/iblock/731/ukaz-418.pdf

[VIII.22] Постановление Совета Министров Республики Беларусь № 857 от 30.09.2013 "Об утверждении проектной документации на строительство атомной электростанции" (in Russian), https://kodeksy-by.com/norm_akt/source-%D0%A1%D0%9C%20%D0%A0%D0%91/type-%D0%9F%D0%BE%D1%81%D1%82%D0%B0%D0%BD%D0%BE%D0%B2%D0%BB%D0%B5%D0%BD%D0%B8%D0%B5/857-30.09.2013.htm

[VIII.23] Указ Президента Республики Беларусь № 499 от 02.11.2013 "О сооружении белорусской атомной электростанции" (in Russian), https://gosatomnadzor.mchs.gov.by/upload/iblock/5a0/ukaz499.pdf#:~:text=УКАЗ%20ПРЕЗИДЕНТА%20РЕСПУБЛИКИ%20БЕЛАРУСЬ%202,Беларусь%20от%2031.12.2016%20N%20515)

[VIII.24] Постановление Совета Министров Республики Беларусь № 460 от 02.06.2015 "Об утверждении Стратегии обращения с радиоактивными отходами Белорусской атомной электростанции" (in Russian), https://kodeksy-by.com/norm_akt/source-%D0%A1%D0%9C%20%D0%A0%D0%91/type-%D0%9F%D0%BE%D1%81%D1%82%D0%B0%D0%BD%D0%BE%D0%B2%D0%BB%D0%B5%D0%BD%D0%B8%D0%B5/460-02.06.2015.htm

[VIII.25] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAOLEX Database, FAO, Vienna (2021), https://cis-legislation.com/document.fwx?rgn=28480

[VIII.26] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAOLEX Database, FAO, Vienna (2021), https://cis-legislation.com/document.fwx?rgn=54538

[VIII.27] ИНТЕРФАКС, В Мире, Премьеры Белоруссии и РФ утвердили изменения в кредитное соглашение по БелАЭС, 14 июля 2020 г. (in Russian),)https://www.interfax.ru/world/717373#:~:text=%D0%9C%D0%B5%D0%B6%D0%BF%D1%80%D0%B0%D0%B2%D0%B8%D1%82%D0%B5%D0%BB%D1%8C%D1%81%D1%82%D0%B2%D0%B5%D0%BD%D0%BD%D0%BE%D0%B5%20%D1%81%D0%BE%D0%B3%D0%BB%D0%B0%D1%88%D0%B5%D0%BD%D0%B8%D0%B5%20%D0%BE%20%D0%BF%D1%80%D0%B5%D0%B4%D0%BE%D1%81%D1%82%D0%B0%D0%B2%D0%BB%D0%B5%D0%BD%D0%B8%D0%B8%20%D0%9C%D0%B8%D0%BD%D1%81%D0%BA%D1%83,%D0%BF%D0%BE%20%D0%B3%D0%B5%D0%BD%D0%BA%D0%BE%D0%BD%D1%82%D1%80%D0%B0%D0%BA%D1%82%D1%83%20%D0%BD%D0%B0%20%D1%81%D1%82%D1%80%D0%BE%D0%B8%D1%82%D0%B5%D0%BB%D1%8C%D1%81%D1%82%D0%B2%D0%BE%20%D0%90%D0%AD%D0%A1

[VIII.28] CIS LEGISLATION DATABASE, Agreement between the Government of the Russian Federation and Government of the Republic of Belarus from 01 February 2013 “About cooperation in the field of nuclear Safety”, SojuzPravoInform, Moscow (2013) https://cis-legislation.com/document.fwx?rgn=66802

[VIII.29] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAOLEX Database, Agreement between the Government of the Republic of Belarus and the Government of the Republic of Armenia on Cooperation in the Field of Peaceful Uses of Nuclear Energy. FAO, Vienna (2016), http://www.fao.org/faolex/results/details/es/c/LEX-FAOC173760

[VIII.30] YAKUSHEV, A.P., POPOV B.I., Optimization of the introduction of nuclear power in the fuel and energy complex of Belarus, Energ. & FEC **9** (2009) 14–24.

[VIII.31] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Assessment of the Planned Nuclear Energy System of Belarus, IAEA-TECDOC-1716, IAEA, Vienna (2013).

[VIII.32] СОЮЗ БЕЛАРУСЬ/РОССИЯ, Специальный проект Российской Газеты rg.ru, В Мире, Как белорусы воспринимают развитие атомной энергетики,07.12.2018 (in Russian), https://rg.ru/2018/12/07/kak-belorusy-vosprinimaiut-razvitie-atomnoj-energetiki.html

[VIII.33] DEPARTMENT OF NUCLEAR AND RADIATION SAFETY OF THE MINISTRY FOR EMERGENCY CITUATIONS OF THE REPUBLIC OF BELARUS, System of Nuclear and Radiation Safety in the Republic of Belarus, https://gosatomnadzor.mchs.gov.by/en/sistema-yadernoy-i-radiatsionnoy-bezopasnosti-v-belarusi/

[VIII.34] ANDRUSHECHKO, S.A., et. al., NPP with VVER-1000 type reactor, Logos, Moscow (2010) (in Russian), https://www.ozon.ru/product/aes-s-reaktorom-tipa-vver-1000-ot-fizicheskih-osnov-ekspluatatsii-do-evolyutsii-proekta-5507406/

[VIII.35] WORLD INFORMATION SERVICE ON ENERGY UNRANIUM PROJECT, Nuclear Fuel Cost Calculator (2016), http://wise-uranium.org/nfcc.html

[VIII.36] EUROPEAN COMMISSION, About the EU (2020), https://europa.eu/european-union/about-eu_en

[VIII.37] INTERNATIONAL ENERGY AGENCY, Key World Energy Statistics 2016, IAEA, Paris (2016).

[VIII.38] INTERNATIONAL ATOMIC ENERGY AGENCY, Romania (2015), https://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2015_CD/countryprofiles/Romania/Romania.htm

[VIII.39] INTERNATIONAL ATOMIC ENERGY AGENCY, Romania (2016), https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2016/countryprofiles/Romania/Romania.htm

[VIII.40] AUTORITATEA NATIONALA DE REGLEMENTARE IN DOMENIUL ENERGIEI, Electricity Market Monitoring 2016, Romania (2016), https://www.anre.ro/en/electric-energy/reports-companies/auditors-managers-energy/2016

[VIII.41] EUROPEAN COMMISSION, EU Energy in Figures, Publications Office of the European Union, Luxembourg (2016).

[VIII.42] MINISTRY OF ECONOMY AND FINANCES, Romanian Energy Strategy for 2007-2020, Romanian Government Decision No. 1069, Official Bulletin No. 781/19.11.2007, Romania (2007).

[VIII.43] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Fuel Cycle Profiles, 2nd edn, Technical Reports Series No. 425, IAEA, Vienna (2005).

[VIII.44] NATIONAL COMMISSION FOR NUCLEAR ACTIVITIES CONTROL, National Report under the Convention on Nuclear Safety, CNCAN, Bucharest (2016).

[VIII.45] Notification to the European Commission in relation to Directive 2011/70/EURATOM on the responsible and safe management of spent fuel and radioactive waste, report on national programme, Romania (2015).

[VIII.46] NATIONAL COMMISSION FOR NUCLEAR ACTIVITIES CONTROL, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, The Fifth National Report, CNCAN, Bucharest (2014).

[VIII.47] MINISTRY OF INDUSTRIES, Elemente de strategie energetica pentru perioada 2011-2035. Directii si obiective strategice in sectorul energiei electrice, Romania (2011) (in Romanian), https://www.fonduri-structurale.ro/Document_Files//Stiri/00009332/p6onv_strategia_energetica_20112035_20042011.pdf

[VIII.48] MINISTRY OF INDUSTRIES, Strategia energetica a Romaniei pentru perioada 2007-2020 actualizata pentru perioada 2011-2020, Romania (2012) (in Romania), http://www.mmediu.ro/beta/wp-content/uploads/2012/07/2012-07-31_evaluare_impact_planuri_proiectstrategiaenergeticaromania.pdf

[VIII.49] ROMANIAN GOVERNMENT, Programul de Guvernare 2013-2016 (2013), http://gov.ro/fisiere/pagini_fisiere/13-08-02-10-48-52program-de-guvernare-2013-20161.pdf

[VIII.50] MINISTRY OF ENERGY, Romanian Energy Strategy 2016-2030, with an Outlook to 2050 (2016),

http://energie.gov.ro/wp-content/uploads/2016/11/Romanian-Energy-Strategy-2016-2030-executive-summary3.pdf

[VIII.51] MINISTRY OF EDUCATION AND RESEARCH, National Strategy for the Development of the Nuclear Field in Romania and the Plan of Action for the implementation of this Strategy, Romanian Government Decision no. 1259, Official Bulletin no. 851 / 26.11.2002, Romania (2002).

[VIII.52] ALEMBERTI, A., VILLABRUNA, G., AGOSTINI, P., TURCU, I., CONSTANTIN M., "The FALCON Consortium: Continuing the Successful Italian Romanian International Collaboration", Proc. Nuclear 2014, Int. Conf. Pitesti, Romania, 2014, NIKIET, Moscow (2014).

[VIII.53] ALEMBERTI, A., AGOSTINI, P., TURCU, I., CONSTANTIN, M., "ALFRED Project and FALCON Consortium", Proc. ISTC NIKIET-2014, 3rd Int. Sci. and Tech. Conf. on Innovative Designs and Technologies of Nuclear Power, Moscow, 2014, NIKIET, Moscow (2014).

[VIII.54] NUCLEARELECTRICA, The Status of the Business Relations between "Societatea Nationala Nuclearelectrica S.A." and "Compania Nationala a Uraniului S.A." (2016), http://www.nuclearelectrica.ro/wp-content/uploads/2016/07/traducere-RELATII-COMERCIALE-SNN-CNU-Conferinta-de-presa_EN.pdf

[VIII.55] WORLD BANK GROUP, Thailand Economic Monitor – Digital Transformation, World Bank, Washington, DC (2017).

[VIII.56] MINISTRY OF ENERGY OF THAILAND, Summary (2020), http://www.eppo.go.th/index.php/en/en-energystatistics/summary-statistic?orders[publishUp]=publishUp&issearch=1

[VIII.57] ELECTRICITY GENERATING AUTHORITY OF THAILAND, Statistical Data (2013),http://www.egat.co.th/en/information/statistical-data

[VIII.58] MINISTRY OF ENERGY OF THAILAND, Power Development Plan (2015), http://www.eppo.go.th/images/POLICY/PDF/PDP_TH.pdf (in Thai)

[VIII.59] INTERNATIONAL ATOMIC ENERGY AGENCY, Thailand (2018), https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2018/countryprofiles/Thailand/Thailand.htm

[VIII.60] GOVERNMENT OF UKRAINE, "Energy strategy of Ukraine until 2030", Order of the Cabinet of Ministers of Ukraine No. 45-Rrfrom 15 March 2006, Kiev (2006).

[VIII.61] GOVERNMENT OF UKRAINE, "Energy strategy of Ukraine until 2030", Order of the Cabinet of Ministers of Ukraine No. 1071-r from 24 June 2013, Kiev (2013).

[VIII.62] Energy strategy of Ukraine to 2035, NISRU, Kiev (2014).

[VIII.63] GOVERNMENT PORTAL, Government approved Energy Strategy of Ukraine until 2035, posted 19 August 2017, State sites of Ukraine, Kiev (2017), https://www.kmu.gov.ua/en/news/250210653

[VIII.64] THE WORLD BANK, World Bank national accounts data, and OECD National Accounts data files, 1987-2019, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=UA

[VIII.65] STATE STATISTICS SERVICE OF UKRAINE, Kiev http://www.ukrstat.gov.ua/operativ/operativ2012/energ/en_bal/arh_2012_e.htm

[VIII.66] КАБІНЕТ МІНІСТРІВ УКРАЇНИ, Розпорядження від 7 грудня 2016 р. № 932-р "Про схвалення Концепції реалізації державної політики у сфері зміни клімату на період до 2030 року", Київ (2016), https://www.kmu.gov.ua/npas/249573705

[VIII.67] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2014: Resources, Production and Demand, OECD Publishing, Paris (2014).

[VIII.68] CIS LEGISTATION, Order of the Cabinet of Ministers of Ukraine No. 943-r from 9 November 2016 "About approval of the Concept of the State target economic development program of nuclear industry complex for the period till 2020", SojuzPravoInform, Moscow (2015), https://cis-legislation.com/document.fwx?rgn=92154

[VIII.69] КАБІНЕТ МІНІСТРІВ УКРАЇНИ, Розпорядження від 27 червня 2012 р. № 437-р "Питання розміщення, проектування та будівництва заводу з виробництва ядерного палива для реакторів типу ВВЕР-1000", Київ (2012), https://zakon.rada.gov.ua/laws/show/437-2012-%D1%80#Text

[VIII.70] НАЦІОНАЛЬНА КОМІСІЯ, ЩО ЗДІЙСНЮЄ ДЕРЖАВНЕ РЕГУЛЮВАННЯ У СФЕРАХ ЕНЕРГЕТИКИ ТА КОМУНАЛЬНИХ ПОСЛУГ, Постанова 21.03.2017 № 294 "Про внесення змін до постанови НКРЕКП від 09 грудня 2016 року № 2156", Київ (2017), https://www.nerc.gov.ua/index.php?id=24344

[VIII.71] Закон України "Про поводження з відпрацьованим ядерним паливом щодо розміщення, проектування та будівництва централізованого сховища відпрацьованого ядерного палива реакторів типу ВВЕР вітчизняних атомних електростанцій", Відомості Верховної Ради України (ВВР), 2012, № 40, ст.476, https://zakon.rada.gov.ua/laws/show/4384-17#Text

[VIII.72] НАЦІОНАЛЬНА КОМІСІЯ, ЩО ЗДІЙСНЮЄ ДЕРЖАВНЕ РЕГУЛЮВАННЯ У СФЕРАХ ЕНЕРГЕТИКИ ТА КОМУНАЛЬНИХ ПОСЛУГ, Постанова 21.03.2017 № 294 "Про внесення змін до постанови НКРЕКП від 09 грудня 2016 року № 2156", Київ (2017), https://www.nerc.gov.ua/index.php?id=24344

[VIII.73] Закон України "Про використання ядерної енергії та радіаційну безпеку", Відомості Верховної Ради України (ВВР), 1995, № 12, ст.81, https://zakon.rada.gov.ua/laws/show/39/95-%D0%B2%D1%80#Text

[VIII.74] NATIONAL ECOLOGICAL CENTRE OF UKRAINE, Attitudes of Ukrainians toward Nucleaqr Energy, Results of All-Ukrainian Social Survey: Summary, Kyiv (2015), https://necu.org.ua/wp-content/uploads/2016/04/Social-Survey-on-Nuclear-Energy-in-Ukraine-NECU_eng.pdf

[VIII.75] Закон України "Про поводження з відпрацьованим ядерним паливом щодо розміщення, проектування та будівництва централізованого сховища відпрацьованого ядерного палива реакторів типу ВВЕР вітчизняних атомних електростанцій", Відомості Верховної Ради України (ВВР), 2012, № 40, ст.476, https://zakon.rada.gov.ua/laws/show/4384-17#Text

[VIII.76] U.S. DEPARTMENT OF STATE, Ukraine (00-65), Implementing Agreement Concerning the Ukraine Nuclear Fuel Qualification Project, TIAS, Office of Treaty Affairs, 5 June 2005, Washington (2005), https://www.state.gov/00-605

[VIII.77] FEDERAL STATE STATISTICS SERVICE OF THE RUSSIAN FEDERATION, The Demographic Yearbook of Russia: Statistical Handbook, Federal State Statistics Service, Moscow (2015).

[VIII.78] INTERNATIONAL MONETARY FUND, World Economic Outlook Database (2017), http://www.imf.org/external/pubs/ft/weo/2016/02/weodata/index.aspx

[VIII.79] UNITED NATIONS CLIMATE CHANGE, Russian Federation. Biennial report (BR). BR 1, published on 14 March 2014, UNFCCCC (2014), https://unfccc.int/documents/199043

[VIII.80] THE ENERGY RESEARCH INSTITUTE OF THE RUSSIAN ACADEMY OF SCIENCES, AnalyticaI Center for the Govemment of the Russian Federation, Global and Russian Energy Outlook up to 2040, ACRF, Moscow (2016), https://www.eriras.ru/files/Global_and_Russian_energy_outlook_up_to_2040.pdf

[VIII.81] INTENATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Power Profiles: Russian Federation (2019), https://cnpp.iaea.org/countryprofiles/Russia/Russia.htm

[VIII.82] ROSATOM STATE ATOMIC ENERGY CORPORATION, Rosatom Group (2020), http://www.rosatom.ru/en/rosatom-group/

[VIII.83] ROSATOM STATE ATOMIC ENERGY CORPORATION, International Relations (2020), http://www.rosatom.ru/en/global-presence/international-relations/

[VIII.84] MINISTRY OF ENERGY OF RUSSIAN FEDERATION, Energy Strategy of the Russian Federation for the Period up to 2035, approved by the Decree of the Government of

Russian Federation No. 1523-r from 9 June 2020, Moscow, (2020, http://www.energystrategy.ru/ab_ins/source/ES-2035_09_2015.pdf (in Russian)

[VIII.85] Decree of the Government of the Russian Federation No. 344-11 from 28.03.2017 “On Amendments to the State Programme “Development of the Nuclear Power Generation Complex”, Official Internet portal of legal information, Registration No. FS77-47467, Electronic passport FGIS No. FS77110096, Published on 06.04.2017, No. 0001201704060026, Mosow (2017), http://publication.pravo.gov.ru/Document/View/0001201704060026#print (in Russian).

[VIII.86] PONOMAREV-STEPNOY, N.N., et al., Two-Component Nuclear Energy System with Thermal and Fast Reactors in Closed Nuclear Fuel Cycle, Tekhnosfera, Moscow (2016) (in Russian).

[VIII.87] FEDERAL ENVIRONMENTAL, INDUSTRIAL AND NUCLEAR SUPERVISION SERVICE, , The Federal Target Programme “Nuclear and Radiation Safety in 2016–2020 and until 2030” approved by the Decree of the Government of the Russian Federation No. 1248 from November 19, 2015, https://www.secnrs.ru/en/news/index.php?ELEMENT_ID=3065

[VIII.88] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual, IAEA-TECDOC-1575 Rev. 1, IAEA, Vienna (2008).

[VIII.89] KAGRAMANYAN, V., USANOV, V., KALASHNIKOV, A., KVYATKOVSKII, S., Medium-term nuclear industry prospects associated with synergistic LWR/SFR system and related closed nuclear fuel cycle, Proc. Int. Conf. Global 2015, Societe Francaise d'Energie Nucleaire - SFEN, 103 rue Reaumur, 75002 Paris (France); 2455 p; ISBN 978-1-4951-6286-2 (2015), p. 15-22.

[VIII.90] JSC ATOMREDMETZOLOTO, Annual Report of JSC Atomredmetzoloto, JSC Atomredmetzoloto, Moscow (2015).

[VIII.91] ROSATOM STATE ATOMIC ENERGY CORPORATION. Rosatom Annual Report 2015, Rosatom, Moscow (2015).

[VIII.92] WORLD NUCLEAR ASSOCIATION, Russia’s Nuclear Fuel Cycle (2020), http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx

[VIII.93] KHAPERSKAYA, A., Problems of SNF Management in Russia and Perspectives of their Resolution (2015), http://www.atomic-energy.ru/articles/2015/04/01/55910 (in Russian)

[VIII.94] INTERNATIONAL PANEL ON FISSILE MATERIALS, Countries: Russia (2020), http://fissilematerials.org/countries/russia.html.