

Modelling of the reactor cycle cost for thorium-fuelled PWR and environmental aspects of a nuclear fuel cycle

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Abstract: The paper presents the methodology applied to the cost modelling of the uranium-thorium nuclear reactor cycle for PWR reactors as well as brief introduction to the environmental impact of the nuclear fuel cycle. The reactor core contains seed uranium fuel and blanket thorium fuel. In such a cycle, energy is produced in the fission of ^{235}U included in the fresh fuel and in the fission of ^{233}U bred from the fertile ^{232}Th . A modified methodology developed by the OECD Nuclear Energy Agency was used for the reactor cycle cost modelling. The method is based on the levelized lifetime cost methodology for a reactor cycle, which is directly related to the heavy metal mass balance. Contrary to the case of uranium-fuelled nuclear reactors, the cost modelling includes the additional cash flow for thorium fuel. The abundance of thorium in the Earth's crust is about 3–5 times larger than that of uranium, which suggests its promising potential as a nuclear fuel. However, this needs to be proved economically.

Keywords: thorium, PWR, fuel cycle, levelized costs, environmental impact

INTRODUCTION

Currently, the main nuclear fuel is uranium dioxide UO_2 enriched with fissile uranium isotope ^{235}U . However, the fission process may also be performed on other heavy isotopes produced synthetically in the core of a nuclear reactor, such as ^{233}U from ^{232}Th and ^{239}Pu from ^{238}U . From the point of view of nuclear energy generation, ^{232}Th is not a fissile but a fertile isotope, which could be transformed into fissile ^{233}U in a series of nuclear transmutation and decay (Serfonteina & Mulder 2014). Natural thorium mainly contains the isotope ^{232}Th with natural abundance of about 99.98%. The abundance of thorium in the Earth's crust is approximately 10 ppm, which is about 3–5 times higher than that of uranium. Therefore, thorium fuel can complement uranium fuel and thus

increase the efficiency of the nuclear fuel cycle and the available resources of fissionable material (Ashley et al. 2014). Unlike pure uranium fuels, thorium produces fewer radioactive minor actinides, which is a strong advantage considering public acceptance of nuclear power (Kidd 2013). Thus, spent nuclear fuel is less radioactive and easier to treat. These incentives, as well as the neutronic and thermo-mechanical properties of thorium-based fuel, suggest its usage for the generation of nuclear energy (IAEA 2005). However, this must be economically proved (Linares & Conchado 2013).

Thorium is widely distributed in the world; however, it has never been commercially exploited on a large scale. The reason is the availability of large uranium resources (IAEA 2019b). Thorium deposits usually occur in association with rare

earth elements and uranium, in various mineral forms, such as oxides, silicates and phosphates. Four main types of deposits could be characteristic of thorium, i.e. placer ($2.182 \cdot 10^6$ t), carbonate-hosted ($1.783 \cdot 10^6$ t), vein-type ($1.528 \cdot 10^6$ t) and alkaline rock hosted deposits ($0.584 \cdot 10^6$ t) (OECD NEA 2016). Placer deposits can be found in Australia, Brazil, India, Mozambique, South Africa and the United States. Carbonite deposits are quite common around the world and can be found in Argentina, Australia, Brazil, Canada, Russia, Finland, Norway, Sweden, South Africa and the United States. Vein-type and alkaline deposits are uniformly distributed worldwide. Thorium is also present in other deposits having the characteristics of all previously defined types ($\sim 0.135 \cdot 10^6$ t). The most common source of thorium is mixed thorium rare earth uranium phosphate (Ce, La, Nd, Th)PO₄ (monazite), available in beach and river sand. The content of ThO₂ in monazite is estimated at about 3–5% (Schulz 2014). The extraction of thorium from monazite is easier than the extraction of uranium from its ores, because it is done in shallow open pits using placer techniques. Hence, the overburden is much smaller and the production of radioactive waste in mining is about two orders of magnitude lower compared to uranium mining. In addition, the short lifetime of thoron (²²⁰Rn, $T_{1/2} = 55.6$ s) from tailings reduces the impact of radon and facilitates tailings management. Therefore, long-term public doses and occupational doses are much lower compared to uranium mining. Currently, only India postulates that its national nuclear power program should be based on thorium fuel, because it has large thorium ($\sim 0.518 \cdot 10^6$ t) and modest uranium resources ($\sim 0.092 \cdot 10^6$ t). Therefore, India is the only

country where thorium is extracted on a commercial scale – from the beach and sand deposits on the Malabar Coast. The total world resources of thorium are estimated at about 6.2–6.4 million tonnes (OECD NEA 2016, IAEA 2019a).

ENVIRONMENTAL IMPACT

Although nuclear power plants do not generate directly greenhouse gases and provide reduction of the carbon dioxide emission, the main public concern is related to the radioactivity of the spent nuclear fuel, high-impact nuclear accidents and its proliferation resistance against production of nuclear weapon. The analysis of the environmental impact of the nuclear fuel cycle is a somewhat difficult task because there is no one single fuel cycle but many options of close and open fuel cycles with different technologies deployed at each step. The nuclear fuel cycle describes the lifetime of nuclear fuel and consists of three main stages, see Figure 1. The first stage, called the *front-end fuel cycle*, encompasses all the processes from uranium or thorium mining to nuclear fuel fabrication. The second stage is called the *in-core fuel management* and includes shuffling of fuel assemblies inside the reactor core. The last stage, the so-called *back-end fuel cycle*, consists in the treatment of spent nuclear fuel discharged from the reactor core until its final disposal or reprocessing (WNA 2017). The nuclear fuel cycle, which concerns reprocessing of the spent nuclear fuel is called *close* nuclear fuel cycle while with no reprocessing *open* fuel cycle. In the first option, the used nuclear fuel is rather concerned as an input for a production of advanced fuels containing bred plutonium and minor actinides for e.g. fast neutron reactors.

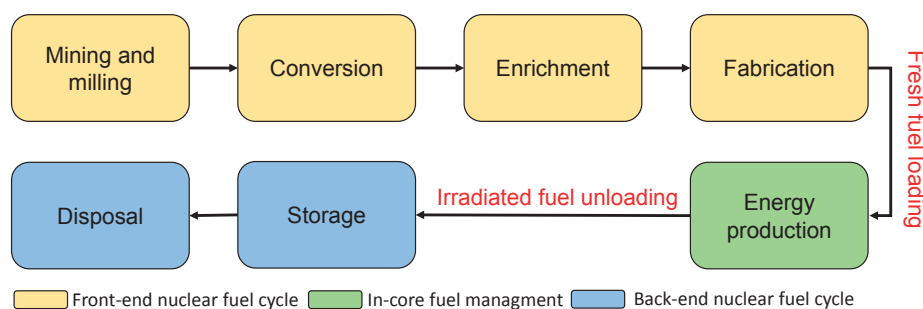


Fig. 1. Main stages of the nuclear fuel cycle

The main environmental impacts related to the mining concern impacts on land and water through wastewater from drainage and drilling, which affects surface and groundwater quality. Additionally, the occupational health hazards due to radon is considered as a direct impact on human health. In the milling process, about 70% of radioactivity is extracted from the uranium concentrate and remains in mining tails. The storage piles of mining tails undergo wind erosion to unrestricted areas and water ingress which causes radium leaching from the material and spreads radioactivity. Therefore, piles must be secured and stabilized against wind and water erosion. The main hazard in the conversion process arises from the toxicity of hydrogen fluoride and fluorine used in production of uranium hexafluoride. In addition, UF_6 is a corrosive gas and in case of leak from the control volume would result in an immediate chemical reaction with the air moisture. One of the reactions products is HF, which constitutes basically the major toxicological risk. The environmental impact related to the enriched UF_6 is like not enriched UF_6 . However, after enrichment process UF_6 contains larger amount of ^{235}U and passes into the IAEA (International Atomic Energy Agency) safeguards system because its agglomeration can follow to the inadvertent chain reaction, however with very low probability. The fabrication of the ceramic fuel pellets is rather free from significant radiological and toxicological risks and impacts. The isotopic composition of the fresh nuclear fuel loaded into the reactor core is changed during reactor operation, which causes formation of notably radioactive isotopes. Therefore, spent nuclear fuel has a major environmental impact considering produced radioactivity and thus must be separated from the environment in the final spent fuel repositories. It is worth mentioning that the thermal pollution of the nuclear power plant is considered high in comparison with fossil-fuel plants. Nuclear power plants inject heat directly into the cooling water. In fossil fuel plants, however, some heat is released via the smokestack with combustion products.

METHODS

There are a lot of nuclear economic tools and methodologies capable of estimating the costs of

nuclear electricity for various reactor types and fuel cycles (Shropshire et al. 2009, Choi et al. 2014, Moore et al. 2017). However, the most common and versatile method is the standardized OECD levelized lifetime methodology (OECD NEA 1994). In this case, for the modelling of the Pressurized Water Reactor (PWR) with thorium fuel, the methodology was modified to include two separate fuel flows – for thorium blanket fuel and for uranium seed fuel respectively. The characteristics of both fuel types under irradiation in the reactor core are different in terms of burnups and refueling intervals; therefore, modification of the methodology was required. In addition, blanket fuel is composed of enriched uranium as well as thorium, which in principle gives an additional, third fuel flow for some steps of fuel preparation. In this study, it is assumed that the core of the PWR reactor is composed of one batch of blanket fuel and three batches of seed fuel. The core was designed using the Whole Assembly Seed and Blanket (WASAB) loading pattern (Wang 2003, IAEA 2012). In WASAB, the differentiation of seed and blanket fuel is made at the level of fuel assemblies (FAs), not at the level of fuel rods. It means that fuel assemblies contain either seed or blanket fuel rods. The applied methodology considers calculations of the unit costs per unit mass of material for each stage of the nuclear fuel cycle. The costs are discounted back to the year of fuel loading and finally summed together. This way, the total fuel cycle costs at the net present value can be calculated. Finally, the net present value of the fuel cycle is divided by the net present value of the total electricity output, which gives the levelized cost of nuclear electricity generation in mills per kilowatt-hour (mills/kWh) (De Roo & Parsons 2011, IAEA 2014). Equations (1)–(5) (Wang 2003) were used for the calculation of the levelized costs of electricity for the PWR core with one batch of thorium blanket fuel and three batches of uranium seed fuel, where:

- C – total levelized costs of electricity [mills/kWh],
- C_{sd} – levelized costs of seed fuel [mills/kWh],
- C_{bt} – levelized costs of blanket fuel for the processing of Th and U [mills/kWh],
- $C_{bt,Th}$ – levelized costs of blanket fuel for the processing of Th [mills/kWh],

- $C_{bt,U}$ – leveled costs of blanket fuel for the processing of U [mills/kWh],
 r – discount rate [yr^{-1}],
 E – whole core net electricity output per year [kWh],
 T_r – residence time in core [yr],
 T – refuelling cycle length [yr],
 F_i – total component cost [\$],
 P_i – unit component cost [\$/kg],
 f_i – total loss factor,
 l_i – component loss factor [wt.%],
 Δt_i – lead or lag time [yr],

where:

- $i = 1$, purchase of natural uranium or thorium,
 $i = 2$, conversion into UF_6 ,
 $i = 3$, enrichment with ^{235}U ,
 $i = 4$, fuel fabrication,
 $i = 5$, spent fuel storage,
 $i = 6$, spent fuel disposal.

$$C = C_{sd} + C_{bt,Th} + C_{bt,U} + C_{bt} \quad (1)$$

$$C_{sd} = \frac{3 \cdot r \cdot (C_{sd1} + C_{sd2} + C_{sd3})}{E \cdot (1 - e^{-rT_{r,sd}})} \quad (2)$$

where:

$$C_{sd1} = \sum_{i=1}^4 (F_{i,sd} \cdot e^{r \cdot \Delta t_i}),$$

$$C_{sd2} = F_{5,sd} \cdot e^{-r(T_{sd} + \Delta t_5)},$$

$$C_{sd3} = F_{6,sd} \cdot e^{-r(T_{sd} + \Delta t_6)},$$

$$C_{bt} = \frac{r \cdot (C_{bt1} + C_{bt2} + C_{bt3})}{E \cdot (1 - e^{-rT_{bt}})} \quad (3)$$

where:

$$C_{bt1} = F_{4,bt} \cdot e^{r \Delta t_4},$$

$$C_{bt2} = F_{5,bt} \cdot e^{-r(T_{bt} + \Delta t_5)},$$

$$C_{bt3} = F_{6,bt} \cdot e^{-r(T_{bt} + \Delta t_6)},$$

$$C_{bt,Th} = \frac{F_{1,bt,Th} \cdot e^{r \Delta t_1}}{E \cdot (1 - e^{-rT_{bt,Th}})} \quad (4)$$

$$C_{bt,U} = \frac{\sum_{i=1}^3 (F_{i,bt,U} \cdot e^{r \Delta t_i})}{E \cdot (1 - e^{-rT_{bt,U}})} \quad (5)$$

Uranium ore is mined using either standard underground and open pit or in-situ leaching and heap leaching techniques. Mined uranium ore is crushed and chemically treated in order to extract uranium in the so-called *milling* process. The chemistry of milling depends on the mineral type. However, the main stages are: ore leaching in sulfuric acid, uranium recovery in ion exchange or solvent extraction, precipitation, filtration and finally – drying and roasting. In the case of the leaching methods, uranium pregnant liquor is treated in a similar way. The final product at this stage is a uranium concentrate (U_3O_8) called *yellowcake*. Thorium mined from monazite is initially concentrated by washing out and electromagnetic separation of lighter minerals. The subsequent treatment is similar to the processing of uranium ore. The obtained ThO_2 is used directly for the fabrication of ceramic fuel elements. It could be also reduced to thorium metal for the fabrication of metallic fuel. The costs of thorium and uranium mining and milling are estimated using Equations (6)–(8), where:

M_f = mass of natural uranium feed [kg],

M_p = mass of the enriched uranium charged to the reactor [kg],

x_j = uranium ^{235}U weight fraction ($j = p$ for product, $j = t$ for tails, $j = f$ for feed).

$$F_1 = M_f \cdot f_1 \cdot P_1 \quad (6)$$

$$M_f = \frac{(x_p - x_t)}{(x_f - x_t)} \cdot M_p \quad (7)$$

$$f_{1,2} = (1 + l_2) \cdot (1 + l_3) \cdot (1 + l_4) \quad (8)$$

In the next stage, the uranium concentrate (yellowcake) is converted into uranium hexafluoride (UF_6), which is necessary for the enrichment process. The most popular is the wet conversion process, in which U_3O_8 is initially dissolved into nitric acid and in the following chemical steps, it is transferred to UO_2 . Next, UO_2 reacts with hydrogen fluoride (HF) and forms uranium tetrafluoride UF_4 . Finally, in a flame tower with gaseous fluorine, UF_6 is produced. UF_6 could have a gaseous, liquid or solid form, depending on the temperature and the pressure in the storage tanks. The gaseous form is used for the enrichment process, the liquid form – for filling the transportation

tanks, and the solid form – for transportation. ThO_2 is not converted because it does not need to be enriched. The costs of uranium conversion are estimated using Equation (9):

$$F_2 = M_f \cdot f_{1,2} \cdot P_2 \quad (9)$$

Uranium fuel for PWR reactors should be enriched with ^{235}U for the efficient nuclear power generation. Natural uranium contains only about 0.7% of fissile ^{235}U and 99.3% of fertile ^{238}U . In the enrichment process, the mass difference between ^{238}U and ^{235}U is used to increase the fraction of ^{235}U in uranium. Currently, the maximum enrichment allowed for commercial nuclear reactors is 5% and for research reactors – 20% of ^{235}U . The enrichment process is mostly conducted in centrifuges. The flows of gaseous $^{235}\text{UF}_6$ and $^{238}\text{UF}_6$ are separated using the centrifugal force principle in the cascades of centrifuges. The enrichment effort is expressed in kilogram separative work units (kgSWU, or simply SWU) by means of the value function – see Equation (10) and the weight fraction of ^{235}U in feed, tails and product – see Equation (11) (Lamarsh & Barrata 2001). Thorium cannot be enriched because it contains only one fertile isotope. The costs of uranium enrichment are estimated using Equation (12), where:

V_j = value function ($j = p$ for product, $j = t$ for tails, $j = f$ for feed),

M_t = mass of uranium in the enrichment plant tails [kg],

S = separative work [kg].

$$V_j = (2x_j - 1) \cdot \ln \frac{x_j}{1 - x_j} \quad (10)$$

$$S = M_p \cdot V_p + M_t \cdot V_t - M_f \cdot V_f \quad (11)$$

$$F_3 = S \cdot f_3 \cdot P_3 \quad (12)$$

$$M_t = M_f - M_p \quad (13)$$

$$f_3 = (1 + l_3) \cdot (1 + l_4) \quad (14)$$

Ceramic nuclear fuel (UO_2) is fabricated in two steps. First, the enriched UF_6 is chemically converted into UO_2 powder. The UO_2 powder is blended and mixed with lubricants, poor-formers and, depending on the demand, with other nuclear materials, such as neutron absorbers. At this stage, UO_2 could be blended with ThO_2 to produce

homogenous uranium-thorium blanket fuel. Then, the conditioned uranium powder is pressed in a pressing machine to produce the so-called green pellets. Green pellets are sintered at about 1750°C . The dimensions of a pellet are about 1 cm in height and about 0.8 cm in diameter. Fuel pellets are loaded into zirconium tubes and plugged from both sides to produce a fuel rod about 4 m high. Fuel rods are assembled together, either into square or hexagonal fuel assemblies. The number of fuel rods in an assembly depends on the reactor type, but usually it is about two–three hundred. Loading of fuel assemblies into the reactor core is the last stage of the front-end nuclear fuel cycle. The costs of nuclear fuel fabrication are estimated using Equation (15):

$$F_4 = M_p \cdot f_4 \cdot P_4 \quad (15)$$

$$f_4 = (1 + l_4) \quad (16)$$

After the reactor fuel cycle, about 1/3 of the irradiated fuel assemblies are unloaded for interim storage. The remaining 2/3 are shuffled to a different position in the reactor core. Spent nuclear fuel is usually stored in the cooling pools at the reactor core under the reactor containment. Spent fuel is cooled for a few years so that its radioactivity and decay heat are decreased. Then, it can either stay in the cooling pool or it can be transported to an intermediate wet or dry storage site, where it can remain for even 50 years until its reprocessing or final disposal. The costs of interim fuel storage are usually related to the operation and maintenance costs of the plant and sometimes they are not included in the fuel cycle costs; however, they are considered in this study. During the operation of the reactor radioactive fission products, activation products and especially minor actinides are produced. These isotopes are mainly retained in the solid fuel pellets and thus the spent fuel assemblies are the most intensely radioactive material in the whole fuel cycle. The costs of nuclear fuel storage may be estimated using Equation (17), where:

$$F_5 = M_p \cdot P_5 \quad (17)$$

Cooled spent fuel assemblies can be either reprocessed to extract bred plutonium for the fabrication of mixed-oxide (MOX) fuel or sent to final disposal (OECD NEA 1989). The environmental

impact considering radioactivity releases is the highest for fuel reprocessing plants because of quite complicated reprocessing procedure considering partitioning spent nuclear fuel. The basis for the partitioning is the PUREX process (Plutonium Uranium Redox Extraction) in which the spent nuclear fuel is chemically treated to extract uranium and plutonium. In this way the radioactive material is extracted from the spent fuel pellets, which increases the risk of uncontrolled releases and produces some losses of radioactive material. The only commercially available spent fuel disposal option is direct disposal in geological repositories. This option has been successfully developed in Finland and in Sweden (Litmanen et al. 2017). Spent fuel assemblies are encapsulated in copper casks and stored in the granite bedrock at a depth of about 400 m. The tunnels are filled with bentonite clay to prevent water ingress and the corrosion of the casks. The radioactivity of spent nuclear fuel without reprocessing reaches the reference level for the safety of human beings and the environment after about 150,000 years. In this time, the spent nuclear fuel repository must be physically secured from any attempts of radioactive material extraction. However, the cost estimates at the back end of the nuclear fuel cycle, especially related to the final disposal, have a high degree of uncertainty. The exact unit component cost is not yet known even by the companies responsible for construction of final spent fuel repository in Finland and Sweden. In the calculations, the official cost estimates provided by IAEA were applied. The costs of nuclear fuel disposal are estimated using Equation (18):

$$F_6 = M_p \cdot P_6 \quad (18)$$

RESULTS

In the economic analysis, two PWRs are considered, i.e. the Westinghouse 4-loop PWR plant with the nominal power of 1130 MW_{el} (WEC 1984, Wang 2003) and the European Pressurized Water reactor EPR with the nominal power of 1630 MW_{el} (Ashley et al. 2014). The calculations were performed for the standard uranium fuel and for the WASAB fuel (indices: PWR_{Th}, EPR_{Th}) at the equilibrium state, which facilitates

the comparison of both reactor-fuelling options. The uranium cores contain three batches of nuclear fuel, while the thorium cores contain one batch of blanket fuel and three batches of seed fuel for both reactor types. In the case of the Westinghouse PWR reactor, the cycle for the uranium fuel batch lasts one year and for the thorium fuel batch – 13.5 years. In the case of EPR, the blanket irradiation time is the same but the reactor cycle for seed fuel equals 1.5 years. The discount rate is fixed at 4% and the yearly load factor equals 90%. The weight percent of ²³⁵U in the uranium feed is 0.711, while the weight percent of ²³⁵U in tails is 0.25. The costs of purchase and fabrication of fuel for thorium were assumed to be the same as for uranium. Table 1 shows the unit costs and the lag/lead times for each stage of the nuclear fuel cycle (IAEA 2014). In Table 2, the level of fuel enrichment and the total mass of heavy metal for all fuel types is shown (Wang 2003, Ashley et al. 2014). The number of FA in the following batch may be odd or even, depending on the designed core reloading pattern.

Table 1
Parameters used in the economic analysis

Stage	Unit cost P_i [\$/kg]	Lead/lag time Δt_i [yr]	Loss factor l_i [wt.%]
Purchase	50	2.0	NA
Conversion	8	1.5	0.005
Enrichment	110	1.0	0.000
Fabrication	275	0.5	0.010
Storage	300	5.0	NA
Disposal	600	10.0	NA

Table 2
Fuel parameters (Bt – blanket, Sd – seed)

Fuel type	Enrichment x_p [wt.%]	Mass of heavy metal m_{HM} [tons]		Number of FAs	
		Core	Batch	Core	Batch
EPR	5.00	127.15	42.38	241	80/81
EPR _{Th,Sd}	20.00	33.27	11.09	105	35
EPR _{Th,Bt,U}	7.65	14.42		136	
EPR _{Th,Bt,Th}	NA	70.43			
PWR	3.20	86.10	28.70	193	64/65
PWR _{Th,Sd}	20.00	37.50	12.50	84	28
PWR _{Th,Bt,U}	10.00	7.54		109	
PWR _{Th,Bt,Th}	NA	36.81			

Table 3 and Figure 2 present the calculated levelized costs of nuclear electricity for each stage of the nuclear fuel cycle as well as the total costs for the front-end and the back-end fuel cycle. Figure 3 depicts the percentage of the costs associated with each stage of the nuclear fuel cycle. Table 4 and Figure 5 show the costs for seed and blanket fuel in the WASAB core loading pattern. In the analysis, the costs for the uranium and thorium component of blanket fuel are presented separately. The costs of purchase of uranium (0.09 mills/kWh) and thorium (0.01 mills/kWh) for blanket fuel were presented as a lump sum. The percentage of the costs for seed and blanket fuel is shown in Figure 5. The results are comprehensively discussed in the following section.

Table 3
Calculated levelized costs of nuclear electricity

Stage	Costs [mills/kWh]			
	EPR	PWR	EPR _{Th}	PWR _{Th}
Purchase	1.37	1.20	1.60	2.53
Conversion	0.20	0.18	0.24	0.37
Enrichment	2.22	1.66	3.22	5.14
Fabrication	0.69	0.97	0.36	0.43
Storage	0.50	0.75	0.22	0.28
Disposal	0.83	1.23	0.37	0.47
Total front-end	4.49	4.00	5.42	8.47
Total back-end	1.33	1.98	0.59	0.75
Total	5.82	5.98	6.01	9.22

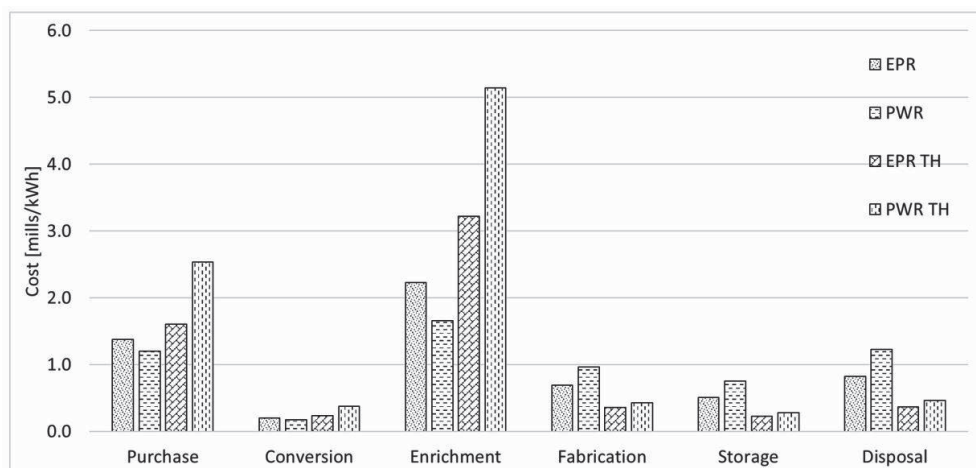


Fig. 2. Calculated levelized costs of nuclear electricity for each stage of the nuclear fuel cycle

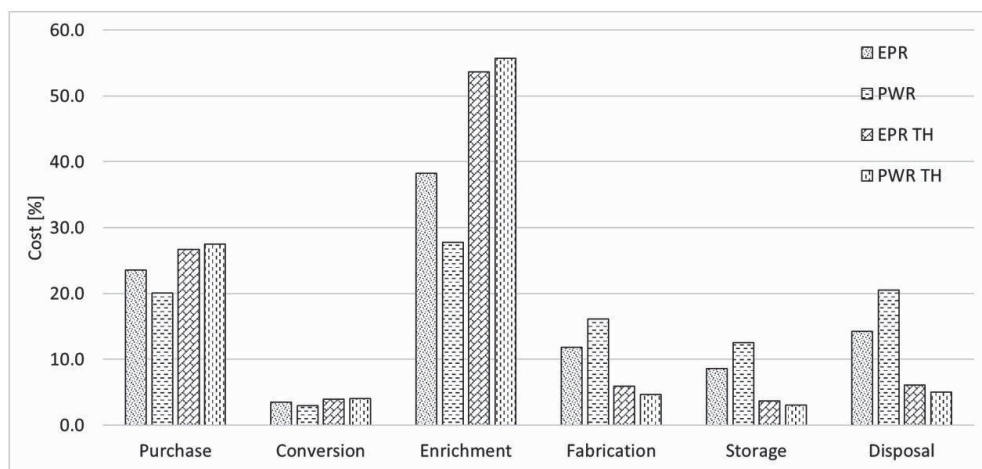


Fig. 3. Percentage of levelized costs of nuclear electricity for each stage of the nuclear fuel cycle

Table 4
Levelized costs of nuclear electricity for seed and blanket fuel

Stage	Costs [mills/kWh]			
	EPR _{Th,Sd}	PWR _{Th,Sd}	EPR _{Th,Bt}	PWR _{Th,Bt}
Purchase	1.49	2.43	0.11	0.10
Conversion	0.22	0.36	0.01	0.01
Enrichment	3.05	4.96	0.17	0.18
Fabrication	0.18	0.29	0.18	0.13
Storage	0.13	0.21	0.09	0.07
Disposal	0.22	0.35	0.15	0.11
Total front-end	4.95	8.05	0.47	0.43
Total back-end	0.35	0.57	0.24	0.18
Total	5.30	8.61	0.71	0.61

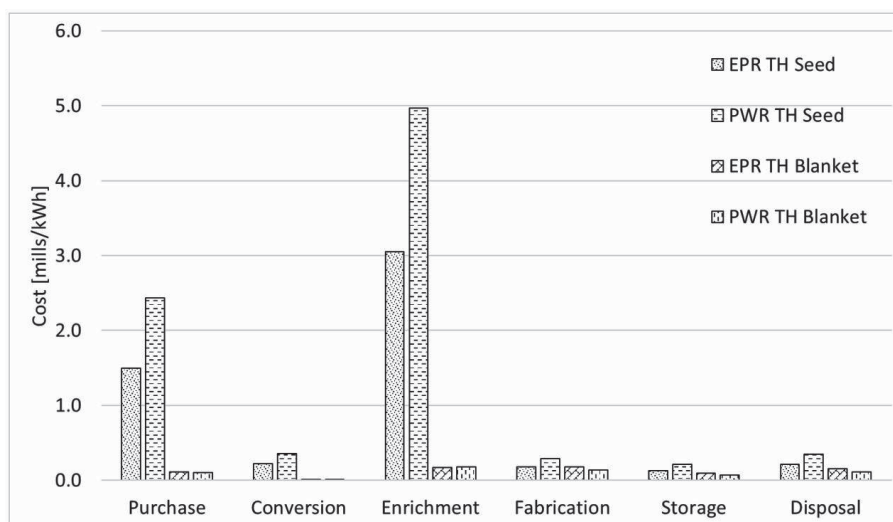


Fig. 4. Partial levelized costs of nuclear electricity for seed and blanket fuel

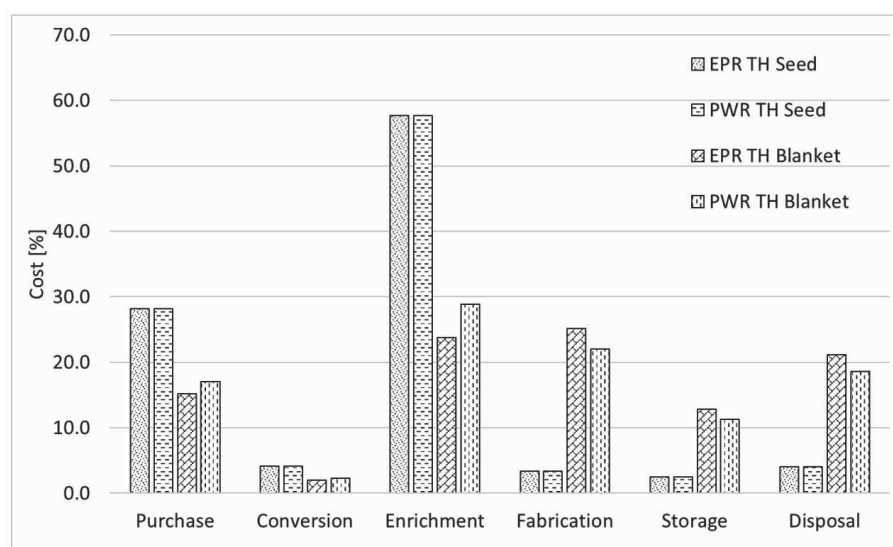


Fig. 5. Partial percentage levelized costs of nuclear electricity for seed and blanket fuel

DISCUSSION

As shown in Table 3, the levelized costs of electricity for the investigated fuels are the highest for the thorium-fuelled Westinghouse 4-loop plant (9.22 mills/kWh) and the lowest for the uranium-fuelled EPR reactor (5.82 mills/kWh). In general, the costs for EPR, EPR_{Th} and PWR are similar and equal about 6 mills/kWh. The large difference between PWR_{Th} and EPR_{Th} in terms of the total cost of electricity is caused by the larger mass of highly enriched seed fuel and the lower nominal power of PWR_{Th}. The ratio of the seed fuel mass to the total fuel mass in PWR_{Th} is 0.46, and in EPR it is 0.28. It means that the core of PWR_{Th} is not optimised for the usage of thorium fuel. The solution is to introduce fewer seed assemblies and more blanket assemblies to the reactor core.

The total costs of the reactor cycle depend mainly on two factors, i.e. the costs of purchase and enrichment of uranium (see Figs. 2, 3). The costs of enrichment mutually increase the costs of the purchase of uranium. The higher the required enrichment, the higher the uranium feed and finally, the larger the enrichment effort, which is shown in Equations (10)–(13). It means that the costs of nuclear electricity depend on the enrichment of the nuclear fuel and the associated mass flow. The applied methodology uses quite a rigorous assumption of fixed tail assay ($x_t = 0.25\%$) in the modelling of the enrichment costs. In reality, the enrichment effort (SWUs) could be decreased in the optimisation process of the enrichment plant. From the point of view of the enrichment company, if the price of natural uranium feed is high and the power costs are low, more SWUs can be applied to obtain the same amount of the enriched product from a lower mass of uranium feed decreasing the tail assay. On the other hand, if the price of uranium feed is low and the power costs are high, fewer SWUs and more uranium feed can be used to obtain the same amount of the product increasing the mass of the feed. These processes are called *underfeeding* and *overfeeding* respectively (WNA 2019). In some studies, the costs of enrichment are even assumed to be the same for fuel with 5% and 20% enrichment with ²³⁵U, which seems an unrealistic assumption. The costs of enrichment may be also decreased by optimising the

in-core fuel management scheme. The core loading pattern, fuel shuffling and the consequent reloading patterns may require fuel with lower enrichment. However, this can reduce the reactor cycle length and impose a shorter time to refuelling. The costs of fuel fabrication may also increase because of the likely introduction of burnable poison material (e.g. Gd₂O₃) in order to compensate for long-term reactivity changes. The core optimisation process is one of the most difficult tasks in nuclear science and engineering, and it demands many time-consuming numerical simulations with regard to criticality and neutronic analysis.

The costs of the back-end nuclear fuel cycle are higher in the case of PWRs without thorium fuel because of the higher mass of spent nuclear fuel and more frequent fuel discharges from the reactor core. In the case of thorium-fuelled PWRs, the costs of the front-end fuel cycle are higher because of the higher enrichment of the seed fuel. The percentage costs of the back-end fuel cycle for thorium-fuelled PWRs equal about 10% of the total fuel cycle costs. On the other hand, in the case of the investigated uranium-fuelled reactors, these costs vary from 23% for EPR to 33% for PWR. In general, the costs of the back-end fuel cycle are much lower than the costs of the front-end fuel cycle. It proves that the treatment of highly radioactive spent nuclear fuel is not responsible for the major part of the nuclear fuel cycle costs when the option of direct disposal is considered. If spent nuclear fuel is reprocessed for the extraction of plutonium for the fabrication of the mixed-oxide fuel PuO₂ + UO₂ (MOX), the back-end costs will depend on the costs of reprocessing and on the so-called plutonium credit related to the production of the surplus fissionable isotopes and its possible usage in the fuel cycle of other reactors (OECD NEA 1989). Additionally, the costs of the storage of spent fuel are usually neglected in the costs of the nuclear fuel cycle and encompassed by the operation and maintenance costs of the plant, which reduces the costs of the back-end fuel cycle.

The analysis for seed and blanket fuel for the WASAB concept (Tab. 4, Figs. 4, 5) shows that the costs of blanket fuel are one order of magnitude lower than the costs of seed fuel for both reactors, 5.3 vs 0.71 and 8.61 vs 0.61 mills/kWh respectively. Therefore, the total costs are driven by the seed

fuel costs for both of the investigated reactors. Figure 5 shows that the costs of blanket fuel are rather uniformly distributed for each stage of the nuclear fuel cycle except for conversion and that in principle they are not driven by any partial costs, unlike the costs of seed fuel. Additionally, the differences between EPR_{Th} and PWR_{Th} are modest.

In general, the order of magnitude of the obtained levelized costs of electricity is within the range of the previous studies, i.e. 5–10 mills/kWh (Wang 2003). However, the levelized costs of nuclear electricity depend strongly on the methodology and assumptions applied. In addition, the assessment methodology of the environmental costs of the thorium nuclear fuel cycle should be developed for detailed economic analysis.

Concerning the environmental aspects of the nuclear fuel cycle, the radioactivity of the spent thorium blanket fuel is much lower due to the longer transmutation and decay path to produce notably radioactive minor actinides. In addition, the mass of gateway isotope to minor actinides i.e. ^{238}U is lower in WASAB concept comparing with the reactors fuelled with a low enriched uranium. The higher enrichment level, the lower mass of ^{238}U and lower radiative capture macroscopic cross section on ^{238}U , which prevents formation of higher actinides. Therefore, in terms of the spent fuel radioactivity, thorium blanket fuel is less hazardous for the environment and reaches an acceptable radioactivity level faster than spent uranium fuel. However, the reprocessing of the spent blanket fuel is more troublesome because it contains strongly radioactive ^{232}U . Additionally, the reprocessing technology of the thorium fuel has not yet been developed on a commercial scale and requires costly research due to the minor experience in full-scale thorium irradiations in the nuclear reactor core.

CONCLUSIONS

The presented study focuses on the modelling of the levelized costs of nuclear electricity for pure uranium and uranium-thorium PWRs of two types: the Westinghouse 4-loop reactor and the European Pressurized Water reactor. The numerical modelling was based on the modified OECD

levelized lifetime methodology. In the economic analysis, the costs of each stage of the nuclear fuel cycle were calculated. Additionally, the costs for thorium reactors were decomposed into partial costs of seed and blanket fuel. The obtained results are reliable for the selected assumptions and have the same order of magnitude as the costs obtained in similar studies, which proves the consistency of the applied methodology. A future study on the levelized costs of nuclear electricity for thorium-fuelled nuclear reactors will focus on the total system costs, consisting of the fuel cycle and reactor costs. The latter include capital, operational and maintenance costs, as well as expenses connected with decommissioning, dismantling and decontamination. Therefore, the applied methodology will be significantly extended to cover all the necessary factors and economic impacts (OECD NEA 2018). The research on the cost estimation of a nuclear fuel cycle will be also extended for other nuclear generators such as the VVER (Vodo-Vodyanoi Energetichesky Reaktor) Eastern reactor design and pressurised heavy-water reactors like CANDU (Canada Deuterium Uranium), which will provide full view on fuel cycle costs. The economic study for the advanced nuclear reactors of the fourth generation fuelled with thorium, e.g. the block-type High Temperature Reactor or the Molten Salt reactor, is also foreseen (Gyorgy & Czifrus 2016). The results of economic modelling using the applied method and other similar methods based on the levelized cost of electricity generation in nuclear energy systems are significantly sensitive to the assumptions. In order to avoid both the over- and underestimation of the costs of nuclear electricity, a benchmarking study considering the estimation of cost uncertainties, is strongly recommended. The establishment of a professional benchmark for thorium nuclear reactors with only a few free parameters for a parametric study will significantly increase the reliability of such an analysis. Moreover, a comparative analysis with other generators, such as fossil fuels and renewables, will help to define the position of nuclear electricity in the energy mix for the selected region (Khatib & Difiglio 2016). The study shows the basic environmental problems related to the nuclear fuel cycle, which could

be elaborated in detail in future analysis. The environmental study on the nuclear fuel cycle depends on the cycle type and requires the detailed analysis of all factors which may influence nature and human beings.

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