

Chapter 5: Economic evaluation

“Science does not know its debt to imagination.”

~ Ralph Waldo Emerson ~

Overview

The respective prices of uranium and thorium are discussed and it is assumed that the price of thorium will follow the same trend as uranium. This chapter focuses on the economic advantages of thorium-based fuel cycles. The economic evaluation will focus on the fuel cycle cost (due to higher burnups) and the refuelling outage costs. Thorium-based fuels can extend refuelling cycles, which reduce the fuel requirements and the spent fuel for disposal as well as the reactor downtime for refuelling.

The results show that (Th/U)O₂ shows economic benefits over traditional uranium fuel cycles. (Th/Pu)O₂ was calculated to be more expensive than traditional uranium fuel. The total savings was calculated by adding the fuel cycle savings and the refuelling outage saving. (Th/U)O₂-fuel could save Eskom up to 49 billion rand in 60 years (with interest).

5.1 Uranium and thorium prices

It is assumed that the future price trend of thorium will be analogous to the uranium price trend in the past. Each time new reserves of uranium were discovered, the price of uranium decreased, due to the increased availability of uranium (Silverio & Lamas, 2011). Thorium is at present more expensive than uranium, due to the smaller amounts mined. If thorium utilization should increase in the future, the prices should decrease, due to increased demand, which results in additional mining (Herring *et al.*, 2001).

In the past, the price of uranium has not directed the development and competitiveness of the nuclear industry (Schneider, 2007). Different predictions show either an increase or decrease

in uranium prices. One prediction showed that the price of uranium might accelerate up to a point where nuclear power would become too expensive (Schneider, 2007). The price of uranium has increased almost 15 times since 2000 and peaked in 2007 as shown in Figure 5.1 (Silverio & Lamas, 2011).

If uranium should follow the same trend than other (similar) minerals, with a longer market history, the price of uranium is predicted to decrease over time (Schneider, 2007). The sustainability of uranium deposits is also debatable and different opinions exist. Whether these predictions are true or not, the fact of the matter is that thorium needs to be implemented before a situation of zero uranium becomes a reality.

The fuel cycle cost is a small fraction of the total busbar cost, which means that the electricity price will not be sensitive to fluctuations in the fuel price (Xu, 2003). The influence of the price of thorium and uranium on the total fuel cost is discussed in section 5.3.1.3.

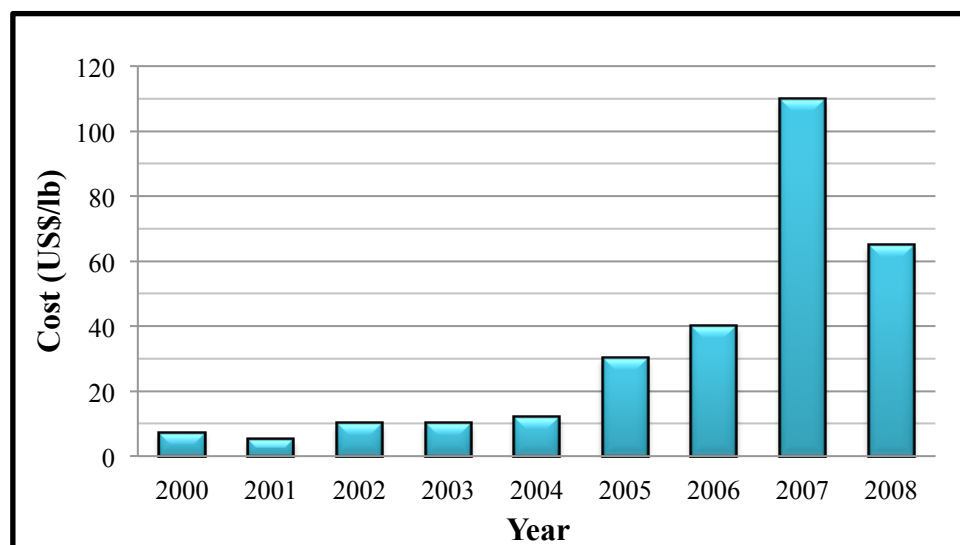


Figure 5.1 The variation of the price of uranium between 2000 and 2008 (Silverio & Lamas, 2011)

5.2 Busbar cost breakdown

Figure 5.2 shows the busbar (levelised) electricity cost breakdown for a typical PWR, divided into 3 main categories: capital cost (57,5%) operation and maintenance (O&M) cost (26,8%) and nuclear fuel cycle cost (15,7%) (Tarjanne & Luostarinen, 2003; Xu, 2003).

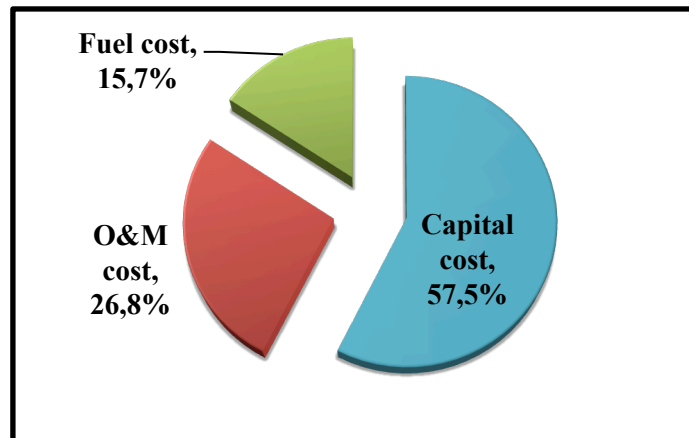


Figure 5.2 Busbar cost breakdown for PWRs (Tarjanne & Luostarinen, 2003; Xu, 2003)

In section 3.3 the different strategies to implement thorium-based fuel in exiting PWRs were chosen to minimise the modifications (complexity and cost) to a standard PWR plant. It is assumed that the capital cost of the thorium-based PWR would be similar to existing PWRs, especially for new PWRs. The use of advanced burnable poisons may increase the fabrication cost (Xu, 2003), but it is assumed the fabrication cost for a PWR is the same for uranium and thorium-based cores.

An Oak Ridge study estimated that thorium-based fuel cycles are 5-10% cheaper in operation than uranium fuel cycles (ThorEnergy, 2009), but higher enriched soluble boron might increase O&M costs. The calculation of operation and maintenance cost on thorium-based fuel cycles needs further investigation and is left out in this section. This section mainly focuses on the cost saving of thorium-based fuel on the fuel cycle cost and the cost of reactor downtime during refuelling.

5.3 Thorium-based fuel savings

Thorium-based fuels can achieve higher burnups and extend the refuelling cycles, which in turn will reduce the fuel requirements and the spent fuel for disposal. One study showed that the natural uranium requirement was reduced, which resulted in a 20-25% reduction in an overall fuel cycle cost (Galperin *et al.*, 1997).

Thorium-based nuclear fuels can reduce the natural uranium requirements by about 20% and the fuel cycle costs by about 20-30% (Unak, 2000). Another study reported that, if spent-fuel disposal costs are included in the fuel cycle cost (at prices above 700\$/kgHM), (Th/U)O₂-fuel would be economically competitive with UO₂-fuel (Hyung-Kook *et al.*, 2004). Section 5.3.1 report on the calculations and results of this study and will verify the above reported economic benefits.

The fuel cycles are extended due to more efficient fuel utilization, with similar initial excess reactivity than those of current 18-month cycles, in the beginning of the fuel introduction. Some PWRs are already 24-month fuel cycle capable with uranium fuel; unfortunately limited information is available on this subject. Most 24-month uranium fuel cycles need to start at much higher excess reactivity to reach 24-month cycle length – resulting in reduced neutron efficiency.

5.3.1 Fuel cycle cost

The fuel cycle cost will be calculated for three different scenarios in one of the Koeberg reactors. For a uranium only cycle, for a (Th/U)O₂-fuel cycle and for a (Th/Pu)O₂-fuel cycle. The (Th/U)O₂ and (Th/Pu)O₂ options are compared against the uranium fuel cycle to highlight the fuel cycle cost savings.

The overall fuel cycle cost can be divided into two main categories, the front end and the back end. The front end takes into account all the fuel-related costs before the fuel enter the reactor such as raw materials, conversion, enrichment and fabrication. Each step is associated with different uranium losses given in the Appendix A. The back end of the fuel cycle takes into account all the cost related to storage, transportation and deposit.

5.3.1.1.1 Assumptions

The unit cost values used for the economic evaluation were taken from several different references (De Roo & Parson, 2011; EMWG, 2007; Haas *et al.*, 2005; Herring *et al.*, 2001; Ko *et al.*, 1998; SA, 2011; Schneider, 2007; Wilson *et al.*, 2009; Zabunoglu & Ozdemir, 2005; Xu, 2003) and the average values are summarised in Table 5.1.

Table 5.1 Unit costs used in the calculations for the economic evaluation

Component	Unit Cost	
Thorium ore	55,8	\$/kgTh
Uranium ore	64,4	\$/kgU
Conversion	7,9	\$/kgHM
Enrichment	107,4	\$/SWU
UO ₂ fabrication	244,2	\$/kgHM
MOX fabrication	1 780,0	\$/kgHM
(Th/U)O ₂ fabrication	300,0	\$/kgHM
Reprocessing	684,4	\$/kgHM
Disposal	536,0	\$/kgHM
Storage	187,5	\$/kgHM

Reactor properties of Koeberg used for the calculations are summarised in Table 5.2

Table 5.2 Reactor properties of Koeberg (ESKOM, 2007)

Properties	Values	Units
Thermal Power	2785	MWth
Capacity Factor	83	%
Refuelling cycle	18	months
Lifetime	60	years

The following assumptions were made:

- The capacity factor was increased by 2,5% for the thorium-based fuel cycles (Herring *et al.*, 2001).
- The fabrication cost for (Th/Pu)O₂-fuel is assumed to be the same as for MOX.
- The refuelling cycles for thorium-based fuel are extended from 18 months to 24 months.
- The interest rate is taken as 6%.
- The exchange rate is taken as 8,5 R/\$ (X-rates, 2012).
- The fractions of thorium and uranium for the (Th/U)O₂ option were taken as 25% UO₂ and 75% ThO₂, with the UO₂ enriched to 19,5% U²³⁵.
- The fractions of thorium and plutonium for the (Th/Pu)O₂ option were taken as 12,7% PuO₂ and 87,3% ThO₂, with the PuO₂ corresponding to the isotopic vector of spent fuel (~8,6% fissile content of total).

- The cost of spent fuel was taken as zero, because it is assumed that the spent fuel from Koeberg is reprocessed to use the plutonium for the (Th/Pu)O₂-fuel option. Please note that the spent fuel could be reprocessed in another country, to adhere to the agreement that South Africa made, viz. not to reprocess spent fuel for Pu. The Pu can also be purchased and imported, but it is a proliferation risk and the cost of Pu is a large uncertainty.

5.3.1.1.2 Results

The (Th/U)O₂ and (Th/Pu)O₂ options were calculated by using the fractions noted in section 5.3.1.1. Table 5.3 shows that (Th/U)O₂ is economically competitive to UO₂ and can save up to 6,2% of the fuel cycle cost. This amounts to more than 142,51 million dollars in the 60-year lifetime (without interest). As noted in section 5.2, the fuel cycle contributes 15,7% to the total busbar cost and a 6,2% saving will result in saving more than 1% on the total busbar cost.

Calculation showed uranium savings of 12,5% for (Th/U)O₂-fuel and 100% for (Th/Pu)O₂-fuel. (Th/U)O₂ showed an economic advantage and (Th/Pu)O₂ proved to be more expensive than UO₂. This was due to the fact that the total amount of spent fuel needs to be reprocessed to extract only 1% of the total mass (Pu). The fabrication price for (Th/Pu)O₂ is also more expensive than for (Th/U)O₂.

Table 5.3 Results for thorium fuel cycle costs compared with uranium fuel cycle costs

	UO ₂	(Th/U)O ₂	(Th/Pu)O ₂	Units
Total fuel cycle cost	38,30	35,92	163,82	M\$/year
Fuel cycle cost for reactor life (60 years)	2 297,89	2 155,38	9 829,15	M\$
Fuel cycle savings compared with U	-	142,51	-7 531,26	M\$
Fuel cycle savings compared with U	-	6,20	-327,75	%

5.3.1.1.3 Sensitivity analysis

A sensitivity analysis was done to see the effect of the price of different components on the total fuel cycle cost. The specific values in Table 5.1 may vary and are sometimes different

for different countries. The purpose of this sensitivity analysis is to show how the total fuel cycle cost is influenced by for instance, higher enrichment costs (\$/SWU).

A sensitivity analysis was done on the (Th/U)O₂ fuel cycle cost by varying the uranium price, thorium price, enrichment price, fabrication price and the final disposal price. From Figure 5.3 it can be seen that the enrichment price has the most significant impact on the fuel cycle cost. The price of uranium also has a significant effect on the fuel cycle cost. The price of thorium had an insignificant effect on the fuel cycle cost, which was expected as from section 5.1.

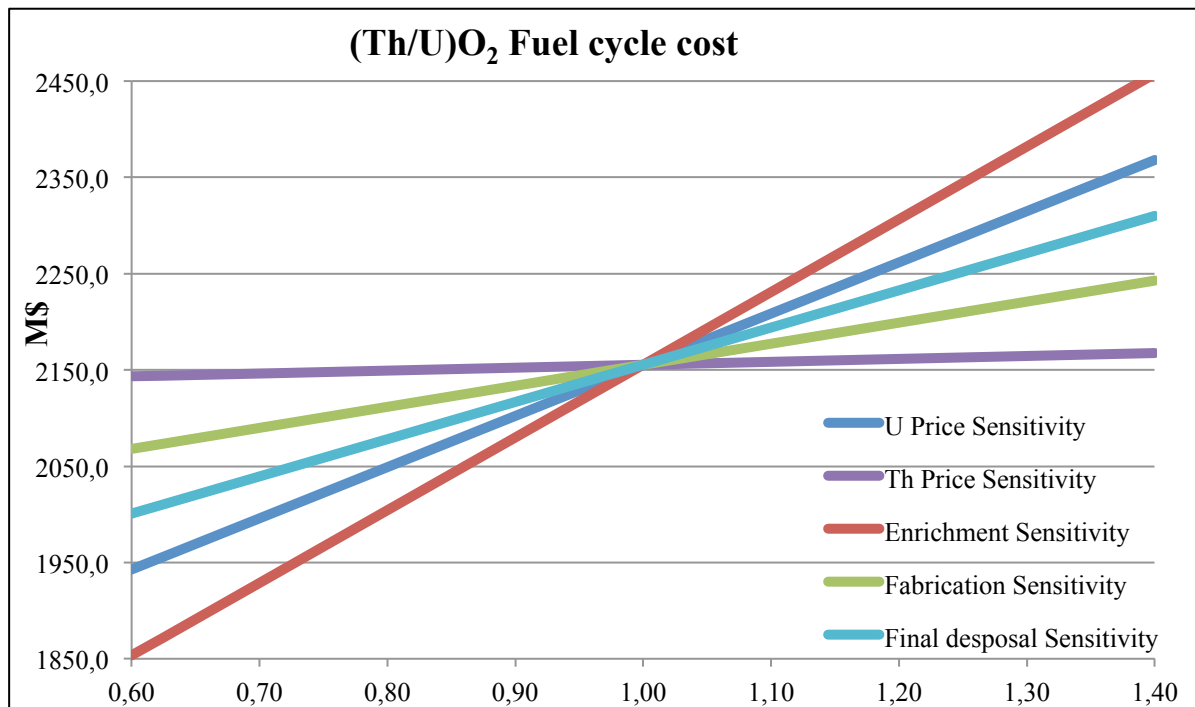


Figure 5.3 Sensitivity analysis for (Th/U)O₂-fuel cycle cost

A sensitivity analysis was done on the fuel cycle cost of (Th/Pu)O₂-fuel by varying the thorium price, reprocessing price, fabrication price and final disposal price. In Figure 5.4 it can be seen that the reprocessing price has the most significant impact on the fuel cycle cost. The fabrication cost for (Th/Pu)O₂ is expensive compared with (Th/U)O₂, hence the significant influence on the fuel cycle cost. Once again it can be seen that the influence of the thorium price on the fuel cycle cost is insignificantly small.

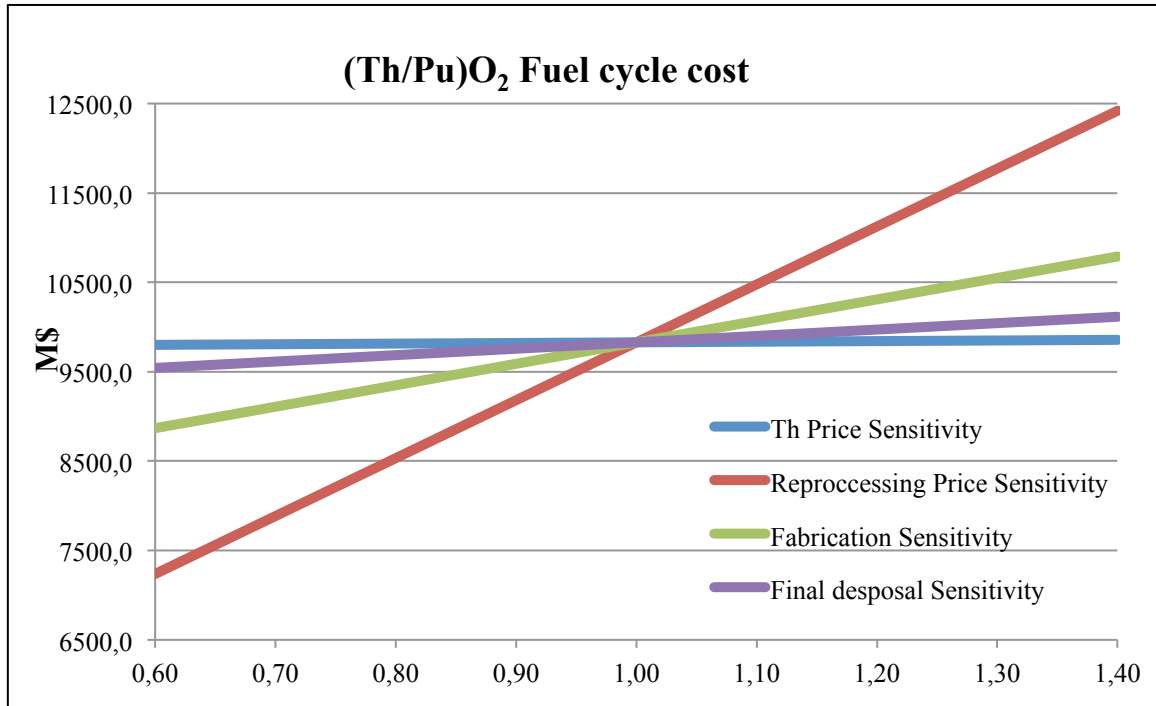


Figure 5.4 Sensitivity analysis for (Th/Pu)O₂-fuel cycle cost

Based on the sensitivity analysis it is concluded that the final disposal cost has a significant and identical impact on both the (Th/U)O₂ and (Th/Pu)O₂ options. It was assumed that the cost of final disposal would be the same for all three scenarios. The disposal cost is foreseen to be less expensive for thorium-based fuels, due to the better utilization of the fuel and less produced actinides.

The ultimate long-term cost of repository disposal is still a large uncertainty and will depend on means of disposal and waste management strategies. The (Th/Pu)O₂-fuel option would become competitive with the (Th/U)O₂-fuel when the enrichment cost could be drastically reduced fabrication. Overall, it is concluded that the cost of thorium has an insignificant effect on the fuel cycle cost.

5.3.2 Cost of refuelling downtime

The extension of the refuelling cycle will result in less reactor downtime for refuelling. The cost of refuelling, due to reactor downtime is a major contributor to the O&M cost. Section 5.3.2 focuses on the savings of thorium-based fuels, due to the reduction of total reactor downtime. The utility loses the income from electricity sales during the refuelling time and also need to pay for replacement electricity during peaks. It is assumed that the refuelling cycle was extended from 18 months to 24 months for both the thorium-based fuel options. The results for both (Th/U)O₂ and (Th/Pu)O₂ are the same. The implication of extending the life and maintenance of some plant components has not been taken into account in this study. The details of the calculations are shown in Appendix A.

5.3.2.1.1 Results

Table 5.5 shows that an extension in refuelling cycles can reduce the number of months for reactor downtime by almost 9 months per reactor for the 60 year reactor lifetime. The savings amount to more than 403 million dollars for both of Koeberg's reactors, without interest.

Table 5.4 Results in reactor downtime savings for thorium-based fuels

	Current (18-month)	Goal (24-month)	Units
Downtime for lifetime	37,89	28,80	months
Cost of one month outage	26 344 821,00	27 664 397,00	\$/month
Downtime cost for lifetime for 2 reactors	1 996,66	1 593,47	M\$
Downtime savings	-	403,19	M\$

5.3.3 Total savings

The combined benefit of thorium-based fuels, in terms of fuel cycle cost and reactor downtime cost is given. These savings are now applied for both of Koeberg's reactors. It is assumed that the interest rate is 6% and the exchange rate is 8,5 R/\$ (X-Rates, 2012).

Table 5.5 Total savings for fuel cycle cost savings added to reactor downtime cost savings

	(Th/U)O ₂	(Th/Pu)O ₂	Units
Total savings for 60 years	407,94	152,15	M\$
Total savings for 60 years with interest	5 778,29	-123 081,97	M\$
Total savings for 60 years with interest	49 115,45	-1 046 196,72	MR

Table 5.6 shows that a utility can save up to 49 billion rand at the end of 60 years by using (Th/U)O₂-fuel in current PWRs. A significant result shows that (Th/Pu)O₂ still proves to be more expensive than conventional uranium fuels in terms of total savings. (Th/U)O₂ is more than four times more economical than (Th/Pu)O₂.

5.3.4 Conclusion

Please note that some current PWRs already use a 24-month fuel cycles with uranium fuel, unfortunately limited information is available on this subject. The advantage here is that fuel cycles are extended due to more efficient fuel utilization, with similar initial excess reactivity than those of current 18-month cycles, in the beginning of the fuel introduction. Some 24-month uranium fuel cycles need to start at much higher excess reactivity to reach 24-month cycle length. A more comprehensive costing study is necessary to make the final decision, most likely a professional and industrial economical evaluation, which falls outside the scope of this project.

Advantages of reduced costs of final disposal cost for thorium-based fuel cycles are difficult to quantify. Final deposit storage costs are not paid up front, but are strongly discounted into the future and are sometimes considered insignificant compared to other fuel cycle costs (Rose *et al.*, 2011).

The cost of thorium has an insignificant effect on the fuel cycle cost and moderate price fluctuations for uranium and thorium will not be an issue. (Th/U)O₂ is less expensive than uranium in terms of fuel cycle cost and (Th/Pu)O₂ is almost 4 times more expensive than UO₂. When refuelling downtime costs were also taken into account, (Th/U)O₂ proved to be more economical than (Th/Pu)O₂ and UOX. Unfortunately, (Th/Pu)O₂ did not show any economic benefit over UOX.

It is proposed that the roadmap starts with (Th/U)O₂ in PWRs until investigations can provide ways to reduce the reprocessing cost of SF and reduce the fabrication cost of MOX. Until then, there's no economic drive to implement Th/Pu fuels in PWRs.