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The Sustainability of Nuclear Fuel Resources in Indonesia with Open and Closed Fuel Cycle

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Abstract

In the wake of climate change and global warming, various alternatives are being considered as a potential replacement for fossil fuels. Despite often being overlooked, nuclear power offers many benefits as a low-carbon energy source. Being a thermal power plant, nuclear power can generate energy reliably without relying on weather without emitting greenhouse gases during its operation. Serialised construction can reduce the capital cost, which often touted as expensive. Due to the commitment to the Paris Protocol, Indonesia is obliged to achieve carbon neutrality in its energy generation, and nuclear power is a plausible option to replace fossil fuel generation. One of the questions regarding nuclear power deployment in Indonesia is the sustainability of the nuclear fuel, especially considering its domestic resources both uranium and thorium. This study estimates how long uranium and thorium resources in Indonesia will last when used to power the nuclear power plants with open and closed fuel cycles. Several reactor designs were considered. The calculation result shows that domestic nuclear fuel resources in Indonesia can be sustainable enough, provided that closed nuclear fuel cycle is deployed.

Keywords: uranium, thorium, open fuel cycle, closed fuel cycle, sustainability

Introduction

One of the most prominent issues on the impact of energy usage to the environment is climate change. Carbon dioxide (CO_2), emitted from fossil fuel combustion, is the primary driver of climate change (Cook *et al.*, 2013). Being a greenhouse gas, CO_2 trapped the infrared heat emitted from the Earth's surface and reflecting it back. In fact, GHG is the primary reason for the Earth to be habitable, allowing the Earth's surface to attain livable temperature so that life can flourish. The increase of GHG in the atmosphere, especially CO_2, concurrently reflects more heat to Earth's surface, increasing its temperature. The increase of temperature on Earth's surface, known as global warming, caused many climate parameters to change, negatively impacting life on Earth (Farmer and Cook, 2013).

To avoid potential catastrophic climate disasters arising from climate change, various pathways have been developed. However, since the largest share of GHG emissions comes from energy use, any climate mitigation strategy without involving massive GHG reduction from energy sector is not expected to noticeably dent global carbon emission. Simply reducing the energy

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consumption from fossil fuel without replacing it, so-called energy efficiency, would not work either, due to rebound effect; with more efficient energy use, people are using more energy-consuming products, negating the reduction of energy consumption (Brännlund, Ghalwash and Nordström, 2007). Furthermore, energy efficiency cannot eliminate most of GHG emission, only reducing it which deeply insufficient to mitigate climate change.

Therefore, the only feasible path to reduce GHG emission from energy sector is by replacing fossil energy with clean energy. Aside from being clean, the energy supply must be affordable, reliable, and sustainable as well, as noted in the Sustainable Development Goals 7 (United Nations, 2023). Major investments in clean energy have been increasing in the past decades (Louw, 2018). This is further strengthened by the Net Zero Emission (NZE) pledge.

Unfortunately, the expansion rate of clean energy infrastructure is insufficient to meet the primary target of limiting global temperature rise at 1.5°C (Tong *et al.*, 2019). This is problematic, as to achieve the target, the GHG emission must be turned into negative (i.e. GHG is removed from the atmosphere as an addition to decreasing GHG emission as low as possible) (Hansen *et al.*, 2017). The cost of replacing fossil energy with clean energy, presently, is astronomical due to the majority of the scenario involves a huge share of renewable energy, especially wind and solar. Although they might be cheap to install, the material demand is huge (Wang *et al.*, 2023), the grid-level costs are exorbitant (OECD NEA, 2018), and the storage/backup issue has not resolved. This hinders a rapid installation of renewable energy.

Another alternative to look at is nuclear energy. Although often being overlooked, nuclear energy offers a clean and reliable energy. The energy comes from splitting a heavy nuclei by bombarding it with neutrons, releasing a vast amount of kinetic energy around 8 million times larger than carbon combustion per atom (Lamarsh, 1966). This ensures that nuclear energy emits no GHG to the atmosphere and, as a thermal generating plant, nuclear power plant (NPP) can produce electricity reliably. Although cost of nuclear energy has been increasing in the 21st century, it is still comparably cheaper than other clean energy options when integrated into electricity grid (Duan *et al.*, 2022).

Studies on nuclear energy have found that nuclear energy is extremely helpful to reduce GHG emission, whilst preventing economic strain from relying on intermittent energy sources (Brook *et al.*, 2014; Hong, Bradshaw and Brook, 2014; Berger *et al.*, 2017). Historically, nuclear energy successfully prevented an average of 1.84 million deaths from fossil fuel whilst simultaneously displacing an average of 64 Gt of CO_2 from the atmosphere (Kharecha and Hansen, 2013). These advantages must be taken into serious consideration to deploy nuclear energy, including in Indonesia.

At the present, Indonesia operates no NPP, despite the plan to build it can be traced back to the 1970-s (Huda, Rohman and Lasman, 2011). Although Indonesia pledge to the Paris Agreement, currently there is no concrete Act as a legal foundation for building NPPs. The position might change in the future, and if nuclear does get support, a certain issue will arise: nuclear fuel sustainability.

Indonesia is not known to possess a large resource of nuclear fuel, namely uranium and thorium. The latest report (CNBC Indonesia, 2022) implies that Indonesia is indicated to possess around 81,090 tonnes of uranium and 140,411 tonnes of thorium. These numbers include inferred and hypothetical resources. As a comparison, Australia has the largest uranium reserve in the world, accounting for 1,664,100 tonnes (Nuclear Energy Agency and International Atomic Energy Agency, 2016). Thorium resource, on the other hand, is still massively underestimated due to it has little economic use at the present. However, Indonesian thorium resource is not particularly massive either compared to other countries. Take Australia again, for example, who possesses 595,000 tonnes of thorium resource (Nuclear Energy Agency and International Atomic Energy Agency, 2016).

Given the nature of highly energy-dense fuel, small nuclear fuel resource does not necessarily mean that nuclear energy is unsustainable. Nevertheless, we need to consider the sustainability of domestic nuclear fuel resources, especially if nuclear power will be massively deployed to achieve carbon neutrality. Although nuclear fuel can be easily imported, using domestic fuel resources can increase energy security.

This study evaluates the sustainability of Indonesian nuclear fuel resources, both uranium and thorium, using mathematical model. Previous study has estimated the sustainability of Indonesian uranium resource (Bastori and Birmano, 2017), but the study is limited to the measured uranium resource and single nuclear fuel cycle. Here, the author extends the study to two nuclear fuel cycles, using both uranium and thorium, and various types of reactor technologies to provide a bigger picture.

Methods

Nuclear fuel cycle: a review. There are primarily two types of nuclear fuel cycle: open nuclear fuel cycle and closed nuclear fuel cycle. The former can be summarised as once-through fuel utilisation. Meaning, after the fuel is used in the reactor, the resulting spent fuel is stored and ultimately disposed in permanent disposal facility. The illustration of open fuel cycle can be seen in Figure 1.

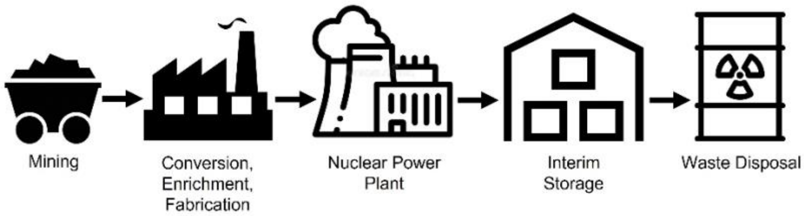


Figure 1. Illustration of open nuclear fuel cycle

An extension of open nuclear fuel cycle is multi-use nuclear fuel cycle. After the used fuel is discharged from the reactor, the fuel is then used in other reactor type that can be operated with the used fuel. This proposal involves a pressurised water reactor (PWR) and pressurised heavy water reactor (PHWR) technologies, where the spent fuel from PWR reactor is used directly in the PHWR, hence the name DUPIC (Direct Use of PWR spent fuel in CANDU, where CANDU is the name of PHWR developed in Canada) (Özdemir *et al.*, 2016). After the PWR spent fuel is used in PHWR, the twice-used fuel is then stored waiting for permanent disposal.

Open nuclear fuel cycle is the simplest among the two, but has lower utilisation value. Although utilisation can be extended, but not by a significant margin. A significant amount of nuclear fuel is required in this cycle.

Closed nuclear fuel cycle is illustrated in Figure 2. This option fully recycles the spent fuel. After the fuel is used in the reactor, the remaining usable fuel is separated from the waste, called fission product (FP) and transuranic (TRU) elements, refabricated, and reinserted into the reactor. The FP and TRU is then disposed permanently as a waste product. This cycle is continuously done with small amount of nuclear fuel is required for the input.

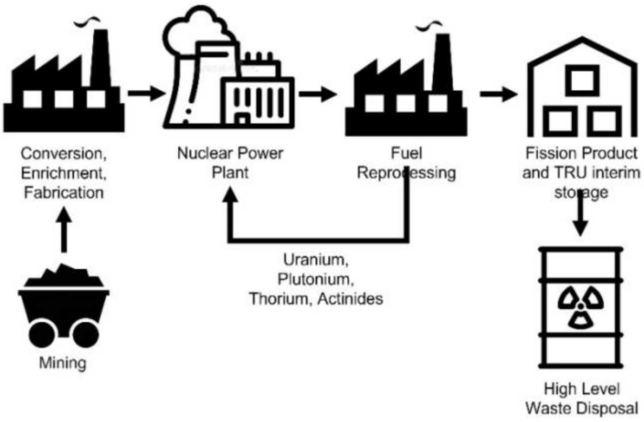
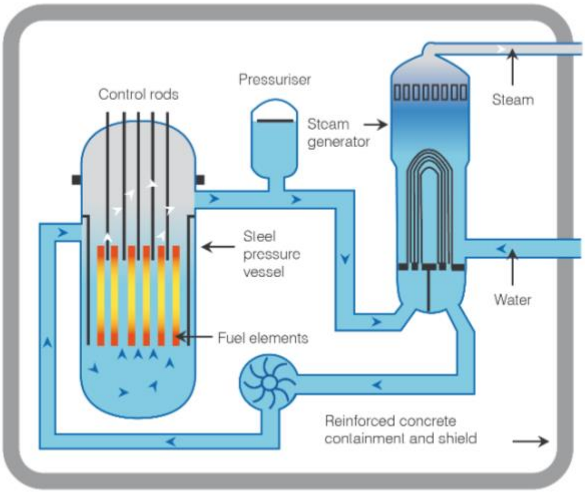


Figure 2. Illustration of closed nuclear fuel cycle

The prerequisite of closed nuclear fuel cycle is primarily an excellent neutron economy, indicated by low parasitic neutron absorption by non-fuel materials. The neutronic aspect of the reactor must be sufficient so that the reactor can breed its own fuel from the small additional input to the reactor. A fuel reprocessing system is also a definite requirement, as without it closed nuclear fuel cycle cannot be achieved (Rubbia, 2016).
In this case, both scenarios will be used to represent the current practice and the best potential use in regard to the sustainability of nuclear fuel.

Reactor technologies. Apart from the nuclear fuel cycle, we also have to determine the reactor technology used in the calculation. Presently, most of nuclear power reactor designs available in the market are Generation III and Generation III+ designs. Both are quite similar and will be singularly referred as GenIII. Among the commercial technologies are AP1000 (Westinghouse-Toshiba, USA), APR-1400 (KEPCO, South Korea), VVER-1200 (Rosatom, Russian Federation), and EPR (Framatome, France). Table 1 summarises the primary characteristics of the aforementioned NPPs. All the aforementioned reactors are PWR, with its general schematic is shown in Figure 3.



Source: World Nuclear Association
Figure 3. Pressurised water reactor (PWR) general schematic

All designs are operational in various nuclear power states. AP1000, for instance, is operational in China and USA. The first two AP1000 units in China, located in Sanmen Nuclear Power Plant, were operational in 2018. In the US, AP1000 construction is met by severe cost overrun, leading to construction in VC Summer Nuclear Generating Station being abandoned.

Table 1. Summary of available GenIII reactor designs

	APR-1400	AP1000	VVER-1200	EPR
Developer	KEPCO	Westinghouse-Toshiba	Rosatom	Framatome
Country	South Korea	United States	Russia	France
Thermal Power (MWt)	3,983	3,415	3,212	4,300
Electrical Power (MWt)	1,400	1,117	1,198	~1,600
Reactor type	PWR	PWR	PWR	PWR

VVER-1200 was being aggressively marketed outside Russia, apart from construction in its homeland. Since NPP is a high-capital investment, Rosatom's business model that funds most of the construction cost with BOO (build, own, operate) contract is more attractive to newcomer states (Thomas, 2018). As such, Russia obtains contracts to build VVER-1200 with various countries, such as Turkey, Egypt, and Bangladesh. In BOO scheme, however, the electricity price contract is considerably expensive. Current geopolitical issue involving Russia and Ukraine complicates the potential business with Russia. Meanwhile, French EPR, much like AP1000, encounters construction delay and cost overrun in some of its projects, such as Finnish Olkiluoto and French Flamanville. Nonetheless, EPR project in Chinese Taishan was successful.

The most apparent success story of NPP construction lies in APR1400 design. Apart from its native South Korea, APR-1400 is being constructed in United Arab Emirates (Hartanto *et al.*, 2020), with two of four units built are finished and connected into the grid. In South Korea, APR-1400 construction was met with slight cost overrun, but nonetheless relatively cheaper compared to other designs. In UAE, however, the NPP was built on schedule with no cost overrun. Since APR-1400 adopted standardisation and learning curve method used in KEPCO's previous design, OPR-1000, its construction time and cost can be reduced even further.

All vendors currently have plans to sell more reactors in the future. French EPR is currently being constructed in Hinkley Point C, UK, with further development is planned in Sizewell C. Poland signed an MoU with Westinghouse to build AP1000, along with APR1400. VVER-1200 was originally planned to be constructed in Finland, but in the wake of Russian invasion in Ukraine, the contract was then terminated. VVER-1000, a variant of VVER with smaller power, was also intended to be constructed in Ukraine, but then cancelled and replaced with the plan to build AP1000 instead.

From these brief descriptions, AP1000 and EPR tend to encounter certain difficulties during construction phase, leading to massive cost overrun. Meanwhile, despite VVER-1200 rarely encounters such problem, expensive contract and therefore high cost of electricity hinders the economic potential of deploying nuclear power in Indonesia. Russian invasion in Ukraine further complicates the issue. Meanwhile, APR1400 has the least problems, both technically and politically. Therefore, APR1400 seems to be the most realistic choice to be built in Indonesia, and taken for consideration in this study.

In the foreseeable future, Generation IV (GenIV) nuclear energy system is expected to be commercialised. The least complex GenIV technology in term of nuclear fuel cycle is converter reactor, the same as GenIII reactors. However, with higher thermal efficiency, fuel consumption is expected to be lower than most GenIII designs. Various GenIV reactors are currently under development, and some vendors show their interest in developing the plant in Indonesia. The earliest and most prominent one is ThorCon Power, with their TMSR-500 design (Devanney *et al.*, 2015). It is a molten salt reactor (MSR) technology with 500 MWe electricity generating capacity from two graphite-moderated cores. TMSR-500 employs liquid salt as the fuel and coolant. Being a liquid fuel, molten salt can achieve significantly higher burnup than conventional LWRs since the fuel can be left in the salt indefinitely, immune to radiation damage as occurs in LWR oxide fuel. Although MSR is still under development, it can be expected to be commercial prior to 2030. As a comparison, the TMSR-500 is then taken for calculation. General schematic of MSR design is shown in Figure 4.

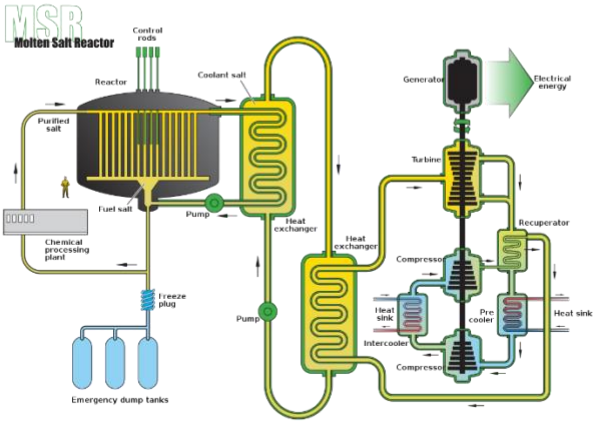


Figure 4. Molten salt reactor (MSR) general schematic (Source: Generation IV Forum)

GenIII reactors are exclusively open fuel cycle, as the neutron economy is insufficient for the reactor to breed enough fuel for itself. GenIV converter reactors suffer from the same issue. Therefore, only uranium is considered in open cycle calculations, since thorium lacks naturally occurring fissile isotope necessary to start and maintain chain fission reaction. Although there is a possibility of using thorium alongside uranium, including the one proposed in the TMSR-500, there is currently little evidence that it brings benefit (Reda *et al.*, 2021).

The most ideal nuclear fuel cycle is the closed fuel cycle. In this scenario, the neutron economy is vast enough so that more fissile material is bred through neutron capture of fertile material than it is consumed. In closed nuclear fuel cycle, no fissile input is required since the reactor breed its own fissile fuel. Only additional fertile material needs to be added periodically into the reactor. An example of breeding process from fertile nuclide to fissile nuclide is shown in Equation 1.

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{90}Th \rightarrow ^{233}_{91}Pa + \beta_{-} \rightarrow ^{233}_{92}U + \beta_{-} \tag{1}$$

This breeder cycle requires a reprocessing system to separate the bred fissile from the fission products, refabricate it, and reintroduce it into the reactor core, as shown in Figure 2. This applies for GenIV reactors with solid fuel. For liquid fueled reactor, fuel reprocessing can be performed online, that is, without shutting down the reactor and performed onsite, so that the reprocessed fuel never leaves the power plant (Jeong *et al.*, 2016). Only by using breeder cycle and fuel reprocessing, maximum potential of nuclear fuel can be harnessed. Thereby, we use breeder cycle as the ideal nuclear power scenario in Indonesia, and included in the calculation of nuclear fuel sustainability.

Closed nuclear fuel cycle can be done in thermal neutron spectrum for thorium and in fast neutron spectrum for both thorium and uranium. In this study, thermal breeding is calculated for thorium and fast breeding is for uranium. The design choice is limited as breeder reactor is not massively deployed yet. Therefore, the molten salt breeder reactor (MSBR), a thermal breeder MSR concept developed in Oak Ridge National Laboratory (ORNL), was taken to represent thermal breeding cycle using thorium fuel cycle (Park *et al.*, 2015). Currently, Russia is developing BN-1200, a sodium-cooled fast breeder reactor (SFR) designed to breed plutonium from uranium (Rachkov *et al.*, 2010). This design is taken to represent fast breeding using uranium fuel cycle. General SFR schematic is depicted in Figure 5.

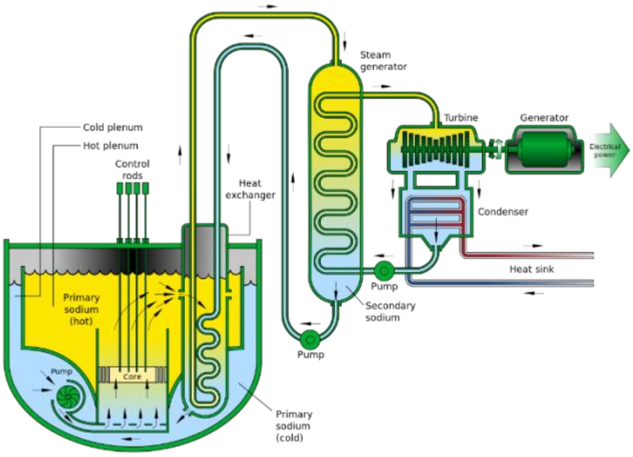


Figure 5. Sodium-cooled Fast Reactor (SFR) general schematic
Source: Generation IV Forum

The main characteristics of TMSR-500, MSBR, and BN-1200 are summarised in Table 2.

Table 2. Summary of selected GenIV reactor technologies

	TMSR-500	MSBR	BN-1200
Developer	ThorCon	ORNL	OKBM Afrikantov
Country	International Consortium	United States	Russia
Thermal Power (MWt)	2 × 557	2,250	2,900
Electrical Power (MWt)	2 × 250	1,000	1,220
Reactor type	MSR	MSR	SFR
Fuel Cycle	Open	Close	Close
Fissile/Fertile Fuel	U-235/U-238 + Th-232	U-233/Th-232	Pu-239/U-239

Calculation Model. As previously mentioned, only uranium is used in the nuclear power industry as the fuel. The lack of naturally occurring fissile isotope in thorium prohibits its use in conventional LWRs, as it requires other fissile isotope in order to be able to be used in the reactor core. For these rationale, in GenIII and GenIV converter, only uranium is considered in the calculation, as thorium provides little to no use to the sustainability of nuclear fuel.

To calculate annual natural uranium consumption for GenIII and GenIV converter reactors, first we must determine the required annual enriched uranium demand for each reactor. This factor depends on the thermal power of the reactor, capacity factor (CF), and fuel enrichment. The enriched uranium requirement in tonne, then, can be calculated using Equation 2.

$$LEU_{mass} = \frac{P_{th} \times 8.766 \times CF \times 3600}{ED_{U235} \times Enr.\%} \tag{2}$$

where P_{th} is reactor thermal power (MWt), CF is capacity factor in %, ED_{U235} is the energy density of U-235, and Enr.% is the fuel enrichment in %wt. In APR-1400, maximum fuel enrichment of 4.65%wt was taken, whilst TMSR-500 is 19.75%wt due to thorium coexistence in the same fuel salt requiring higher uranium enrichment.

Energy density (ED) of fissile fuel (in MJ/kg), meanwhile, can be calculated using Equation 3.

$$ED = \frac{\kappa_{fis} \times 6.023 \times 10^{23}}{A} \times \frac{1.60217 \times 10^{-19}}{0.001} \tag{3}$$

where κ_{fis} is the energy released per fission (MeV/fission) and A is the atomic mass of fissile nuclide in interest (g/mol).

After finding the annual enriched uranium requirement, annual fuel consumption (AFC), translated into natural uranium feed, can be calculated by using Equation 4.

$$AFC = LEU_{mass} \times 1000 \times \frac{(Enr.\% - Tail\%)}{(Feed\% - Tail\%)} \tag{4}$$

where Tail% is the tail assay of the depleted uranium and Feed% is the original U-235 content in natural uranium. To standardise the calculation, tail assay is treated at 0.2% and feed assay is constant at 0.711% U-235.

The natural uranium requirement is normalised to nominal reactor power of 1000 MWe. To estimate uranium sustainability, 10 units of APR-1400 for GenIII case and 28 units of TMSR-500, giving a total generating capacity of 14 GWe. This is roughly a third of total installed electricity generation capacity in Indonesia.

Meanwhile, to calculate nuclear fuel sustainability in GenIV breeder reactors, it was assumed that the reactors are purely run with a single fissile nuclide at the beginning of cycle (BOC) to simplify calculations. Then, ED must be calculated for U-233 and Pu-239 as the fissile drivers for MSBR and BN-1200, respectively. Then, annual fuel consumption is obtained using Eq. 5.

$$AFC = \frac{P_{th} \times CF \times 8.766}{2.78 \times 10^{-4} \times ED \times RE} \tag{5}$$

with RE is reprocessing efficiency. This study treated RE at 95%, implying 5% fuel loss due to reprocessing. Similar to previous scenario, annual fuel consumption is normalised to 1000 MWe with total installed generating capacity of 14 GWe, translated into 12 units of BN-1200 (rounded above) and 14 units of MSBR.

To figure out how long domestic nuclear fuel can last, the uranium resource value was then divided by the AFC for GenIII, GenIV converter, and BN-1200 reactors. Meanwhile, thorium resource was divided by the AFC for MSBR, since it is the only reactor modelled in this study capable of optimally exploiting thorium resource.

Results and Discussions

Calculation result of nuclear fuel sustainability is summarised in Table 3. For all cases, the CF is assumed at 90%, in accordance with the best practice in the US and South Korea.

Table 3. Fuel sustainability for various reactor designs

Parameter	APR-1400	TMSR-500	BN-1200	MSBR
AFC (tonnes)	252	157.5	1.02	0.8
Normalised AFC (tonnes)	180	157.5	0.9	0.8
NPP units	10	14	12	14
Annual fuel requirement (tonnes)	2,520	2,205	12.25	11.26
Fuel sustainability (years)	32.18	36.78	6619.60	12,474.45
Generated electricity (TWh)	3,554.17	4,061.91	764,569.1	1,377,823

Assuming that 100% of domestic fuel resources can be exploited, APR-1400 and TMSR-500 show a small difference in sustainability. Ten units of APR-1400 consume 2,520 tonnes of natural uranium annually, exhausting Indonesian uranium resource in around 32 years. TMSR-500 fares a little bit better, can be operated for 36 years prior to the exhaustion of domestic uranium. Better fuel utilisation in TMSR-500 is predominantly due to higher thermal efficiency (44.88%) compared to APR-1400 (35.15%), so that less fission reaction is required to generate the same amount of electricity. High thermal efficiency in Generation IV reactor is achieved by operating the reactor in higher temperature (700°C), more than twice as high than in PWR (330°C) and using supercritical steam generator instead of saturated steam generator. Apart from helping to reduce uranium consumption, high operating temperature is also beneficial for various cogeneration system, such as hydrogen generation and enhanced oil recovery.

Nevertheless, the sustainability of domestic uranium resources is lower than the design lifetime of the aforementioned reactors at 60 years. This is rather problematic, since we have to import uranium to cover the rest of the design lifetime. Not to mention that lifetime extension is possible in NPPs, allowing the NPP to be operational up to 80-100 years. Reducing the installed capacity by half can allow the domestic uranium to last until the end of design lifetime, at the cost of lower nuclear share in total energy generation. In reality, even this reduction cannot reliably increase the sustainability, since it is practically impossible that all of the uranium potential can be extracted from the ground.

PWR spent fuel contains a small amount of plutonium, and it can be extracted and refabricated into mixed oxide (MOX) fuel, as being performed in France and Japan, to be reused in the NPP. However, even this reprocessing cannot significantly increase the sustainability of nuclear fuel. As Indonesia presently adopts open fuel cycle, meaning that the spent fuel is not reprocessed, this option to extend sustainability is not particularly feasible. In addition, only a handful of nuclear power states are allowed to reprocess the spent nuclear fuel, due to the fear of nuclear proliferation. Indonesia, obviously, is not among the countries that are allowed to do so.

TMSR-500, whilst using open fuel cycle, can increase the nuclear fuel sustainability by re-enriching its spent fuel. Converting uranium in salt compound into uranium hexafluoride (UF_6) for enrichment is far easier than reprocess oxide-based fuel, thus this step is theoretically more realistic. ThorCon claimed that uranium re-enrichment can halve its uranium consumption (Devanney *et al.*, 2015). Assuming that the claim is true, then 14 GWe of TMSR-500 can be operated up to 70 years before domestic uranium resource is exhausted.

Despite all the possible effort to extend the uranium sustainability, judging from the numbers above, it is clear that Indonesian uranium potential cannot be relied upon sustainably when used in GenIII and GenIV converter reactors. In normal scenarios, the uranium will be used up completely in under 50 years for 14 GWe of generating capacity. In term of sustainable nuclear fuel cycle, open fuel cycle in these reactors cannot realise that purpose.

When used in GenIV breeder reactors, however, uranium resource for 14 GWe of BN-1200 can last for more than six millennia, over 200 times longer than using open fuel cycle. Meanwhile, 14 GWe of MSBR, using thorium, can last for almost two limes longer than uranium, due to higher abundance of thorium in Indonesia. This shows an extremely high efficiency of nuclear fuel utilisation when operated in a closed fuel cycle, where the fuel is constantly reprocessed and reused in the reactor with high neutron economy for the reactor to be self-sufficient, only requiring fertile fuel input to replace the ones that was converted to fissile fuel.

Even if we included lower RE and more realistic nuclear fuel exploitation potential in the calculation, nuclear fuel sustainability in breeder reactors with closed fuel cycle is outstanding. This ensures that nuclear energy can be exploited for extremely long time. This raises another question, what if nuclear energy is used in a higher share? How long it will last?

Let us take the National Energy Masterplan (*Rencana Umum Energi Nasional*/RUEN) (Government of Indonesia, 2017) as the example scenario. In this old Masterplan, fossil energy still dominates the energy generation in 2050, amounting for 69%. With the insurgence of NZE, this Masterplan will definitely be adjusted in the future. However, the Decree has not been issued. Therefore, for the sake of estimation, we will consider this existing Masterplan

In this estimation, it is assumed that nuclear will replace coal and/or gas consumption, both account for 49.3% of total energy generation in 2050. Two scenarios are used, namely nuclear replaces coal (Scenario 1), and nuclear replaces both coal and gas (Scenario 2). Since natural gas is less polluting than coal, it makes no sense to replace gas but keep using coal, so nuclear replaces gas is not considered. Considering the uneven domestic resource of uranium and thorium, their share of energy generation is split into 36.61% of uranium-fueled reactors and 63.39% of thorium-fueled reactors. Both BN-1200 and MSBR are used in this study. Since the RUEN projection is limited to 2050, it was assumed that the energy consumption beyond 2050 is flat.

The expected energy generation from coal and gas in RUEN is provided in Table 4.

Table 4. Fossil energy generation in 2050 according to RUEN

	Coal	Gas	Total
Energy Generation (MTOE)	255.9	242.9	498.8
Energy Generation (TWh)	2976.12	2824.93	5801.04

The calculation result is shown in Table 5.

Table 5. Nuclear fuel sustainability using two scenarios

	Scenario 1		Scenario 2	
	Uranium	Thorium	Uranium	Thorium
Replacement energy (TWh)	1089.54	1886.58	2123.72	3677.32
Generating capacity (GWe)	138	239	269	466
Fuel sustainability (years)	701.26	729.83	359.77	374.42

Due to a small difference in thermal efficiency of BN-1200 (42.1%) and MSBR (44.44%), thorium consumption in MSBR is slightly lower than uranium consumption in BN-1200. In short-term, this difference might be trivial. In longer term, however, lower thorium consumption lead its sustainability to be 14-28 years longer than uranium. In a bigger picture, if nuclear were used to replace coal only, both uranium and thorium can last for at least 700 years, a significantly longer timescale compared to current fossil fuel sustainability. In Scenario 2, nuclear fuel can last for more than 350 years. For a mined mineral, nuclear fuel is extremely sustainable.

Considering that a large number of NPPs that must be built to replace coal and gas altogether, it may be unrealistic within the timescale to 2050. If we consider that the first build of MSBR or BN-1200 is in 2030, until 2050, around 37 GWe-worth of breeder reactors must be built annually. A significant increase of industrial capacity must be met in order to comply with this construction capacity, and it will be quite a challenge to do that. Energy generation beyond 2050 will not be flat either as being considered in this study, so that the sustainability of domestic nuclear fuel resources can be diminished faster.

Nevertheless, a long sustainability of nuclear fuel using closed fuel cycle will allow humanity to discover more nuclear fuel resources from unexplored sites, maturing the technology to extract uranium from seawater, and commercialising nuclear fusion. Since the timeline of climate change mitigation is under a century anyway, massively using breeder reactor in closed fuel cycle can effectively provide a rapid and sustainable pathway to reduce carbon emissions in Indonesia without compromising grid reliability and energy affordability.

Conclusion

Nuclear fuel cycle can be deployed either in open fuel cycle or closed fuel cycle. Using open nuclear fuel cycle, the sustainability of nuclear energy using domestic fuel resources is far from adequate, even by assuming unrealistic scenario of 100% exploitation. On the other hand, by using closed nuclear fuel cycle, the maximum potential of nuclear energy can be utilised. If Indonesia were to build a total 736 GWe-worth of NPPs in 2050, referring to existing RUEN, coal and gas consumption can be completely eliminated, ensuring that 80% of Indonesian energy generation is low-carbon. It is worth noting that breeder reactor, the key of closed nuclear fuel cycle, is far from commercial, especially MSBR-type reactors. Moreover, Indonesia is not permitted to reprocess spent fuel, further exacerbating the issue. Online fuel reprocessing inherent to MSR can potentially overcome this issue, although fast-spectrum MSR must be developed in order to close uranium fuel cycle.

Nuclear power has a strong case of being sustainable as long as closed nuclear fuel cycle can be achieved. It is technically plausible, but a lot of development is necessary. In the meantime, open fuel cycle can be deployed and the resulting spent fuel need not to be disposed directly, instead stored temporarily to be later used in a GenIV breeder reactor. This way, the benefits of low-carbon energy inherent in nuclear power can be deployed without the need to wait for closed fuel cycle.

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