

# ASSESSMENT OF GLOBAL NUCLEAR ENERGY STRATEGY WITH OPTIMAL NUCLEAR FUEL CYCLE MODEL

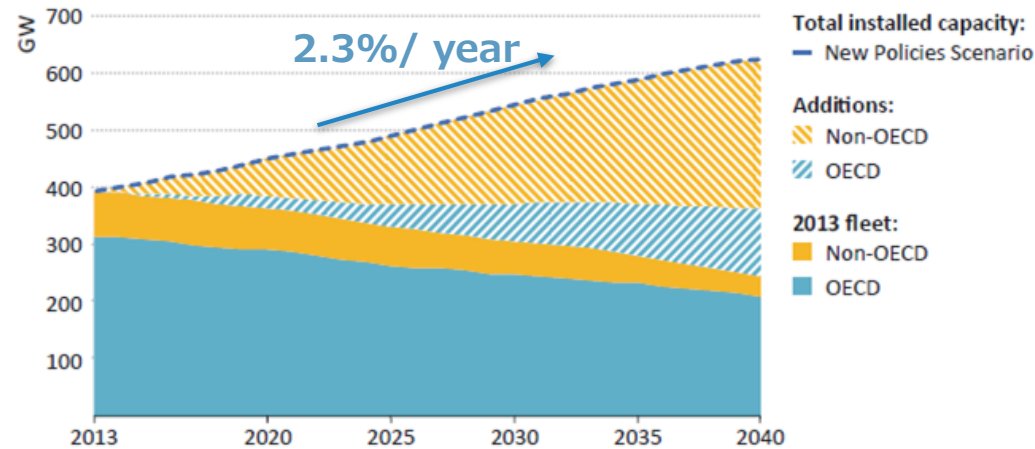
Undarmaa Baatarkhuu  
The University of Tokyo  
FUJII-KOMIYAMA Laboratory

- Research Overview**
- Current Work: Competitiveness with Coal-fired Power**
- Results**
- Future Work**

# Background

- Nuclear power capacity increases by almost 60%, from 392 GW in 2013 to 624 GW in 2040

Current policies and policy proposals:  
World Energy Outlook 2014.  
New Policies Scenario



Transition of nuclear power capacity by region

## Future Challenges in Nuclear Power

- Stability of fuel supply
- Economics
- Nuclear non-proliferation
- Nuclear safety



## Consideration of Future Nuclear Fuel Cycle

- Generation III and IV reactors, FBRs ...
- Undiscovered resources
- Unconventional uranium resource: phosphates, seawater uranium
- Alternative fuel cycles based on thorium

## Objective of this study

Analysis of the **optimal nuclear power generation** and the flow of the nuclear material, using a nuclear fuel cycle model.

# Model

Determines the **economically rational optimal operation** through minimization of the **total expenses for electricity generation** within the target period, expressed in present value of money.

## Features

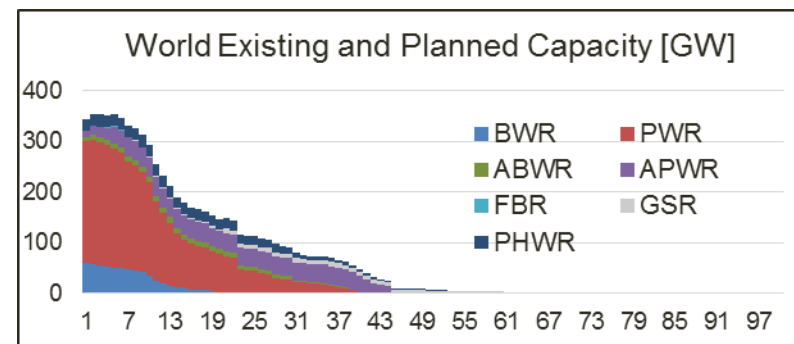
- Analysis of **long-term operation**  
-100 years
- Transition of **Pu isotopic composition**  
-due to radioactive decay
- Consideration of **technology trends**  
-Advanced LWRs, recycling, seawater Uranium, Thorium utilization
- **Resource limitation**

## Target processes

- Uranium/thorium procurement
- Uranium enrichment
- UOX/MOX fuel fabrication
- Heavy water production
- Electricity generation
- Storage
- Reprocessing (U/Pu cycle)
- Vitrification
- Direct disposal

## Power Generation

- Existing Reactors: IAEA. World Nuclear Reactors(2015)



- Advanced LWR (GEN III, III+)
- Fast Breeder Reactor
- High Temperature Gas Cooled Reactor
- Thorium fuel: HWR, LWR

# Method

## Linear Programming

Minimize the **object function**(linear) while satisfying the given **constraints**(linear).

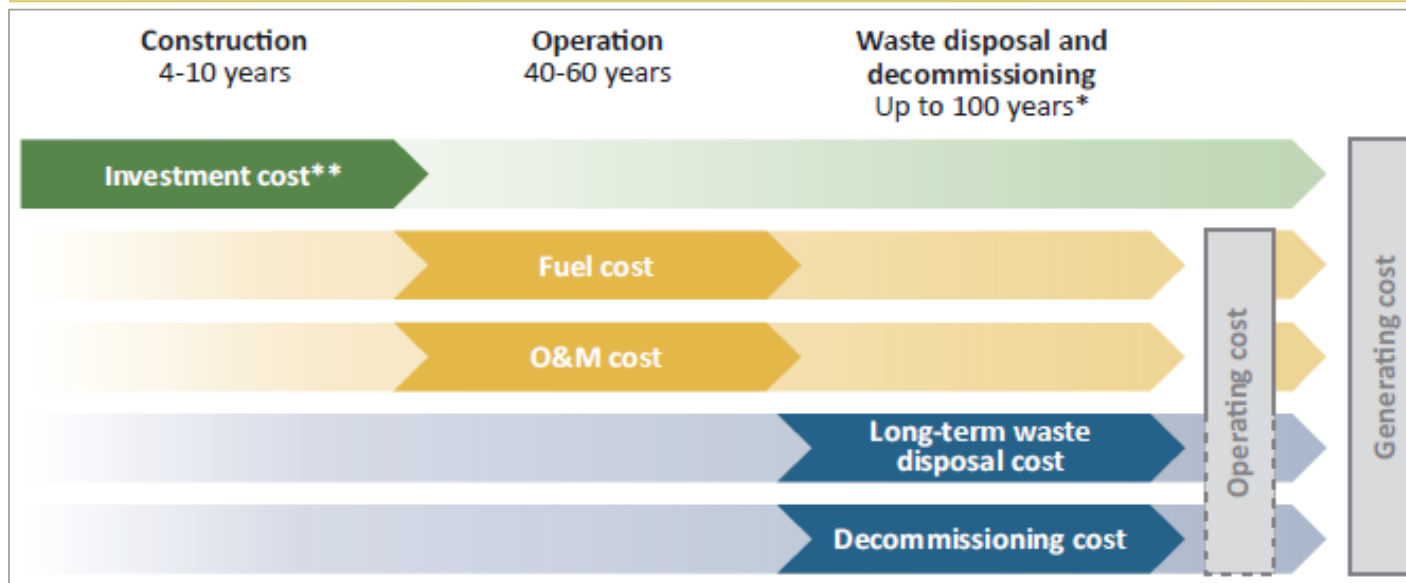
### Objective function

#### Overall cost of nuclear fuel cycle (Economy)

$$Obj = \sum_y \sigma \times (f_c + v c_y)$$

$\sigma$  term of discount rate,  $f_c$  fixed cost,  $v c_y$  variable cost,  $y$  time point

- Fixed cost: capital cost of facilities
- Variable cost: fuel and operation costs



# Method

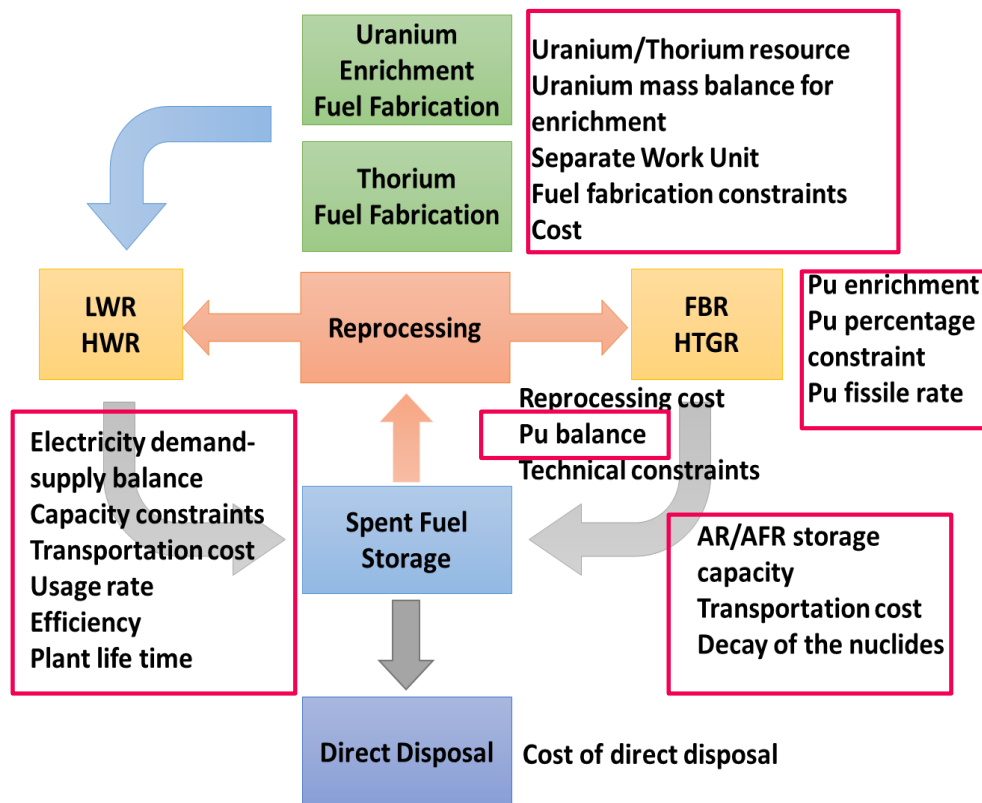
## Linear Programming

Minimize the **object function**(linear) while satisfying the given **constraints**(linear).

### Constraints

#### Various constraints on operation

- Electricity supply-demand balance
- Capacity constraints of facilities
- Sf storage capacity(AR,AFR)
- Mass balance of materials (U, Pu, Th)
- Resource limit of uranium
- Pu enrichment limitation etc.. at each stage



# Method

## Transition of Isotopic Composition Ratio of Plutonium

Nuclide	Fissile	Half-life
$^{238}\text{Pu}$	×	87.74
$^{239}\text{Pu}$	○	24110
$^{240}\text{Pu}$	×	6564
$^{241}\text{Pu}$	○	14.29
$^{242}\text{Pu}$	×	373300

Spent Fuel Cooling/Storage



Change in Pu composition ratio



Mass balance in  
Reprocessing/MOX fabrication

### Mass balance of Plutonium

$$\begin{aligned}
 & NFI_{i,\text{Pu}} \times \text{Fuel}_{i,y+Lfr} \\
 &= EFP_i \times (VT_{y-y0,f,\text{Pu}} \times RPF_{y,y0,i,f} \\
 &+ VT_{y-y0,s\text{Pu},\text{Pu}} \times SPu_{y,i})
 \end{aligned}$$

*i* fuel, *f* spent fuel, *sPu* separated Pu, *NFI* isotopic composition of fuel, *Fuel* amount of fuel fabricated, *Lfr* time lag from reprocessing to fuel fabrication, *EFP* efficiency of fabrication for fuel *i*, *VT* Pu isotopic composition after *y-y0* years, *RPF* amount of spent fuel to reprocess, *Spu* amount of separated Pu for fuel

# Scenario Settings: Resource and Demand

## Natural Uranium

Cost increases with the supply, according to resource grade

Resource category	Identified	Undiscovered	Total
<40\$/kgU	0.68	-	0.68
<80\$/kgU	1.96	0.67	2.62
<30\$/kgU	5.90	3.86	9.77
<260\$/kgU	7.63	4.70	12.33

World uranium resources Mt by end-2013. WEO 2014.

## Seawater Uranium

Annual O&M Cost Rate	0.03
Life Time [year]	15
Electricity Consumption [GWh/t]	0.5
Variable Cost [\$/kg SWU or HM]	1230
Construction Cost[\$/kg /year]	1775

Science & Global Security, 21:134–163, 2013

## Thorium

OECD/NEA Uranium 2014

Initial price 80\$/kg Th

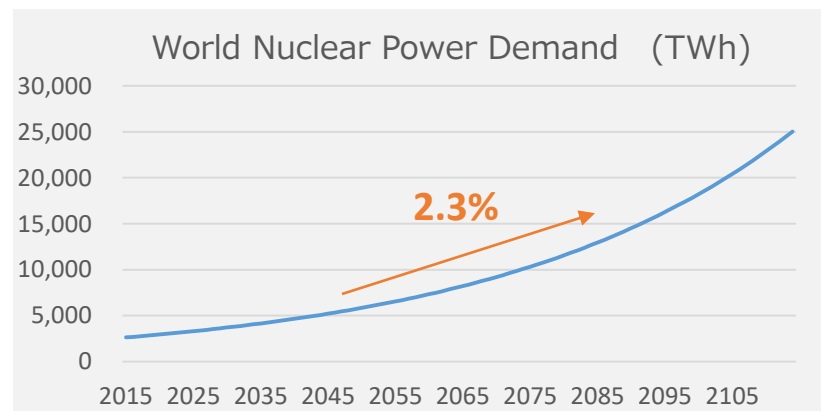
Annual increase rate 0.5%

## Nuclear Power Demand

Outlook for Nuclear Power. WEO 2014

2461 TWh(2012) + 2.3%/year until 2040

Increase rate assumed to remain constant during the calculation period.



# Scenario Settings: Cost

## Reactor Capital Costs

Reactor type	Construction cost [\$/kW]	Decommissioning cost [\$/kW]
BWR, PWR	2000	500
ABWR, APWR	2000	500
FBR	2500	500
FR, HTGR	2000	500
HWR	2200	500

## Fuel Cycle Costs

Cycle cost [\$/kg SWU · HM]	
Uranium enrichment	118
UOX fuel fabrication	275
MOX fuel fabrication	325
Heavy water production	300
UOX reprocess	800
MOX reprocessing U235, Pu	800
Spent fuel transport	160
Vitrification	90
Direct disposal	350

- IAEA. *Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems*. (2012)
- OECD NEA. *Costs of Decommissioning Nuclear Power Plants*. (2016)
- 電力事業連合会. コスト等検討小委員会. (2003)

# Scenario Settings: Other

## Global spent fuel in AR and AFR interim storage 258,700 t HM

IAEA. Nuclear Technology Report. 2015

- Subject to reprocessing
- Considered as LWR spent fuel at AFR site

## Separated Plutonium 505 t

IPFM. Global Fissile Material Report. 2015

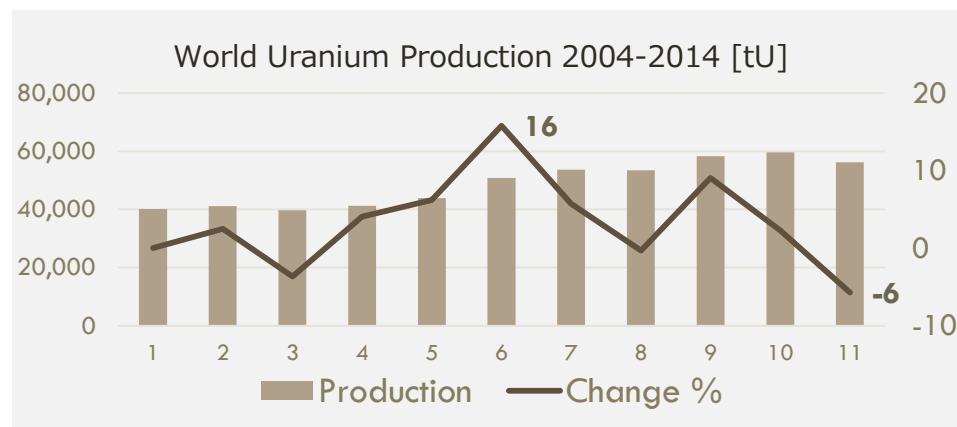
- Subject to MOX fuel Fabrication
- Storage cost 1000\$/kg-Pu/year

## Growth rate Constraint for Natural Uranium demand

$$unt_{y+1} \leq (1 + LU) \times unt_y$$

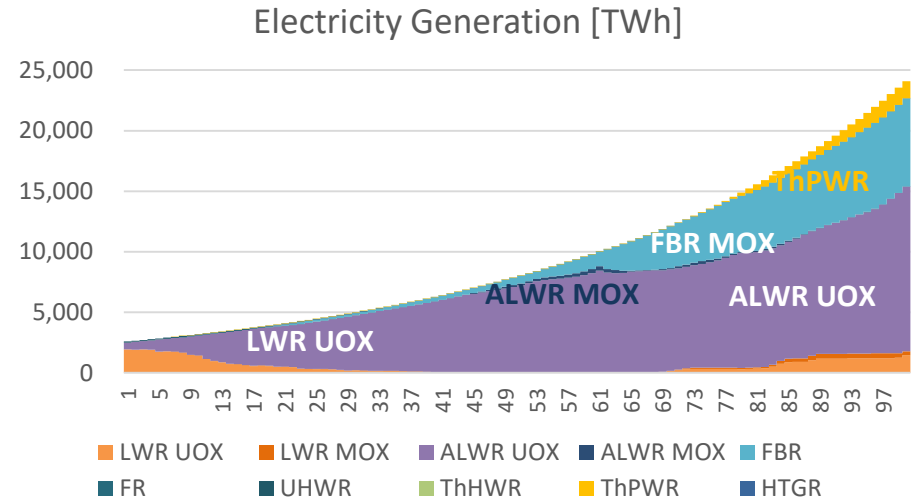
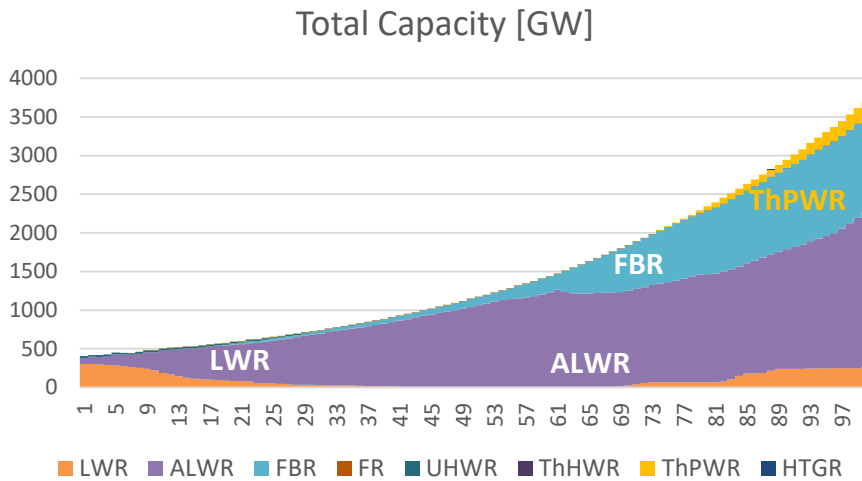
$$(1 - LL) \times unt_{y-1} \leq unt_y$$

$unt_y$  Natural uranium supply in year  $y$ ,  $LU$ : growth rate upper,  $LL$ : growth rate lower



# Results

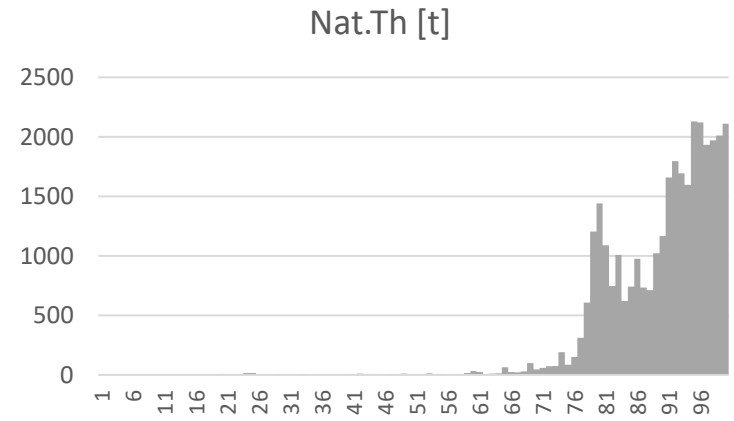
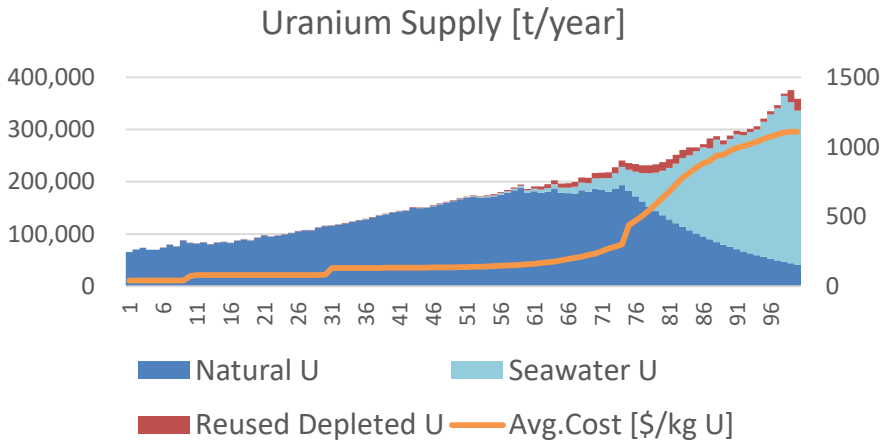
## Power Generation



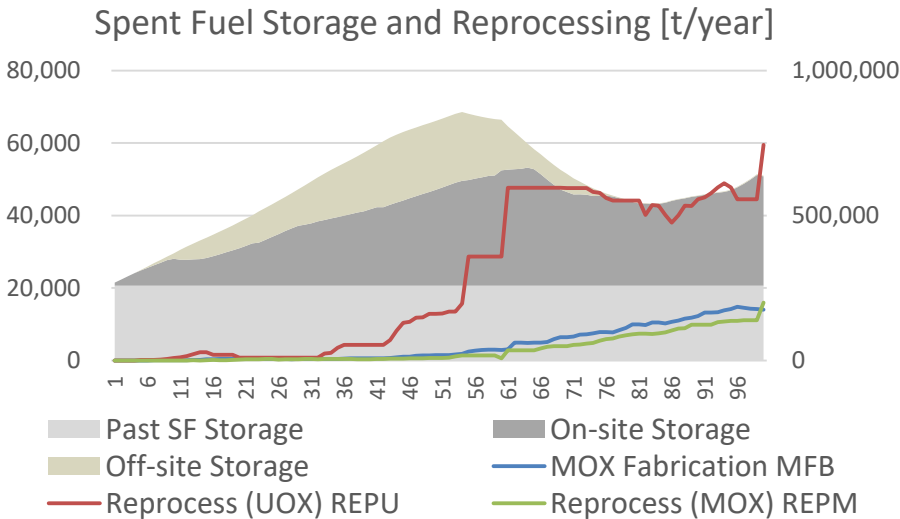
- Current LWR fleet was replaced with **advanced LWRs**
- Uranium price increases and MOX generation becomes economically competent → **Large scale deployment of FBRs** in the second half
- LWR reactor with **Thorium MOX fuel** also becomes economical, however the proportion was small, due to relatively low efficiency and availability of plutonium.

# Results

## Uranium Supply



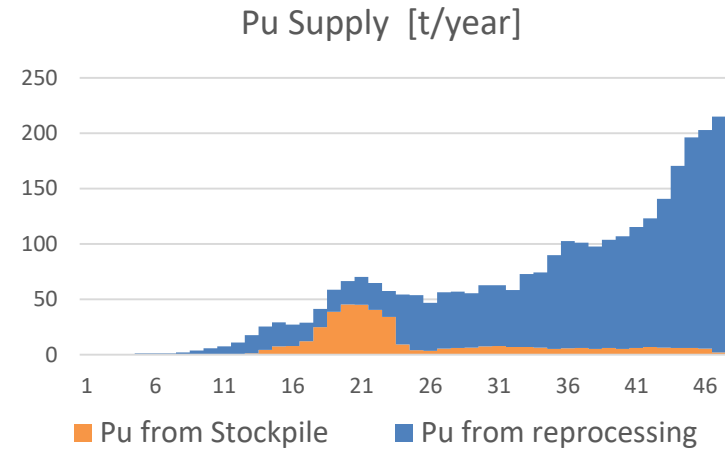
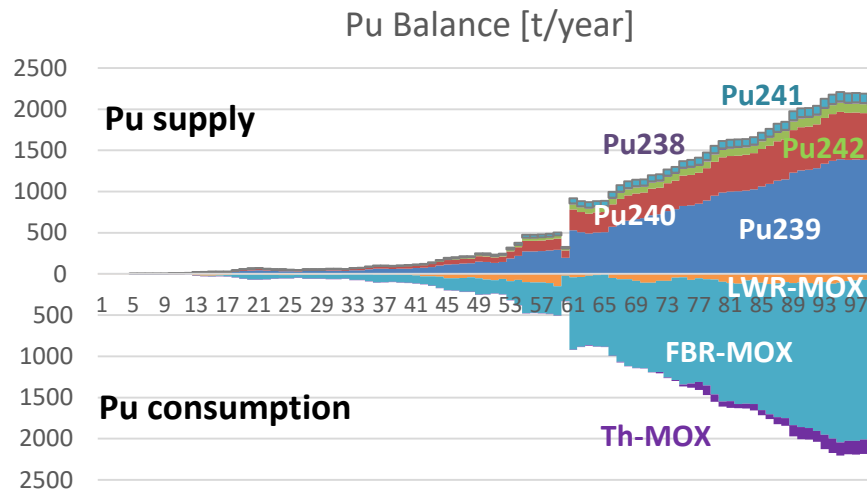
## Spent Fuel and Reprocessing Plutonium



- Reprocessing and MOX fabrication increase as Uranium price grows
- Spent fuel storage decreases as reprocessing increase
- Spent fuel from the past was not reprocessed because of lower rate of Pu, compared to discharged fuel

# Results

## Plutonium Balance

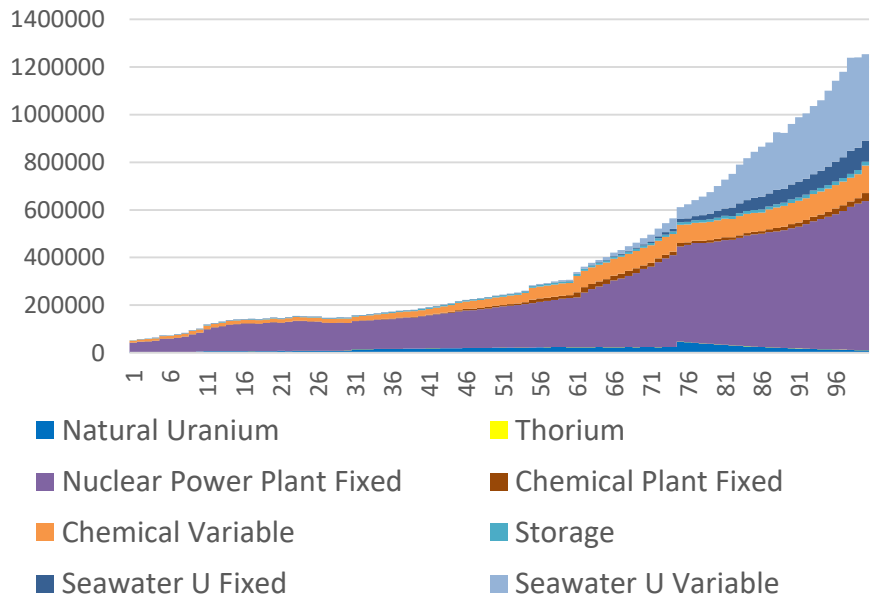


- Plutonium balance stabled around 2500 t/year at the end
- Current Plutonium stockpile was used up in early stage

# Results

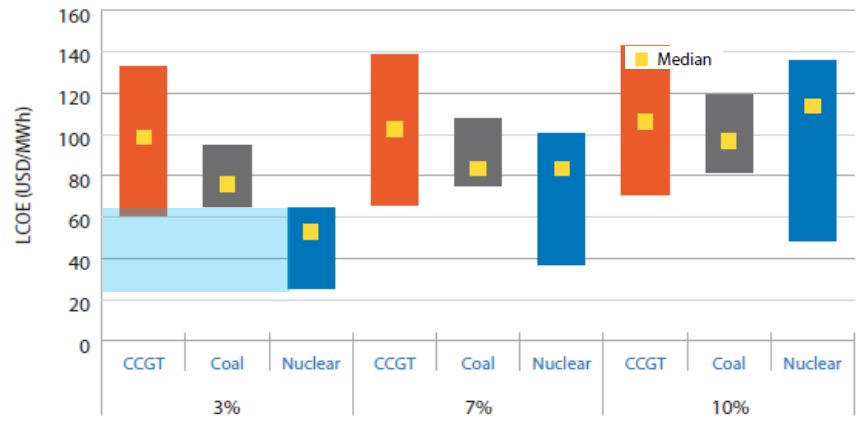
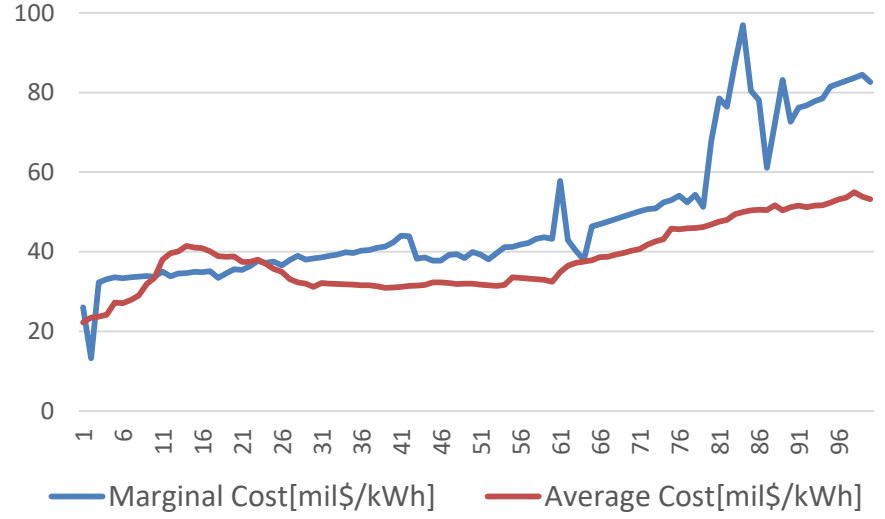
## Cost Structure

Cost Structure [Million \$/year]



- About 80% is fixed cost of NPPs
- Fuel cost proportion grows with U from seawater
- Electricity price within the period is consistent with projection by IEA

Electricity Cost [\$/MWh]



OECD/IEA-NEA, Projected Costs of Generating Electricity, 2015

# Competitiveness with Coal-fired Power Plants

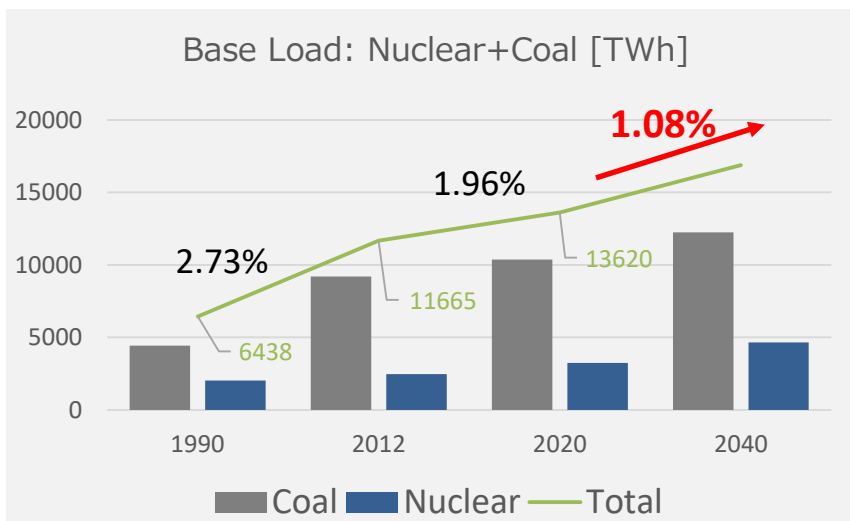
Base Load Share: Nuclear power demand is decided by **competitiveness with thermal power generation**



Estimate the **impact of measures against global warming on use of nuclear energy** in the model :CO<sub>2</sub> tax, CO<sub>2</sub> emission limit etc.

## Base Load Demand

World Energy Outlook 2014. New Policies Scenario



## Coal Price

IEA. Resources 2013

Increases with the supply, according to resource category.

## Electricity demand-supply balance

$$\sum_p gen_p + \sum_{cp} gen_{cp} = Load + X_i \times swu$$

$p$ : nuclear power plant,  $cp$ : coal power plant,  $X_i$ : electricity consumption of chemical plants,  $Load$ : electricity demand

## Objective Function

$$Obj = \sum_y \sigma \times (f_c + v c_y + CO2tax + STC)$$

$\sigma$  term of discount rate,  $f_c$  fixed cost,  $v$  variable cost,  $y$  time point,  $CO2tax^y$  carbon tax,  $STC$  carbon storage cost

# Competitiveness with Coal-fired Power Plants

## Power Plant Parameters

	Coal	CCS Coal	IGCC-CCS
Efficiency	0.39	0.39	0.431
Annual O&M cost rate	0.048	0.048	0.048
Own consumption rate	0.06	0.06	0.06
Life time [year]	40	40	40
Heat content [GWd/t]	3.08E-04	3.08E-04	3.08E-04
Carbon intensity [kg C/kWh]	2.28E-01	2.28E-01	2.28E-01
Capital cost [\$ /kW]	1500	1625	1950
Capture rate	0	0.9	0.9
Electricity for capture/storage	0	0.815	0.269
Carbon storage cost [\$ /kg-C]	0	0.05	0.05

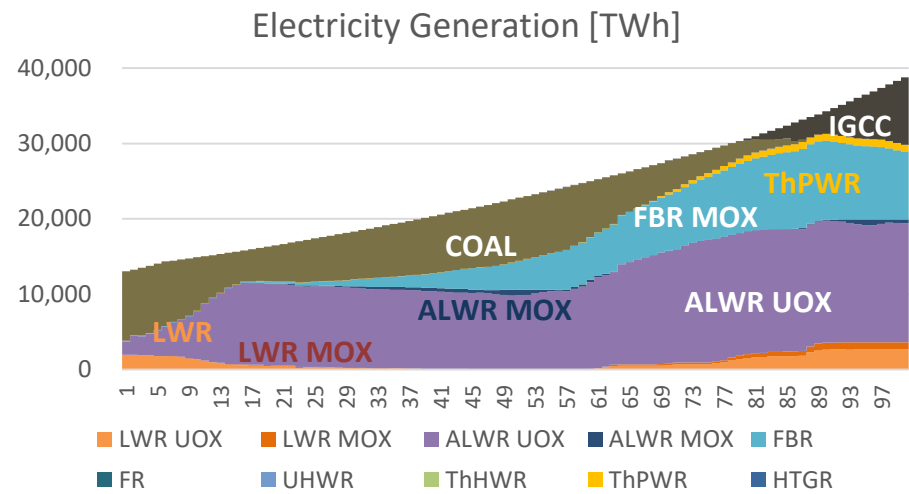
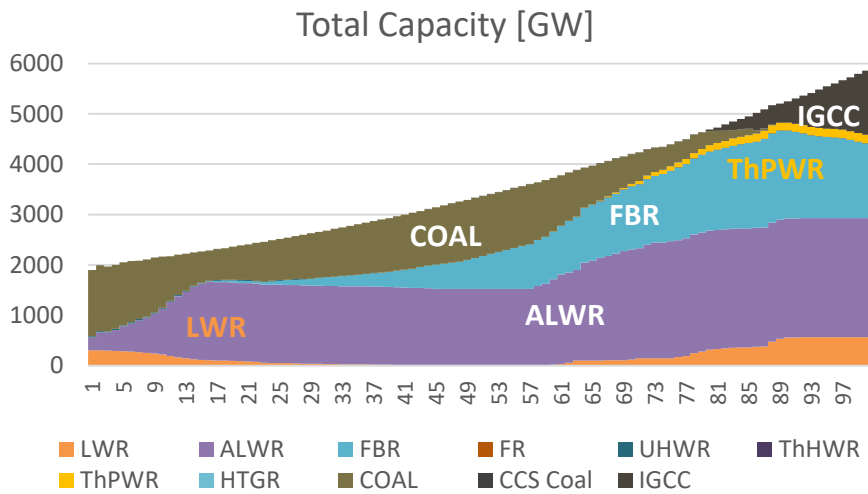
### Result Example: Carbon Budget Scenario

IPCC: to have 50% chance of meeting the internationally agreed goal of **limiting the temperature increase to 2°C**, the world cannot emit more than a total of around **1000 Gt of CO<sub>2</sub> from 2014 onwards**.  
*IEA WEO 2014*

- Limit of total carbon **emission from coal-fired** within the calculation period: **120 Gt-C** (44% of total carbon budget)

# Effect of Carbon Budget (Example)

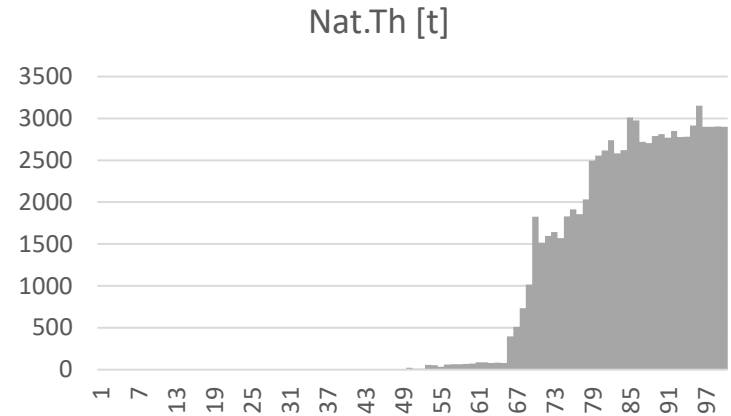
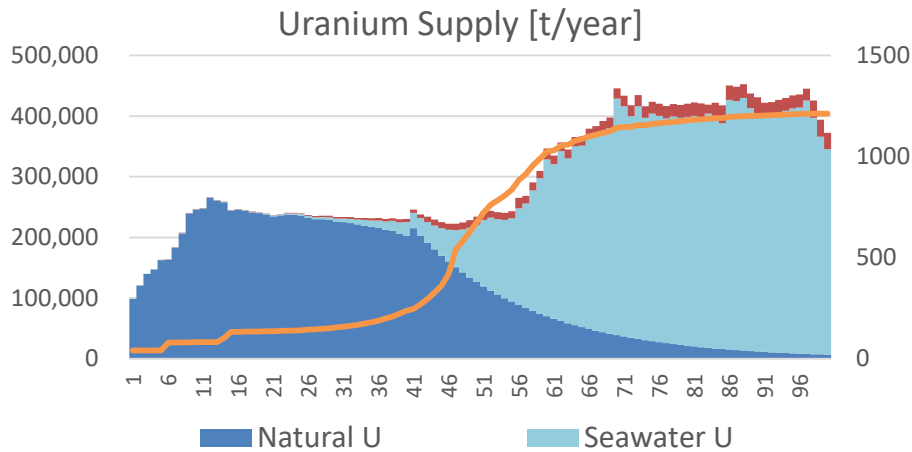
## Power Generation



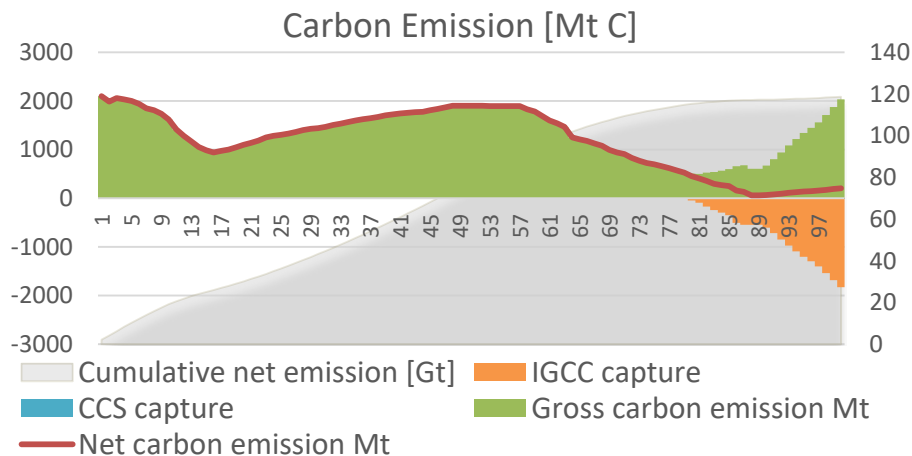
- Due to the carbon emission constraint, proportion of nuclear was large
- Coal-fired power plant was used due to its cost competitiveness
- Carbon budget was used up about in 80 years
- Coal fired IGCC-CCS power generation starts growing afterwards, due to low emission and economic competitiveness

# Effect of Carbon Budget (Example)

## Uranium Supply



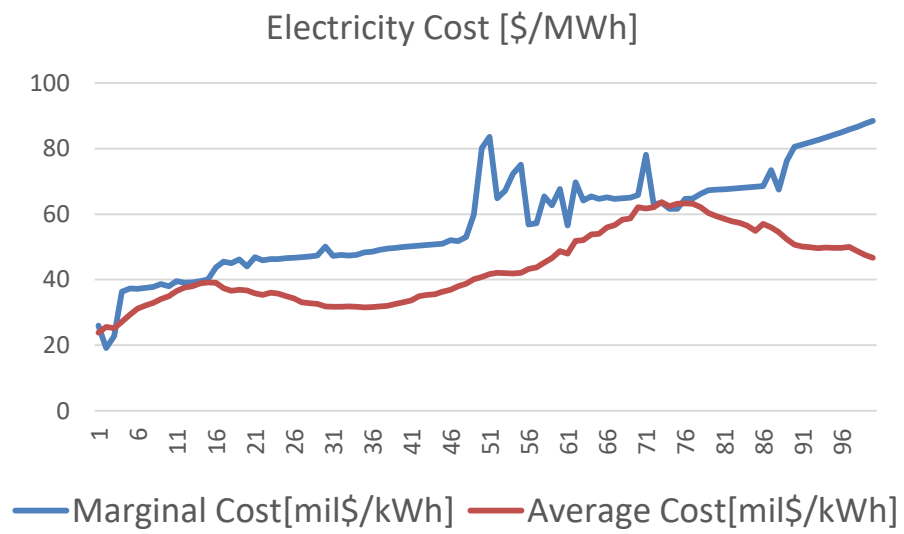
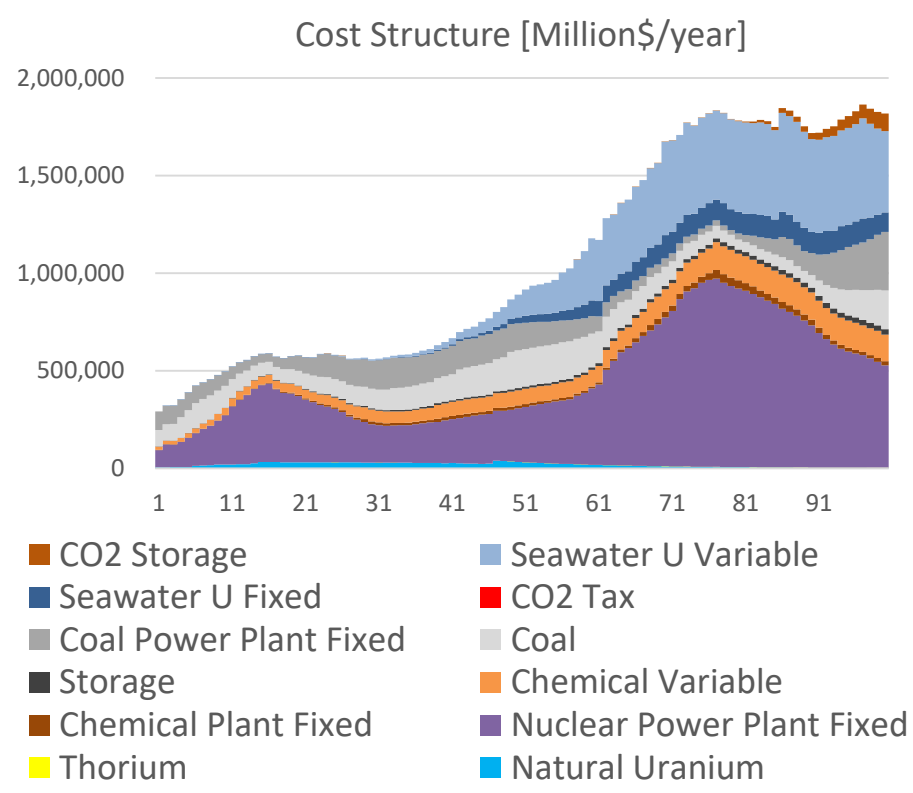
## Carbon Emission



- Total carbon emission remains under budget with deployment of Carbon Capture and Storage.

# Effect of Carbon Budget (Example)

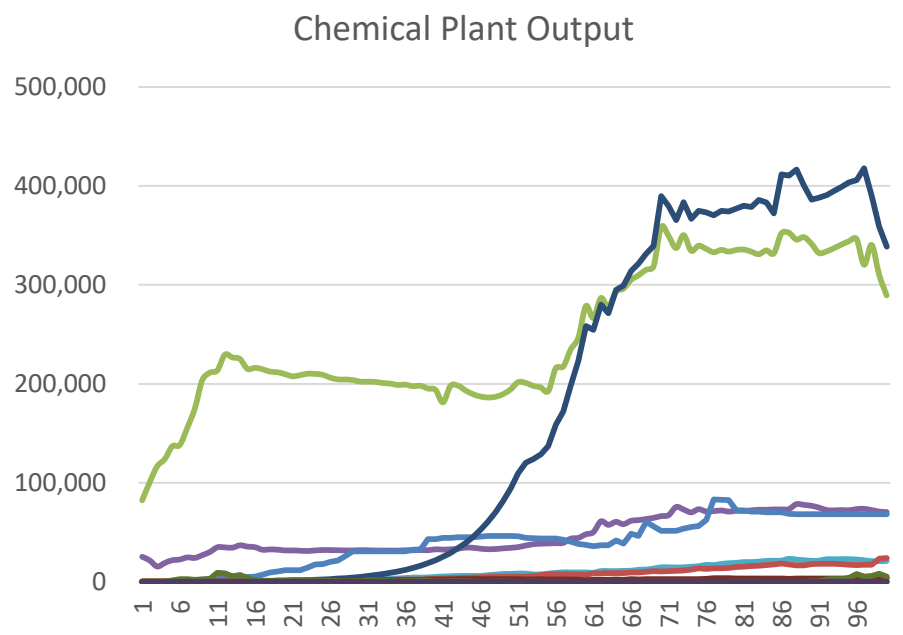
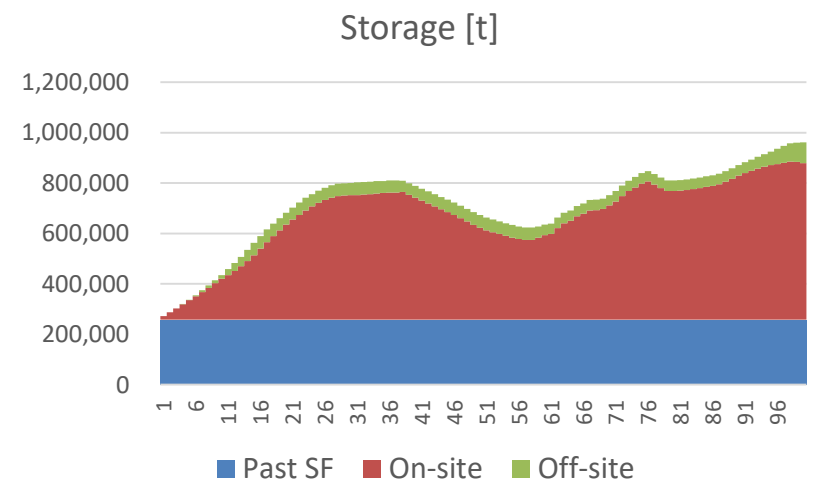
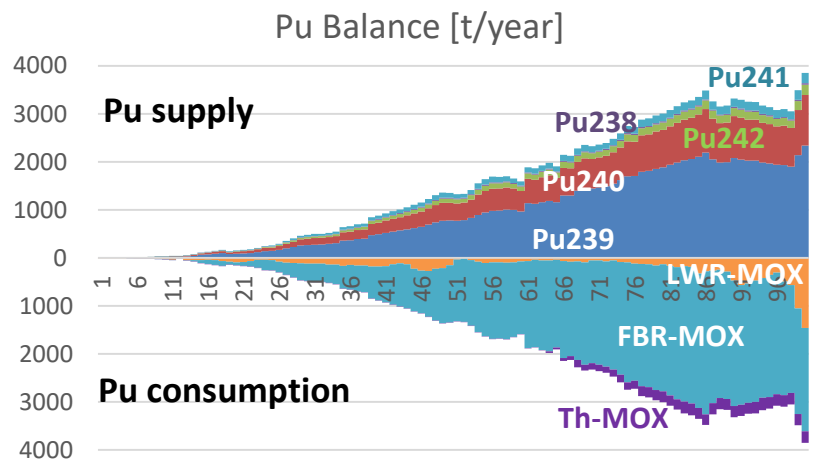
## Cost Structure



- Average cost decreases as proportion of coal power increases
- Electricity cost remains low despite the use of seawater uranium, with the contribution of IGCC-CCS

# Effect of Carbon Budget (Example)

## Other Fuel Cycle Activities



- Enrichment ENR
- MOX Fabrication MFB
- Reprocess (MOX) REPM
- Uranium from Seawater SWUR
- SF Transportation TRA
- UOX Fabrication UFB
- Reprocess (UOX) REPU
- Heavy Water Production HWP
- Vitrification VIT
- SF Direct Disposal DDS

# Tasks

## **Sensitivity analysis:**

- Fuel/Cycle Cost
- Plutonium consumption etc.

## **Calculations for various scenarios**

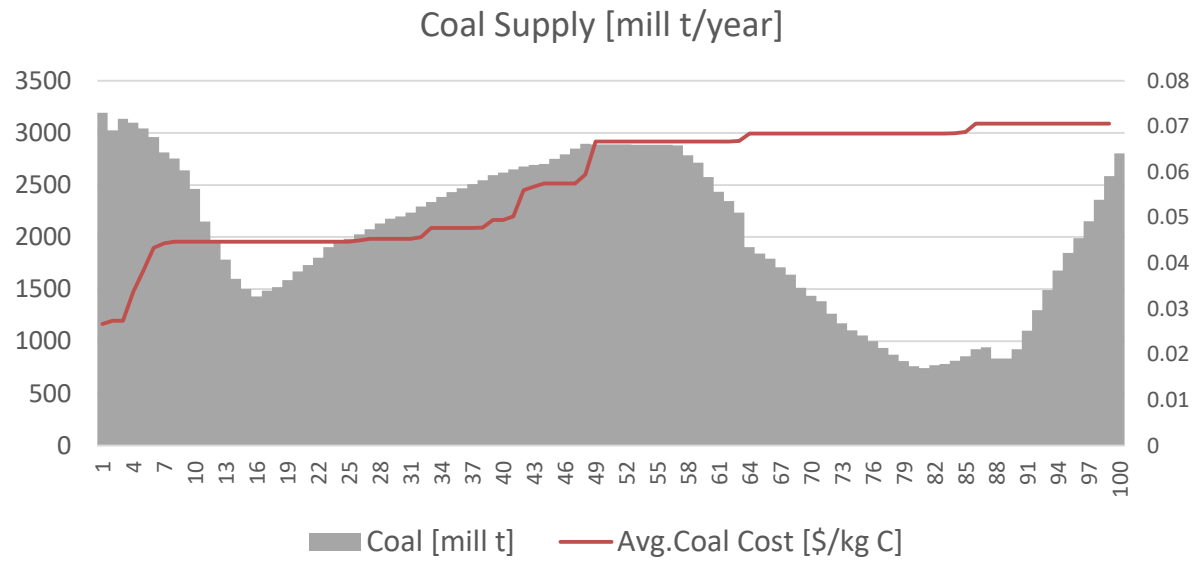
- BAU only etc.

## **Consideration of Recovered Uranium and Thorium recycle**

## **Advanced analysis on back-end:**

- Volume of fuel for direct disposal
- MA content etc.

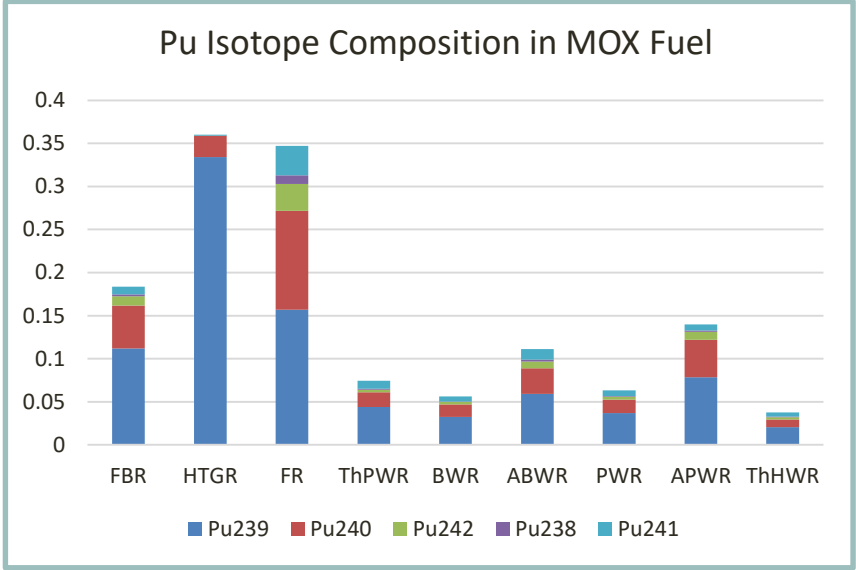
# Coal Price



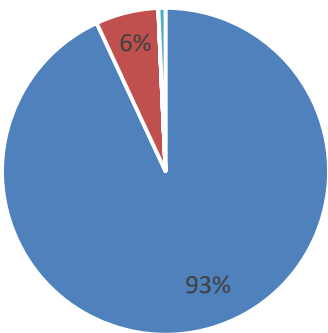
## Parameters of Nuclear Reactors

		Efficiency	Operating period	Burnup GWd/t
Boiling Water Reactor	BWR	0.33	40	30
Pressurized Water Reactor	PWR	0.33	40	30
Advanced BWR	ABWR	0.33	60	45
Advanced PWR	APWR	0.33	60	48
Fast Breeder Reactor	FBR	0.406	40	75
Fast Reactor	FR	0.42	40	90
HWR Nat.U	UHWR	0.29	60	8.5
HWR Th/Pu MOX	ThHWR	0.32	60	20.2
PWR Th/Pu MOX	ThPWR	0.324	60	40.5
High Temperature Gas Reactor	HTGR	0.45	40	651

- IAEA. Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems. (2012)
- Hirohide Kofuji, Kiyoshi Ono. Transition of Plutonium Isotopic Composition by multi-recycling.(1997)



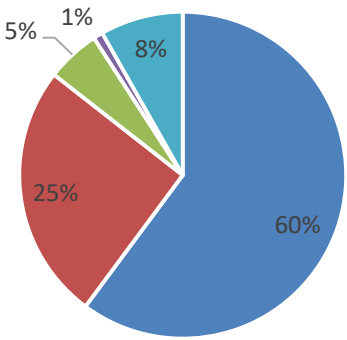
Military Pu [150 t]



Pu239 Pu240 Pu242 Pu238 Pu241

**AEC Introduction to Nuclear Weapons 1972**

Civilian Pu [271 t]



Pu239 Pu240 Pu242 Pu238 Pu241

**Separated from BWR-UOX**

# APPENDIX 4

	Enrichment	UOX Fabrication	MOX Fabrication	Reprocessing (UOX)	Reprocessing (MOX)	Heavy water production	Seawater Uranium Recovery	Vitrification	SF Transportation	SF Direct Disposal
	ENR	UFB	MFB	REPU	REPM	HWP	SWUR	VIT	TRA	DDS
Loss Rate of Material	0.005	0.001	0.001	0.005	0.005	0.005	0	0	0	0
Annual O&M Cost Rate	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.05	0.05	0.05
Life Time [year]	40	40	40	40	40	40	15	40	40	40
Usage Rate	0.9	0.9	0.9	0.9	0.9	0.6	1	0.9	0.9	0.9
Electricity Consumption [GWh/t or tSWU]	0.05	0	0	0	0	2.4	0.5	0	0	0
Legal Durable Period [year]	15	15	15	15	15	15	15	15	15	15
Loan Period [year]	15	15	15	15	15	15	15	15	15	15
Variable Cost [\$/kg SWU or HM]	118	275	325	800	800	300	1230	90	160	600
Construction Cost [\$/kg SWU or HM/year]	1	1	6000	3600	6000	6000	2610	1	1	1

	SF Storage	Depleted Uranium Storage	Recoverd Uranium Storage	Pu Storage
Loss Rate of Material	0	0	0	0
Annual O&M Cost Rate	3.00E-02	0.03	0.03	0.03
Life Time [year]	100	100	100	100
Usage Rate	1	1	1	1
Legal Durable Period [year]	15	15	15	15
Loan Period [year]	15	15	15	15
Construction cost [\$/kg HM]	63	1	63	63
Cost per year [\$/kg HM or Pu]	2.4	1	1	1000