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sck cen
Exploring
a better tomorrow

First approach to the LCOE with ANICCA

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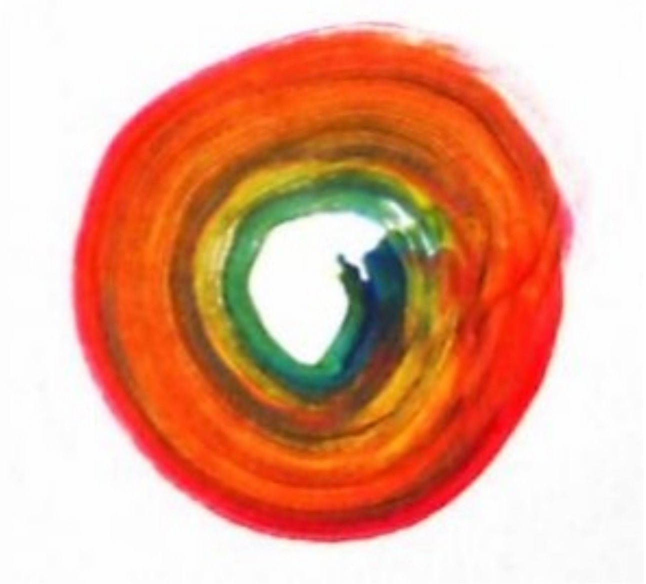
- ANICCA code
- Economic module
- Results for a fuel cycle scenario
- Summary and future works

ANICCA code

- A homemade SCK-CEN code.
- Designed to be a flexible tool to simulate nuclear fuel cycle scenarios
- Written in Python (v3.9)
- Material flows as packages.
- Each package contains:
  - ✓ Isotopic vector (all available in the Evaluated Nuclear Data File)
  - ✓ Amount
  - ✓ Name
- It uses reactor libraries from Aleph2 or Serpent

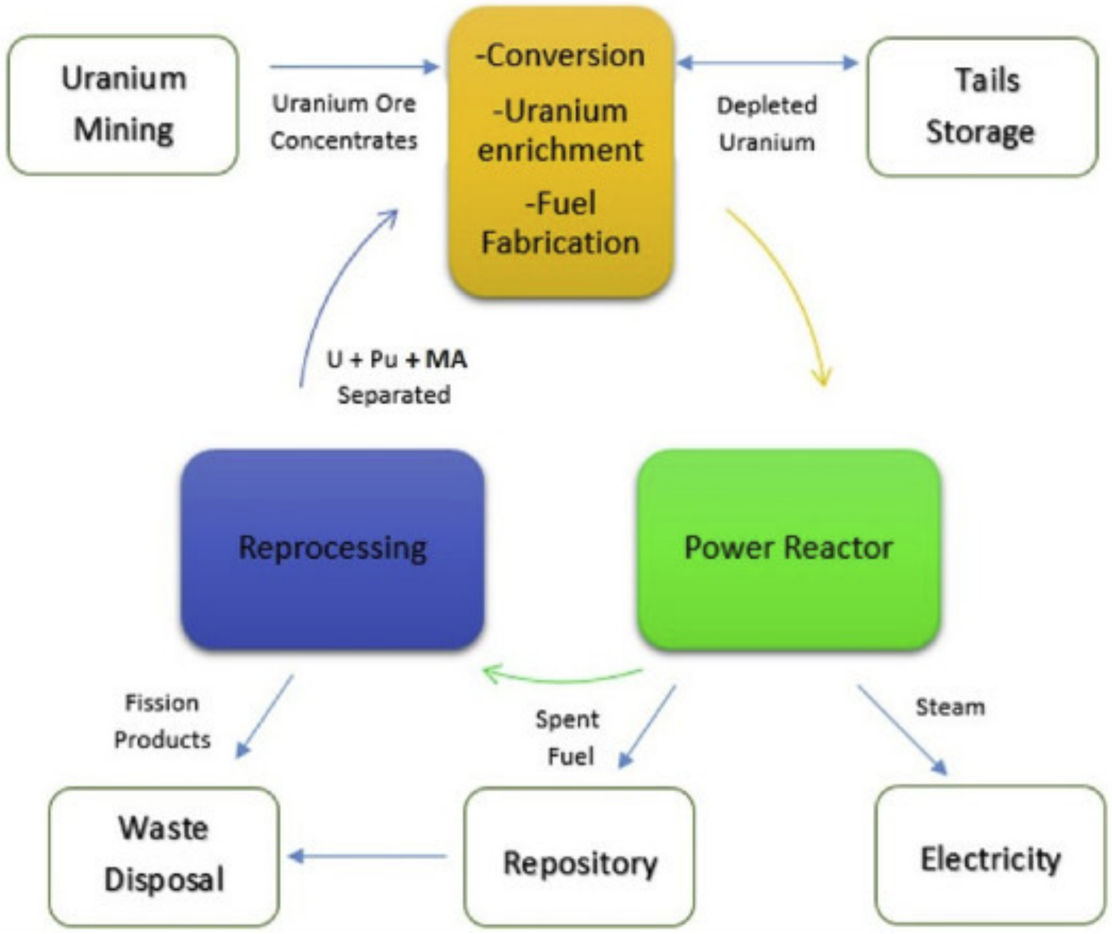


ANICCA code

- ANICCA can model different FC strategies

- …and different facilities:
  - ✓ Mining
  - ✓ Fuel Fabrication plant
  - ✓ Different reactors
  - ✓ Reprocessing plant
  - ✓ Repositories (interim or final)

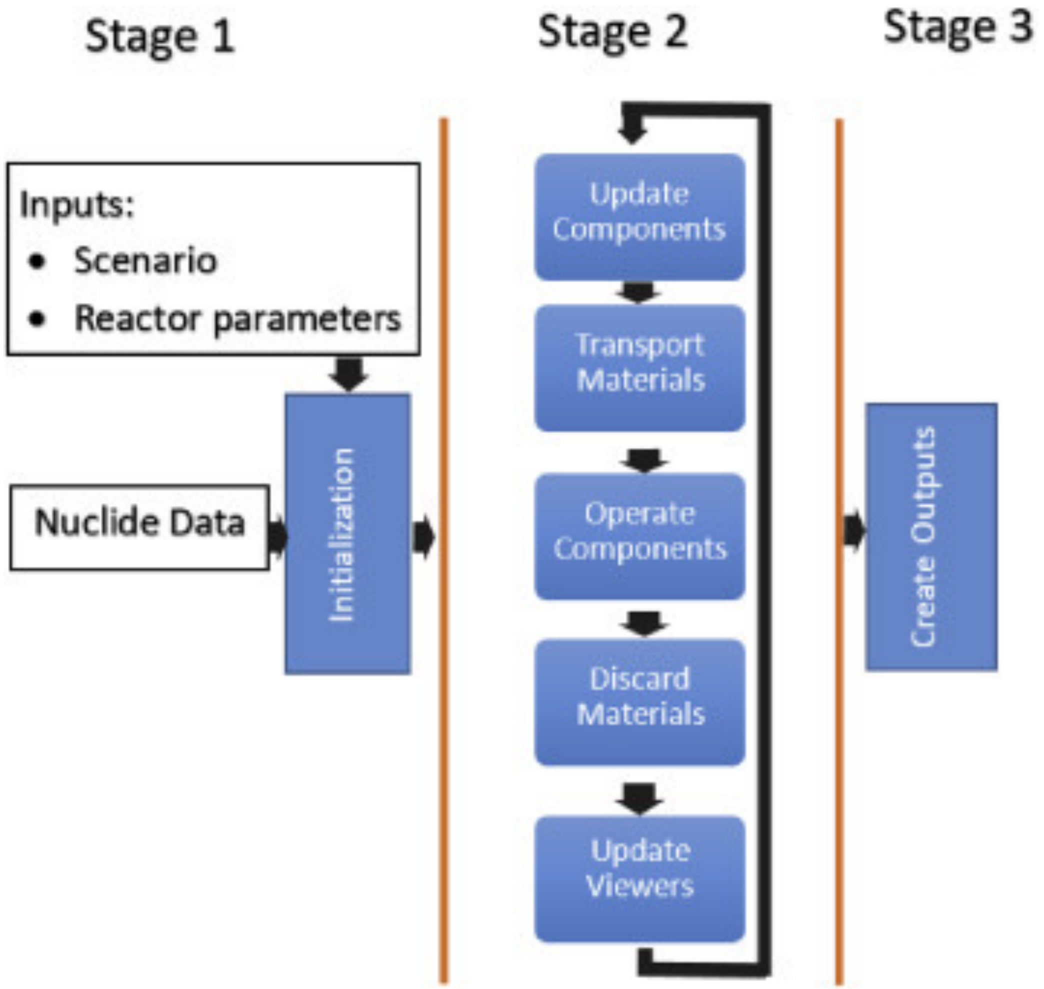
- It is possible to add external materials or an initial legacy



ANICCA code

- Inputs:
  - Scenario (parameters, facilities, connections, outputs)
  - Reactor parameters (Power generation, BU, etc.)
  - Nuclear data (ENDF, reactor XS)

- Outputs:
  - Resources (and other FC parameters)
  - Economics parameters (new)



ANICCA runtime

ANICCA outputs

Resources and other parameters

- Material mass and composition in any facility
  - ✓ By isotopes
  - ✓ By elements
- Radiotoxicity and decay heat
- Fuel fabrication parameters
  - ✓ SWU
- Power production and installed

Economic parameters

- Electricity generation by reactor
- Installed Capacity by reactor
- Reactor In/out
- Storage Capacities
- Material movement
- Parameters for UOX and MOX fuels
- Material reprocessed

ANICCA Economic output (example)

- This is an example of an input for the economic module
- Special ID words are used to name the columns

	A	B	C	D	E	F	G	H	I	J	
1		PWR_UOX-installed	PWR_UOX-thermal	PWR_UOX-netpower	PWR_UOX-loadfactor	PWR_UOX-generated	PWR_UOX-IN	PWR_UOX-OUT	PWR_UOX-BU	PWR_UOX-uoxfuelcost-NAT-UOX	PWR_UOX-uoxfu
2	2038	720	2200	0	0	0	0	0	0	320.0467489	
3	2039	720	2200	0	0	0	0	0	0	390.2556109	
4	2040	720	2200	0.411364	0.9	0.3702276	0.601409	0	60	460.4646564	
5	2041	720	2200	0.822727	0.9	0.7404543	0.601409	0	60	530.6736917	
6	2042	720	2200	1.234091	0.9	1.1106819	0.601409	0	60	600.8825639	
7	2043	720	2200	1.645455	0.9	1.4809095	0.601409	0	60	671.0915992	
8	2044	720	2200	2.056818	0.9	1.8511362	0.601409	0	60	741.3004713	
9	2045	720	2200	2.468182	0.9	2.2213638	0.601409	0	60	811.5095066	
10	2046	720	2200	2.879545	0.9	2.5915905	0.601409	0	60	881.7185521	
11	2047	720	2200	3.290909	0.9	2.9618181	0.601409	0	60	951.9274243	
12	2048	720	2200	3.702273	0.9	3.3320457	0.601409	0	60	1022.13646	
13	2049	720	2200	4.113636	0.9	3.7022724	0.601409	0	60	822.9127592	
14	2050	720	2200	4.525	0.9	4.0725	0.601409	0	60	834.0159471	
15	2051	720	2200	4.590056	0.9	4.1310504	0.09511	0	60	845.1192981	
16	2052	720	2200	4.655111	0.9	4.1895999	0.09511	0	60	856.2224758	
17	2053	720	2200	4.720167	0.9	4.2481503	0.09511	0	60	867.3258268	
18	2054	720	2200	4.785222	0.9	4.3066998	0.09511	0	60	878.4290147	
19	2055	720	2200	4.850278	0.9	4.3652502	0.09511	0	60	889.5323657	
20	2056	720	2200	4.915333	0.9	4.4237997	0.09511	0	60	900.6355434	
21	2057	720	2200	4.980389	0.9	4.4823501	0.09511	0	60	911.7388944	
22	2058	720	2200	5.045444	0.9	4.5408996	0.09511	0	60	922.8422454	
23	2059	720	2200	5.1105	0.9	4.59945	0.09511	0	60	933.9454333	

ANICCA Economic output (weak points)

- Reprocessing “on demand” not implemented (yet)
  - It is not possible to allocate the reprocessing cost to a specific reactor

- Waste management facility not implemented (yet)
  - It works only with masses
  - No encapsulation process
  - No vitrified waste units

- Unknown units:
  - Millions, Kilos, GW, MW, $?...

	A	B	C
1		PWR_UOX-installed	PWR_UOX-thermal
2	2038	720	2200
3	2039	720	2200
4	2040	720	2200

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Economic module

- Intended to further comparison between different FC strategies
- Stand alone script written in Python
- It divides the LCOE into the four main sources of cost
  - ✓Investment
  - ✓Operation and Maintenance
  - ✓Fuel
  - ✓Back-end
- It gives the LCOE by reactor and for the whole cycle
- It allows uncertainties in the unit costs for Monte Carlo analysis

Economic module

$$LCOE = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}}$$

?

Investment + Operation and Maintenance + Fuel + Back-End

Investment

It includes:
- Overnight cost
- Interest during construction (3 models)
- Loan Interest

Operation and Maintenance

A fixed percentage of the overnight cost

Fuel

UOX: Fabrication, NatU, conversion, SWU.
MOX: Fabrication (reprocessing, not here!)

Back-End

It includes:
- Reprocessing
- Storages
- Decommissioning
- Transport

Economic module

Investment:

```
investment:
    PWR_UOX:
        overnight: 3000  4500 7000  triangular 1
        loan_rate:   8
        construction_interest:   8
        construction_time:    4  8 uniform 2
        payback_period: 30
```

The sum of the next three cost:

1. Overnight cost : The total cost of the project

2. Interest during construction (three models):
   - All money at the beginning
   - All money in the middle
   - The money is splitted into the construction time

3. Loan Cost: For the payback period

Economic module

O&M:

- Fixed cost per GWe/year

```
oandm:
    PWR_UOX: 40 75 110  triangular
```

FUEL:

1. UOX cost:
2. MOX cost:

```
fuel:
    UOX_FUEL:
        UOX:
            raw_uranium: 40 100 160  TRIANGULAR 2
            enrichment:  80 100 120  TRIANGULAR 3
            conversion1: 5 8 13  TRIANGULAR 2
            fabrication: 200 250 300  TRIANGULAR 4

    MOX_FUEL:
        MOX:
            fabrication: 1000 1800 2700  TRIANGULAR 4
```

* Warning! No real data

Economic module

Backend:

- Reprocessing:
  - Variable cost per ton
- Storage:
  - Fixed cost
  - Variable cost per ton
- Transport:
  - Variable cost per ton
- Decommissioning
  - Fixed cost (%) or a variable cost per energy unit

```
backend:
    Reprocessing:
        Reproplant:
            Packages:
                - UOX_SPENT: 720 1700 4000 triangular 5
```

```
        Storage:
            Type: Interim
            Fixed_cost: 150  200   300  TRIANGULAR 1
            Packages:
              - UOX_SPENT: 120 160 200 triangular 9
              -  WASTE_UOX1: 200 250 300  triangular 9
```

```
        Transport:
            Rute1:
                From: PWR_UOX
                To: Storage
                Packages:
                  - UOX_SPENT: 25 50 75 TRIANGULAR 10
```

```
        Decommissioning:
            PWR_UOX:
                Fixed_cost:  10 20  uniform 1 # in %
#               Variable_cost: 0.001 #in dollars
```

* Warning! No real data

Economic module: Data

Data: The Economics of the Back End of the Nuclear Fuel Cycle (NEA,2013)

Lack of data and large discrepancies between sources.

Fuel cycle description	Units	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	BCG (2006)	Oxford (2011)
		Nominal							Low-High
Base year of monetary units		2008	2007	1991	2006	2011	2003	2006	2011
Front end									
Natural uranium	USD per kgU	60	80	50	50	110	40	80	30-70
Conversion (natural)	USD per SWU	10	10	8	5	11	6	12	10-30
Enrichment (natural)	USD per kgU	105	160	110	100	130	100	110	100-180
UOX fuel fabrication	USD per kgU	240	250	275	250	275	250	200	150-300
Depleted uranium disposition	USD per kgU	10	10			6.56	6		
Back end									
Interim dry storage UOX	USD per kgHM	120	200	150	150		200	150	
Geological disposal of spent UOX	USD per kgHM	1 000	470	610	610*	225	400	700	405-2 025
Geological disposal of spent MOX	USD per kgHM		3 130			940		2 240	
Geological disposal of reprocessed waste	USD per kgHM			90	90*		200		
Geological repository (HLW FPs + Ln + Tc)**	USD per kgFP	10 000	3 650						
Recycling									
Recycled U/TRU product storage	USD per kgHM	200			300				
UOX reprocessing	USD per kgHM	1 000	4 000	720	1 000	2 500	1 000	630†	
LWR MOX fuel fabrication	USD per kgHM	1 950	2 400	980	1 250	2 701	1 500		
Fabrication of FR metal fuel	USD per kgHM	2 500	2 400		2 600		1 750		

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Economic module: Data

DATA: "Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates" (Merino,2014)

Reactor Technology	SFR			T-SFR			ADS		
	L-B	B-E	U-B	L-B	B-E	U-B	L-B	B-E	U-B
Investment Costs									
Facility (€/kWe)	2465	3902	4724	2465	3902	4724	11500	14760	18000
DR (Financial)	8%	8%	8%	8%	8%	8%	8%	8%	8%
Constr. Time (yr)	4	6	8	4	6	8	4	6	8
IDC (Construction)	8%	8%	8%	8%	8%	8%	8%	8%	8%
O&M Costs									
M€/GWe/yr	65	86	108	65	86	108	168	223	279
Fuel Costs									
Fabrication (€/kg)	1000	1500	2000	5000	10000	15000	9100	20000	27300
Reprocessing (€/kg)	455	1000	1364	4550	10000	13640	14300	20000	34300
MOX&ADS fuel (€/kg)[28]	1400	2000	2400	4000	8300	11200	10800	15700	28100

Reactor Technology	LWR-UOX			LWR-MOX			LWR-GENIII		
	L-B	B-E	U-B	L-B	B-E	U-B	L-B	B-E	U-B
Investment Costs									
Facility (€/kWe)	1875	2500	2970	1875	2500	2970	2251	3002	3565
DR (Financial)	8%	8%	8%	8%	8%	8%	8%	8%	8%
Constr. Time (yr)	4	6	8	4	6	8	4	6	8
IDC (Construction)	8%	8%	8%	8%	8%	8%	8%	8%	8%
O&M Costs									
M€/GWe/yr	56	75	94	56	75	94	56	75	94
Fuel Costs									
Natural U €/kgU3O8	40	100	160	-	-	-	40	100	160
Conversion 1 (€/kgU)	5	8	13	-	-	-	5	8	13
Enrichment (€/SWU)	80	100	120	-	-	-	80	100	120
Conversion 2 (€/kgU)	5	8	13	-	-	-	5	8	13
Fabrication (€/kg)	200	250	300	800	1000	1200	200	250	300
Reprocessing (€/kg)	875	1000	1125	875	1000	1250	875	1000	1125
MOX&ADS fuel (€/kg)	-	-	-	5400	6100	6900	-	-	-

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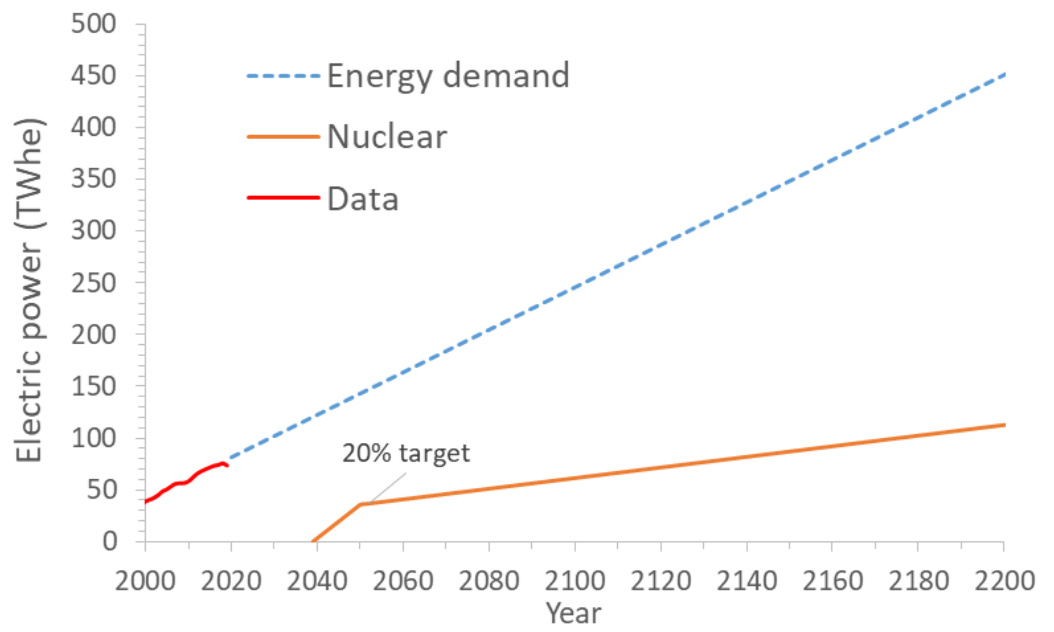
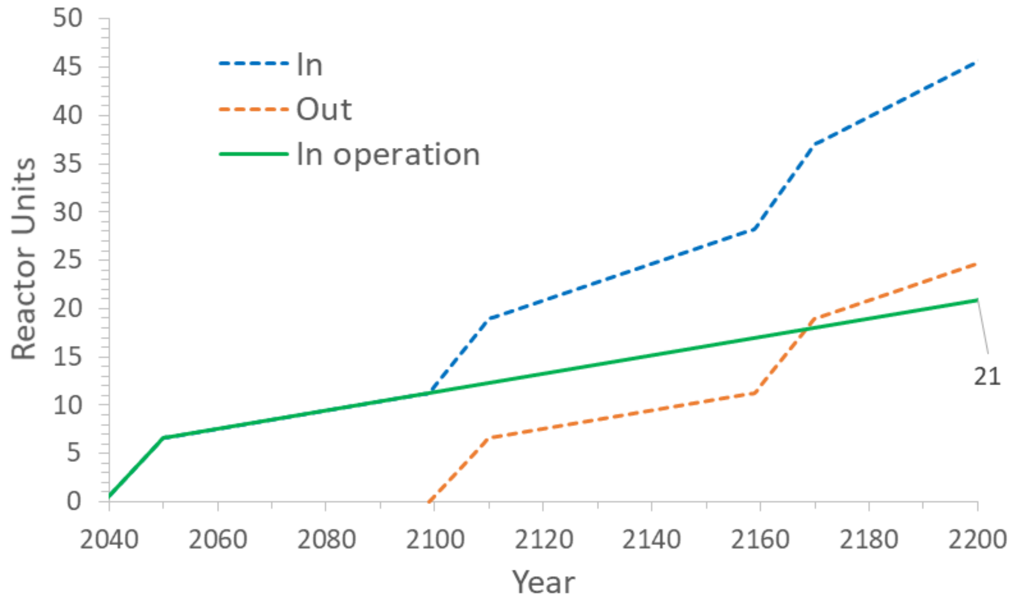
The fuel cycle scenario:

Assumptions:

- New nuclear power country (2040)
- 20% of the electricity with nuclear (by 2050)
- Comparison between two scenarios
    - Open fuel cycle (SC-1):
        - A FD for SF (UOX)
    - Open fuel cycle with reprocessing (SC-2)
        - We pay for the reprocessing
        - RepU, Pu, MA are not considered anymore and sent somewhere (for free)
        - We keep the vitrified HLW



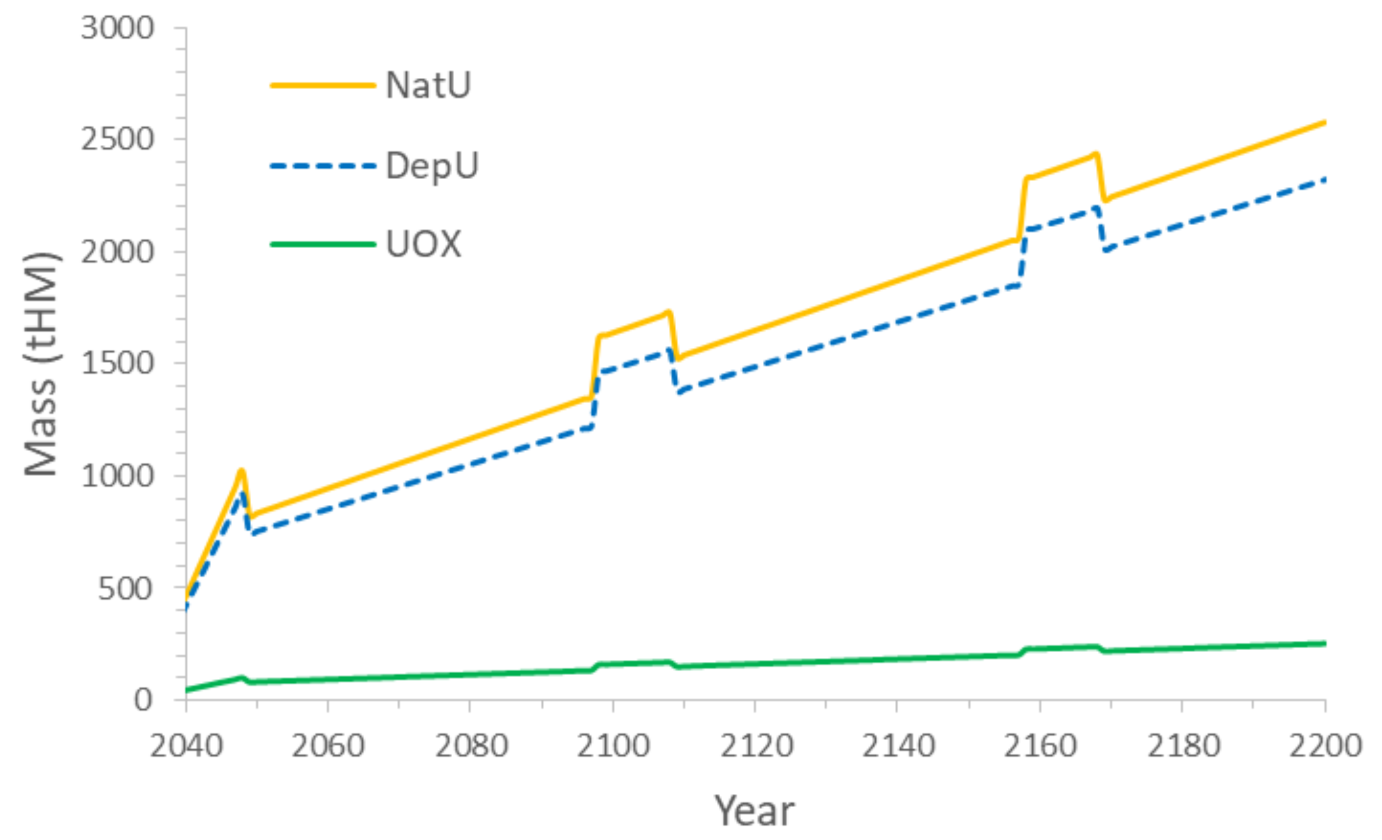


FC scenario: Material balance results

Fuel Fabrication:

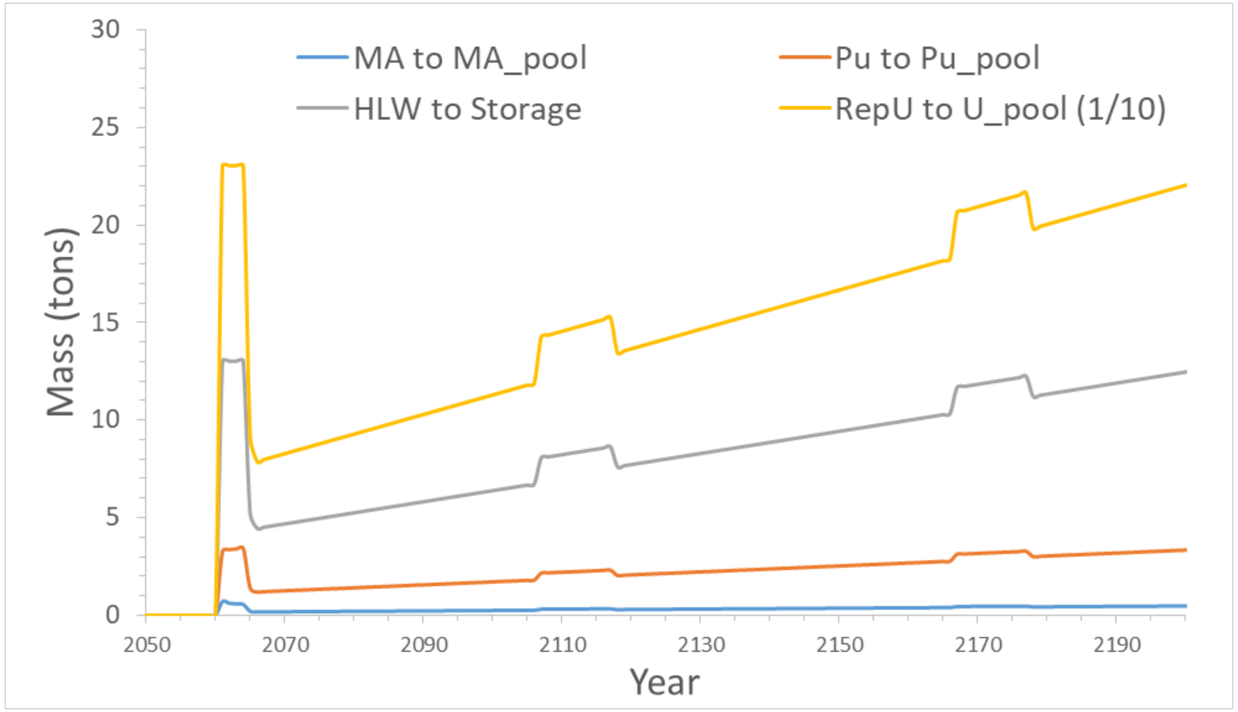
Total Production (tHM)

	SC-1/SC-2
UOX Fuel	**26.000**
Nat. Uranium	270.000
Dep. Uranium	244.000

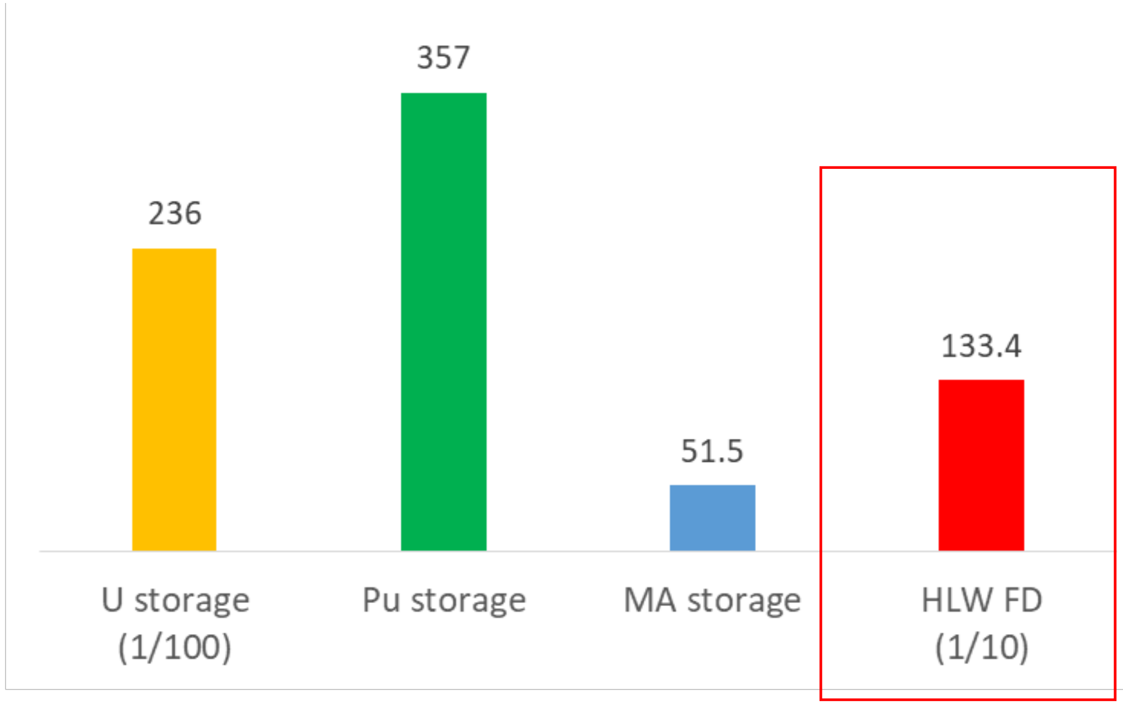


FC scenario: Material balance results

Reprocessing in SC-2: Max: 250 tHM/year (from 2060)



Material separated and transported



Storage Capacity
(Only Interim and FD are considered in the economics)

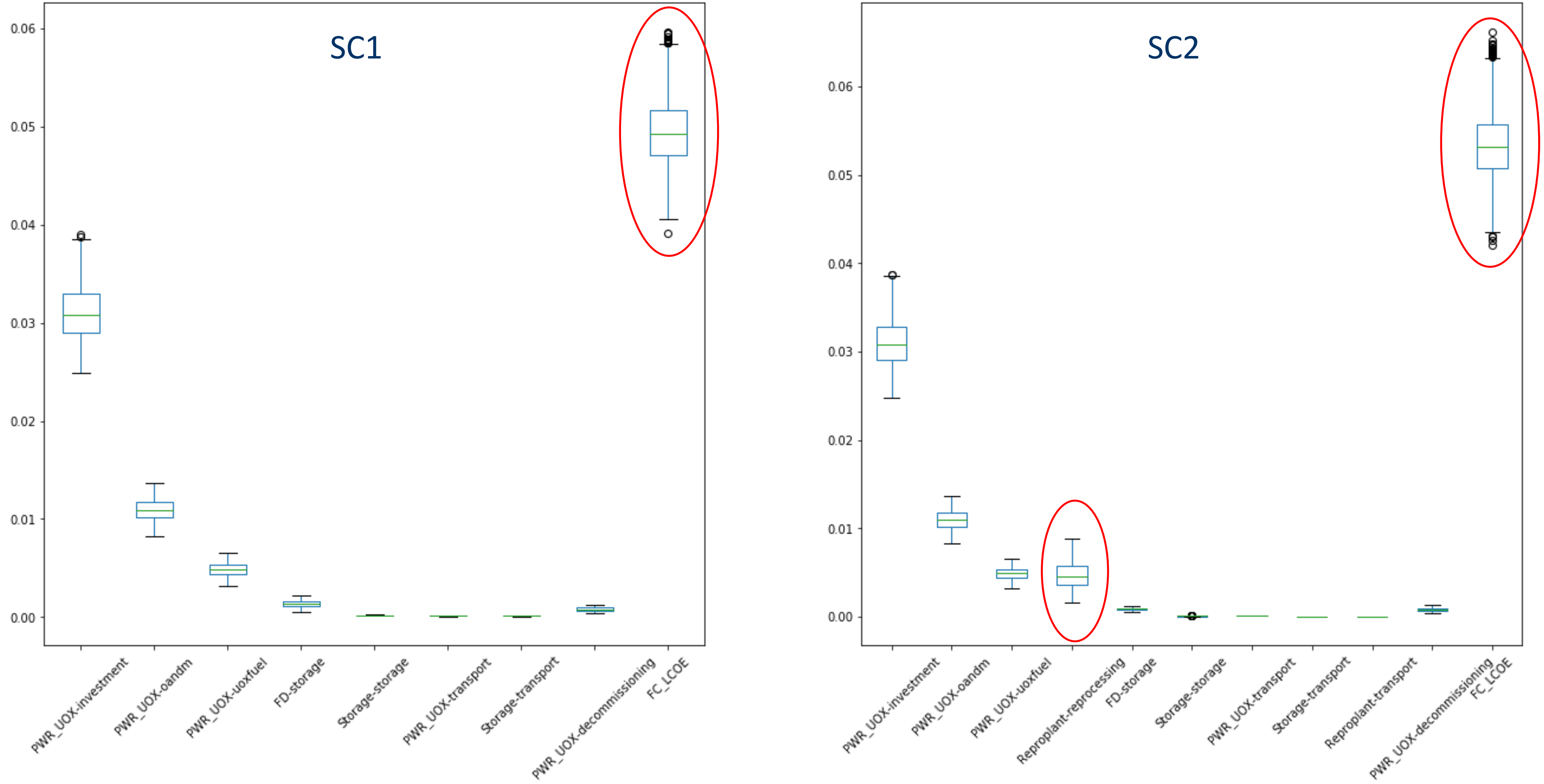
FC scenario: Economics results

Based on Best Estimate unit costs:

- SC-2 is ~6% more expensive than SC-1
- The investment cost is the greater contributor
- Reprocessing makes more expensive the scenario (It has to be for free to make sense)
- What about fuel leasing?
  - We can pay up to 50% more
  - No need to deal with HLW

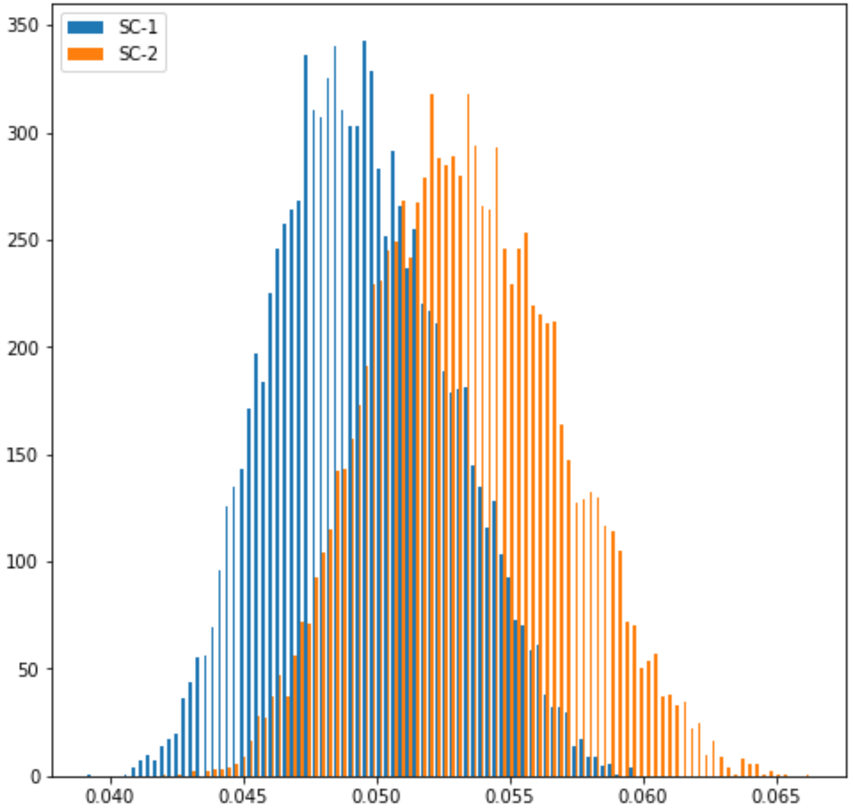
Scenario	SC-1 (%)	SC-2 (%)
Investment	61.92	58.23
O&M	22.76	21.40
Fuel	10.17	9.56
Back-end:	5.15	10.81
Reprocessing	*--*	*7.37*
Storage	*3.13*	*1.73*
Transport	*0.46*	*0.24*
Decommissioning	*1.56*	*1.46*
LCOE (¢/kWh)	**4.79**	**5.09**

FC scenario: Economics results (Monte Carlo)



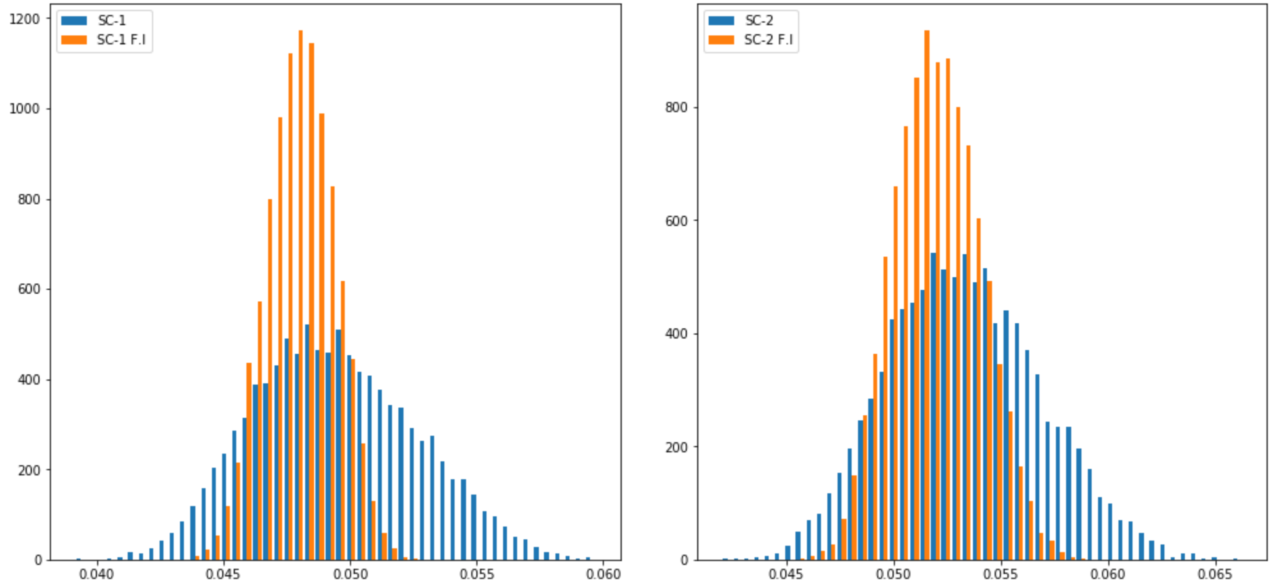
FC scenario: Economics results (Monte Carlo)

SC-1 & SC-2 comparison



*Averages: SC-1 = 4.94 and SC-2= 5.33

SC-1 & SC-2 (when removing the Investment uncertainties)



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Summary

- ANICCA can model different fuel cycle strategies
- Two types of outputs can be obtained
  - Materials balance
  - Economics parameters
- It is provided with a new capability to estimate the LCOE (with some limitations)
- First results shows that the module works properly

Future works

- Reprocessing on demand in ANICCA
- Waste management facility in ANICCA
- Solve flags in the economic output (from the FC analysis)
- More methods to calculate the LCOE
- Robustness

An open personal question!

Does it make sense going further with these types of analyses (more complex methods), if the uncertainties and lack of data devour most of the main outcomes that we can obtain?