Wir schaffen Wissen - heute für morgen

Nuclear fuel cycle options for climate change mitigation

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Energy Economics Group, Paul Scherrer Institute

International Energy Workshop Cape Town, 21st June 2012

Outline

Role of nuclear power for climate mitigation

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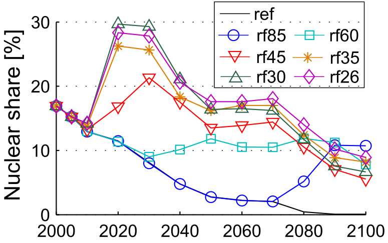
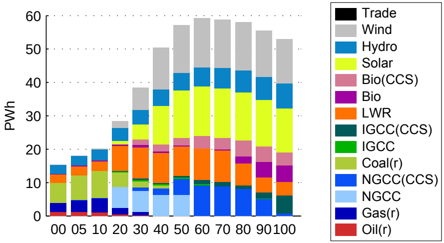
Using a MERGE-ETL model. Radiative forcing = 2.6-8.5 W/m^2





Role of nuclear power for climate mitigation

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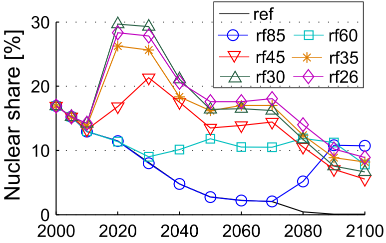

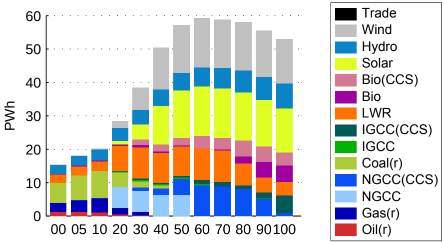

Depletion of uranium resources

Role of nuclear power for climate mitigation

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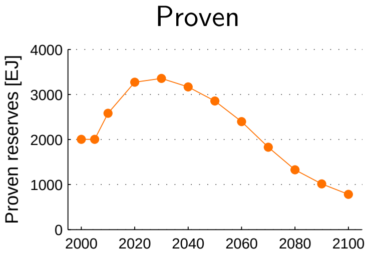
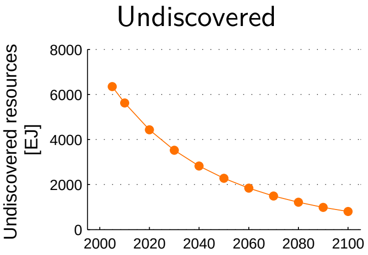
Uranium resources [500 GJ/kg]. From: 2009 Red Book



Reasonably Assured Resources (RAR)

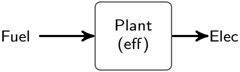


Inferred + Prognosticated + Speculative Resources

Depletion of uranium resources

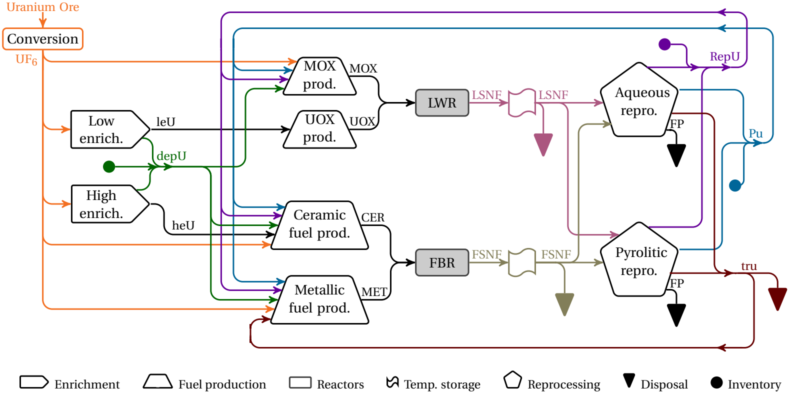
Motivation

- Potential important role (or not after Fukushima) of nuclear power
- Nuclear-based electricity more complicated



- Reprocessing: In 2009, 8% reactors in OECD used MOX fuel (NEA/IAEA, 2008)
- Enhanced nuclear fuel cycle:
    - LWR and FBR
    - Uranium enrichment processes
    - Fuel production: UOX, MOX, Ceramic and metallic fuel
    - Spent fuel reprocessing: Aqueous and Pyrolitic
    - Storage and geological disposal

New nuclear cycle



LEU Low Enriched Uramium
MOX Mixed Oxide
Pu Plutonium
HEU High Enriched Uramium
UOX Uranium Oxide
RepU Reprocessed uranium
DU Depleted Uramium
CER Ceramic fuel
FP Fission products
MET Metallic fuel
tru Transuranic elements other than Pu
SNF Spent nuclear fuel

Flexible fuel production

The model decides the optimal breeding factors

Assumptions

- Mass balance
- Inputs are interchangeable

$(0.8\text{-}0.95)x = x_1 \text{ UF}_6 + x_2 \text{ depU} + x_3 \text{ RepU}$ →
$(0.05\text{-}0.2)x \text{ Pu}$ →
MOX Production → x MOX

$(0.8\text{-}0.95)x = x_1 \text{ UF}_6 + x_2 \text{ depU} + x_3 \text{ RepU}$ →
$(0.05\text{-}0.2)x = x_4 \text{ heU} + x_5 \text{ Pu}$ →
CER Production → x CER

$(0.8\text{-}0.95)x = x_1 \text{ UF}_6 + x_2 \text{ depU} + x_3 \text{ RepU}$ →
$(0.05\text{-}0.2)x = x_4 \text{ Pu} + x_5 \text{ transuranics}$ →
MET Production → x MET

Reactors and reprocessing

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Modeled based on European Pressurized Reactor (EPR) and European Fast reactor

Reactors

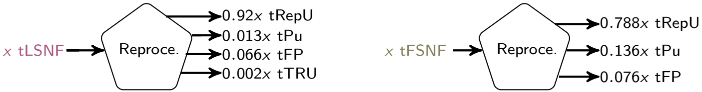
Reactors and reprocessing

Modeled based on European Pressurized Reactor (EPR) and European Fast reactor

Reactors

Reprocessing

- Aqueous
- Pytolitic



Disposal and storage

- Disposal: Spent fuel not reprocessed, fission products and transuranics
- Storage: Depleted uranium, reprocessed uranium and plutonium

Initial conditions [2005]:

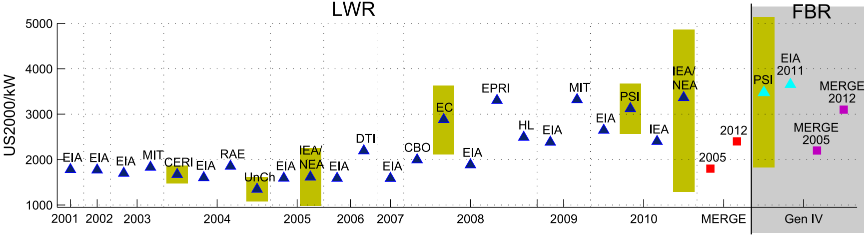
	EUP	SWI	RUS	MEA	IND	CHI	JPN	USA	CANZ	ROW
Depleted Uranium [ktHM]	227		495		4	20		47	4	
Plutonium [tHM]	430.3	13	83		12	25.3	106	388	130	103.6
Spent UOX [ktHM]	32.2	0.74	13			1.3	19	61	37.3	10.9

Source:
IAEA(2001), Analysis of uranium supply to 2050
Institute for Science and Security (2005), Plutonium Watch: Tracking Plutonium inventories
Spent fuel: National reports of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management

Costs

Fuel cycle: Shropshire et al. (2007). Idaho National Laboratory

Reactors:



EIA(2001-2011)	Annual Energy Outlook 2001-2011
MIT(2003/2009)	Future of Nuclear Power/ 2009 Update
CERI(2004)	Canadian Research Institute. Levelized Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario
RAE(2004)	Royal Academy of Engineering. The cost of Generating electricity
UnCh(2004)	University of Chicago. The economic future of nuclear power
IEA/NEA(2005,2010)	2005/2010 Projected costs of generating electricity
DTI(2006)	UK, Department of Trade and Industry. The Energy Challenge
CBO(2008)	US, Congressional Budget Office. Nuclear Power's Role in Generating Electricity
EC(2008)	Energy sources, production costs and performance of technologies for power generation, heating and transport
EPRI(2008)	Integrated Generation Technology Options
HL(2008)	House of Lords, The Economics of Renewable Energy
PSI(2010)	Energie Spiegel
IEA(2010)	Energy technology perspectives

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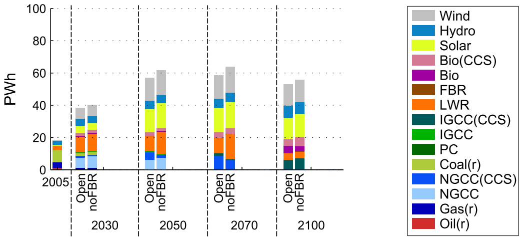
Scenarios

Scenario description	Name	Nuclear options UOX	MOX	FBR
MOX + No FBR	NoFBR	x	x	
100% nuclear support	FC	x	x	x
No Nuclear				
Swiss policy				
No Nuclear	NoNuc	x(-)	x(-)	-(-)
No LWR	NoLWR	x(-)	x(-)	x(x)

MOX + No FBR


PWh
100
80
60
40
20
0
2005
Open
noFBR
2030
2050
2070
2100
Wind
Hydro
Solar
Bio(CCS)
Bio
FBR
LWR
IGCC(CCS)
IGCC
PC
Coal(r)
NGCC(CCS)
NGCC
Gas(r)
Oil(r)

MOX + No FBR

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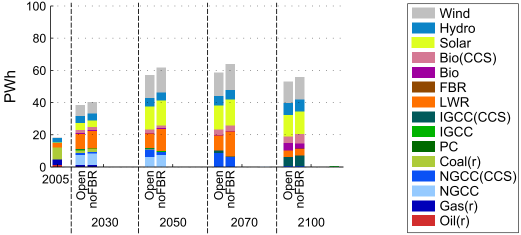
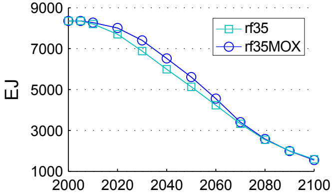
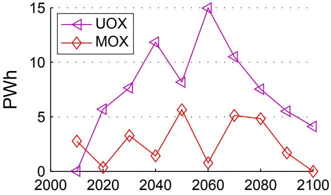


Uranium resources

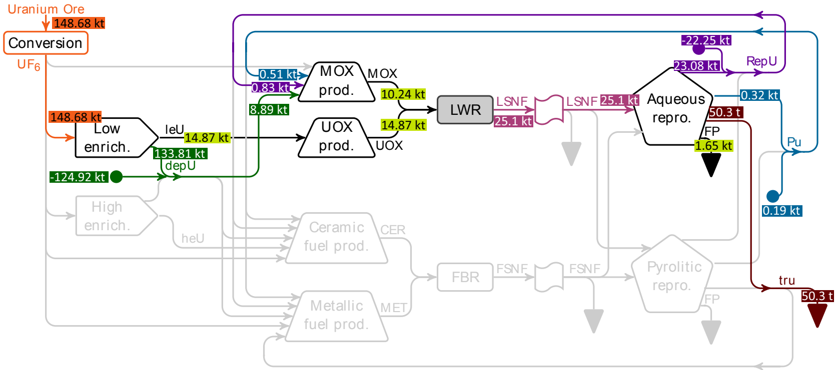


Fuels

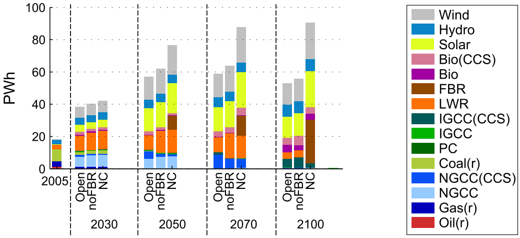


MOX + No FBR

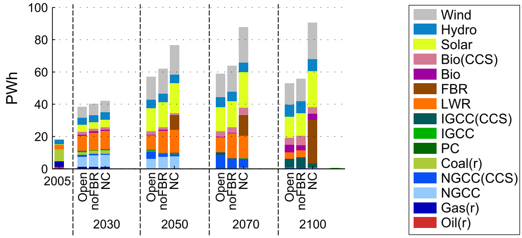
2050 mass fuel flows



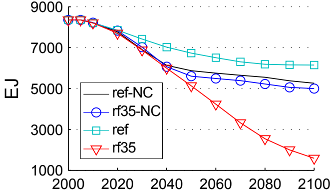
Full nuclear support policy



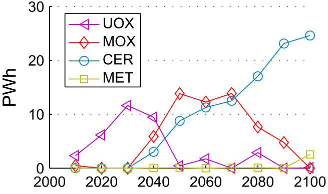
Full nuclear support policy



Uranium resources



Fuels



Full nuclear support policy

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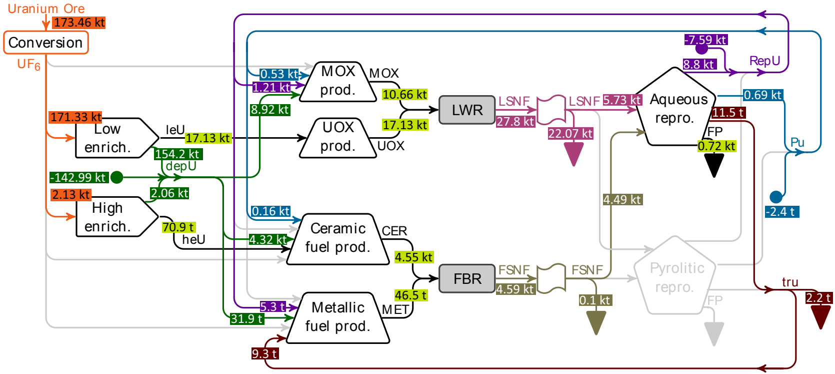
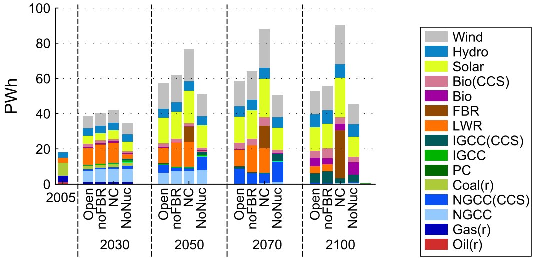
2040 mass fuel flows

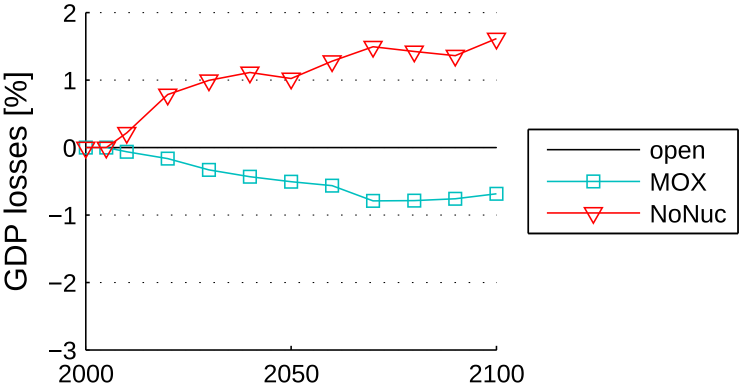


No nuclear

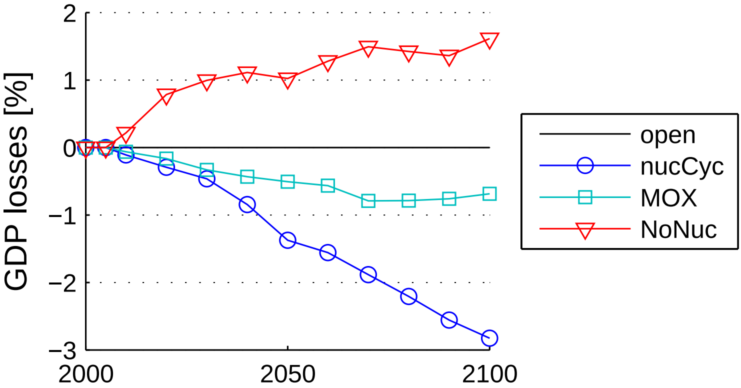


- Demand reductions
- CCS
- Renewables

Economic consequences



Economic consequences



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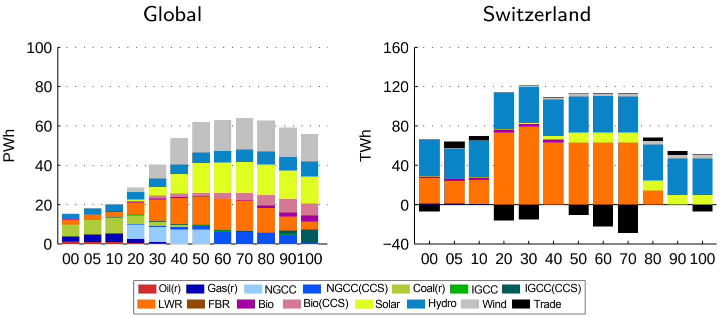
Climate policy



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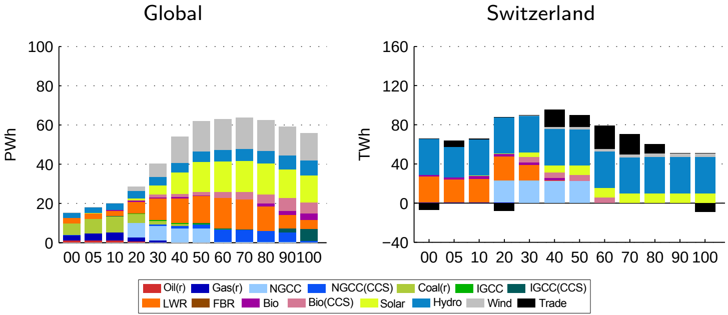
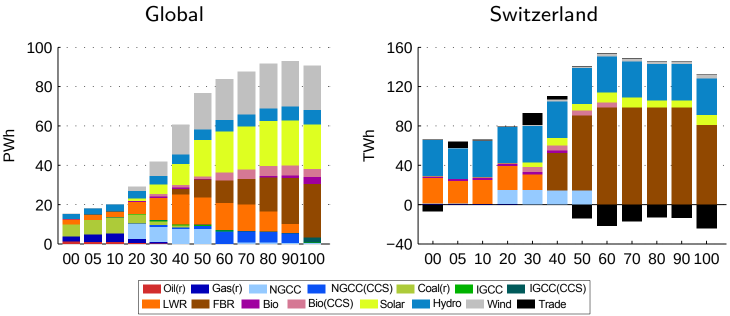
Nuclear phase-out



- Nuclear partially replaced with imports from EU
- NGCC transition technology

Swiss nuclear policy

New technologies + No LWR



- NGCC transition technology
- Higher demand
- Resource independence
- Switzerland benefits from global learning of FBR

Outcome

- New fuel cycle model that improves analysis of nuclear generation in long-term scenarios
- No Nuclear $\rightarrow$ demand reductions + CCS + renewables
- Economic advantage of fuel reprocessing + new nuclear technologies?

Outlook

- Room for improvement. Other reactors: Thorium; Costs of reprocessing; additional premium for safety
- Many different scenarios:
  - Spent MOX $\rightarrow$ Pyrolitic reprocessing
  - FBR in Switzerland but limited in the other regions
  - Importance of transport costs
  - Limits on waste
  - Capacity waste repositories


Thank you for your attention
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