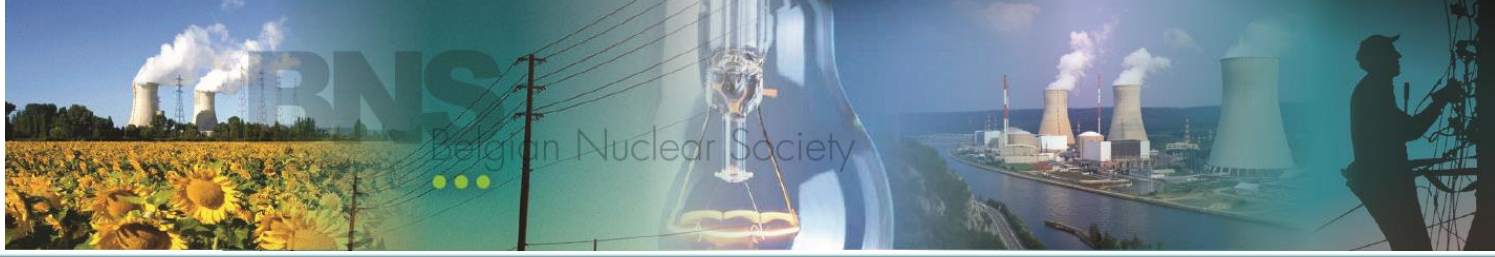


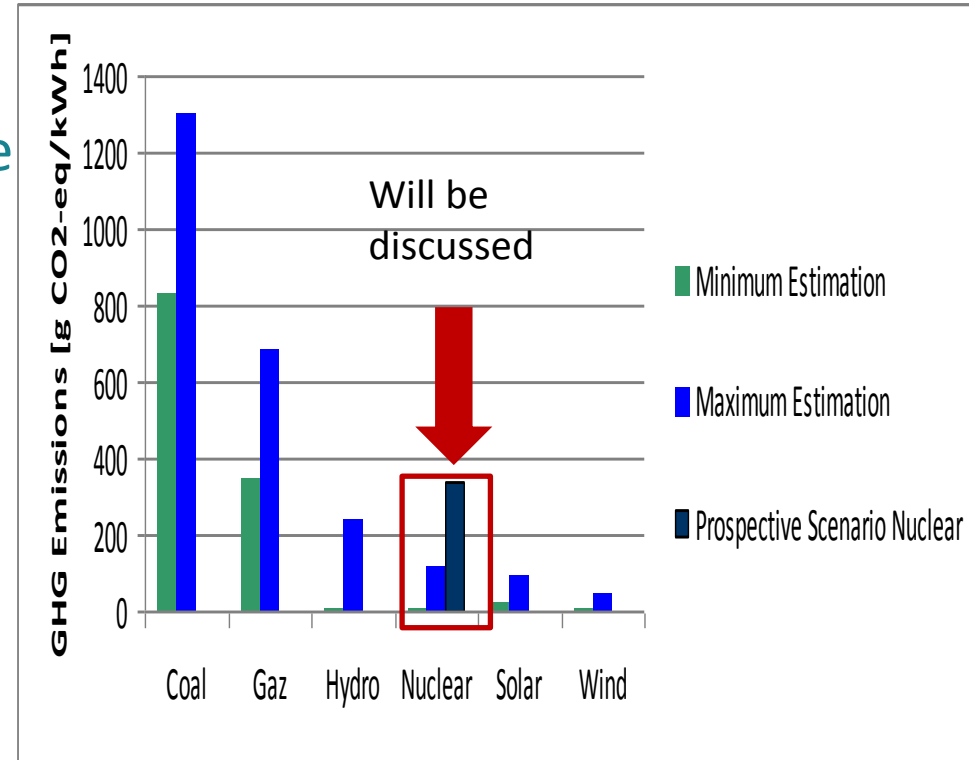
Nuclear Energy and CO₂

Arnaud Meert



Welcome!

- The purposes of this evening speech are...
 - To address the CO₂ cost of the nuclear energy
 - To put it in the context of the “climate gamble”
 - To understand the current situation of the (Belgian) nuclear market
- But prior to address those topics, some background is needed...



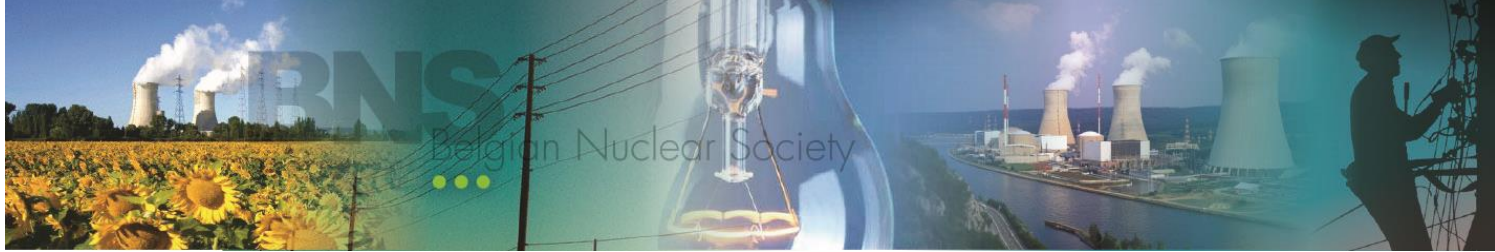
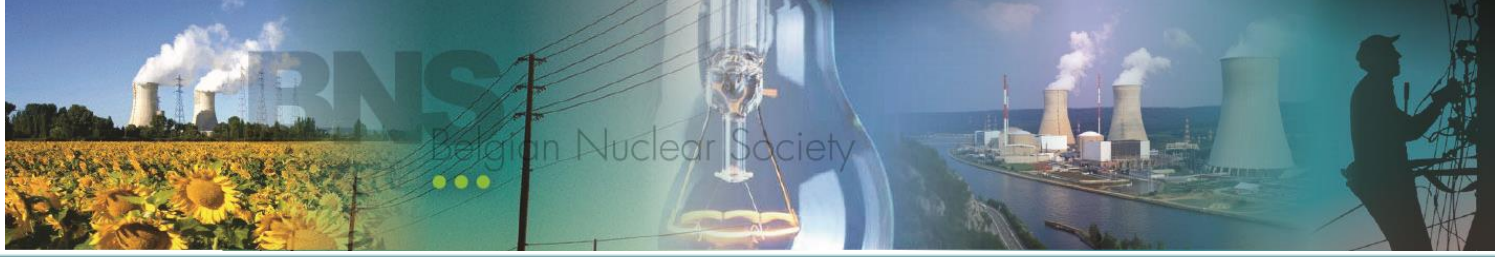


Table of contents

- I. Introduction (for non-nuclear specialist public)
 - Some generalities about the nuclear
 - Main milestones of Belgian Nuclear history
 - Reserves and wastes
 - Regulation – Euratom
 - Economicity, market, new challenges (modulation)
- II. Climate change - from Kyoto to COP-21: place of the nuclear
- III. CO₂ cost of Nuclear
 - Reminder of some nuclear basic concepts used as assumptions for the studies to be presented
 - Presentation of the results of 3 interesting studies
 - Long Term Operation (LTO) and CO₂
- IV. Conclusion



Part I

Introduction

(for non-nuclear specialist public)

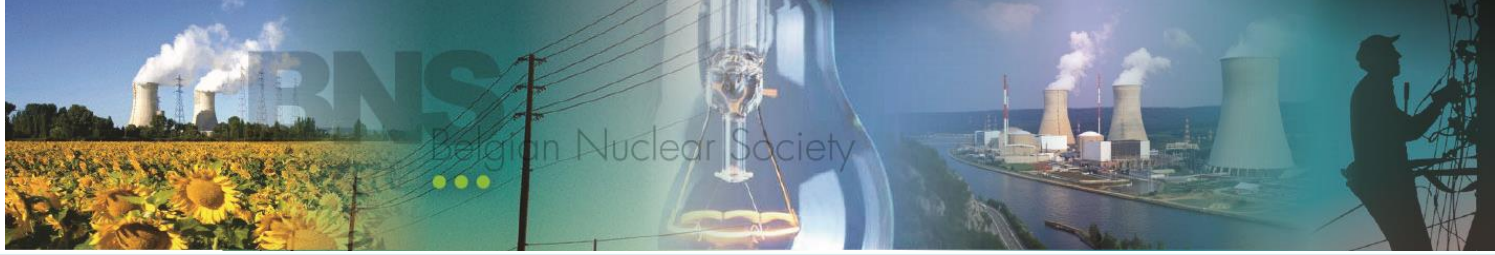
Nuclear industry and the Belgian park

Main milestones of Belgian Nuclear history

Reserves and wastes

Regulation – Euratom

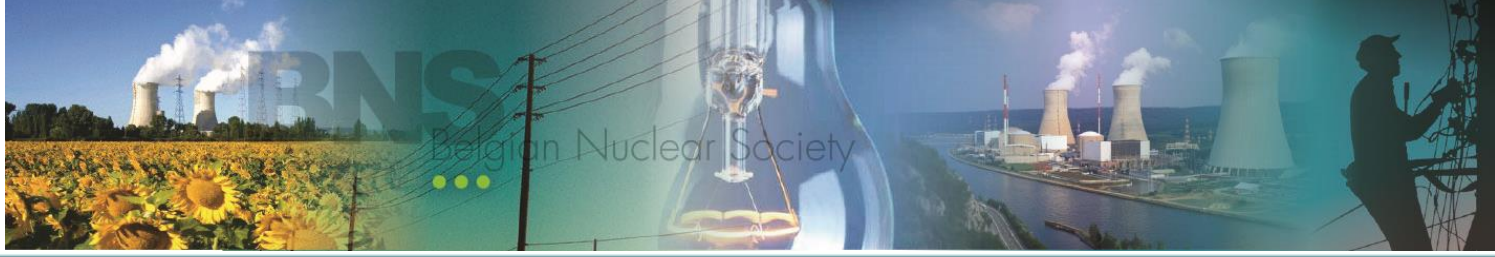
Economicity, market, new challenges (modulation)



History (civil applications)

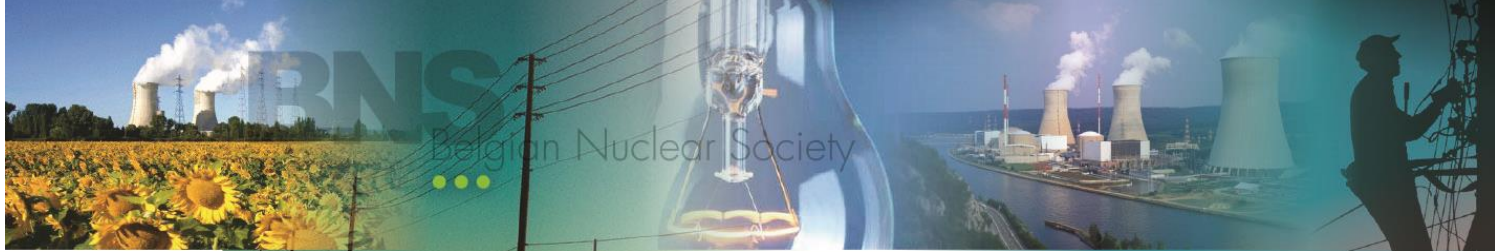
- 1951 : first experimental nuclear reactor (USA)
- 1954 : first reactor (URSS)
- 1956-1960 : UK, France & Canada constructed their own reactors
- 1962 : first West-European PWR (Belgium): BR3 (SCK•CEN)
- 2015: 40 years of Tihange 1, Doel 1 and Doel 2
- 2025: 40 years of Doel 4 and Tihange 3





Backup slide – Belgian nuclear production park (data)

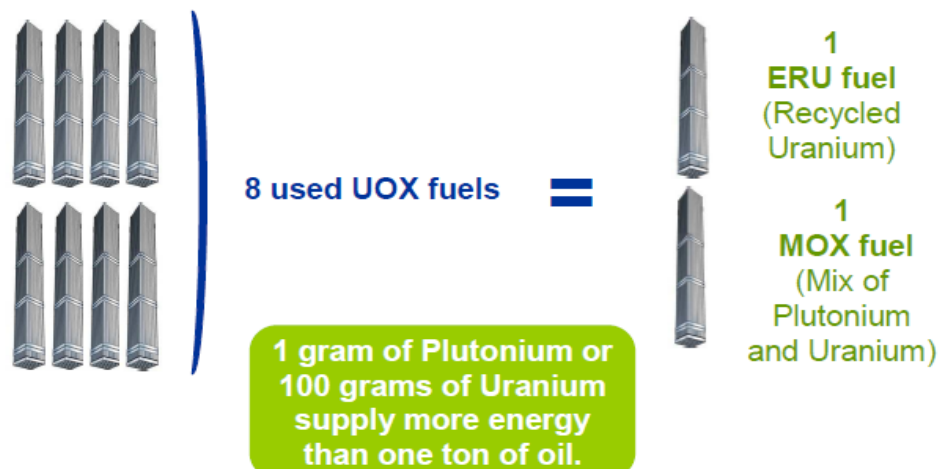
	Doel				Tihange		
	1	2	3	4	1	2	3
Commissioning	02/1975 and 12/1975		oct-82	juil-85	oct-75	juin-83	sept-85
Reactor type	2 loops PWR (Westinghouse)		3 loops PWR (Framatome)	3 loops PWR (Westinghouse)	3 loops PWR (Framatome)		3 loops PWR (Westinghouse)
Power	2 x 433 MWe		1006 MWe	1039 MWe	962 MWe	1008 MWe	1045 MWe
Reactor confinement	Double containment : - primary : steel sphere - secondary : reinforced concrete		Double containment : - primary : prestressed concrete + liner - secondary : reinforced concrete				
Safeguard systems	- 1 st level : 2 x 100%, ultimate heat sink = River - 2 nd level (external events special building) : 1 x 100 %, ultimate heat sink = aerocooler		- 1 st level : 3x100%, ultimate heat sink = River - 2 nd level : 3x 100% bunkerized, ultimate heat sink = lake		- 1 st level : 2 x 100%, ultimate heat sink = River - 2 nd level (special building) 1x100%, ultimate heat sink = wells	- 1 st level : 3x 100%, ultimate heat sink = River - 2 nd level : 3x100%, bunkerized, ultimate heat sink = wells	
Seismic design basis	0.058 g		0.1 g		0.17 g		
Protection H2	Passive autocatalytic recombiners						
Additional Spent Fuel Storage	Dry casks designed against airplane crash; passive cooling (natural air convection)				Spent fuel Pool attached to Tihange 3 and designed against the same threads (earthquake, airplane crash) Capacity : 3800 positions		

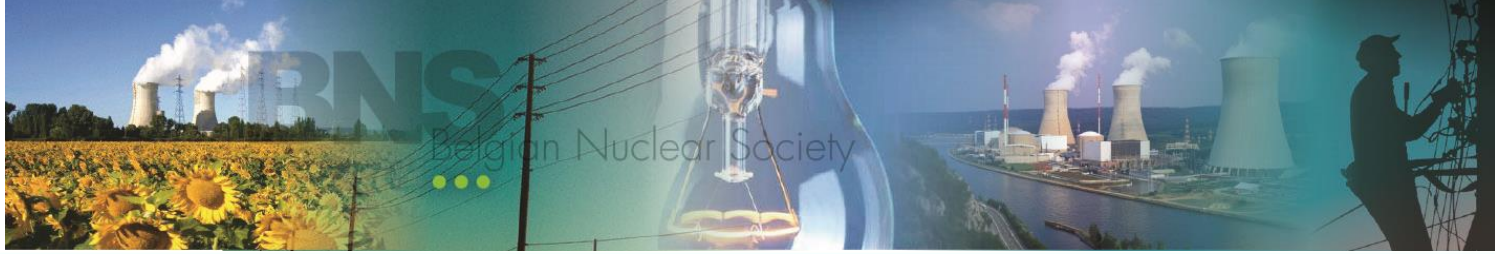


Reserves

- Up to 60 years of reserve for a production cost $< 80 \$ / \text{kg U}$ (source : IAEA)
 - ! Insufficient prospection has been made ! $\rightarrow$ underestimation of the reserves
 - Addition of the mining resources $\rightarrow$ up to 300 years (17.106 tons)

- Alternative solutions
 - Use of breeder reactor may multiply the reserves by 50 (source : [1])
 - Use of recyclage (MOX) saves up to 25% in natural uranium (source : [10])

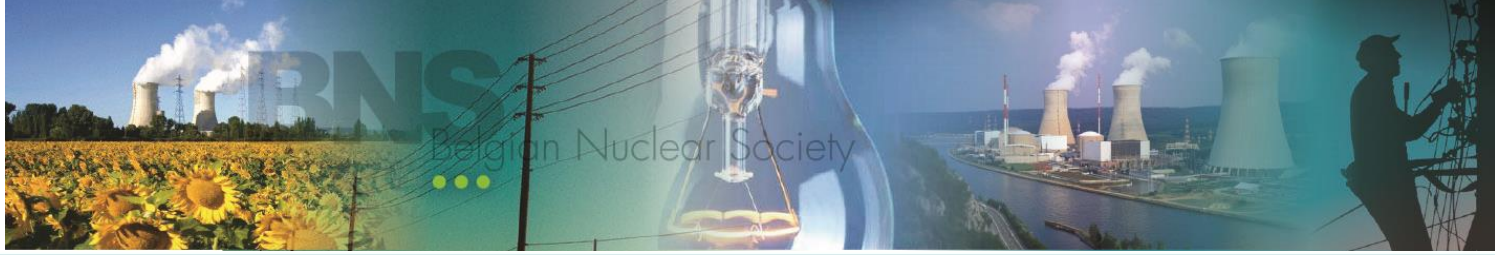




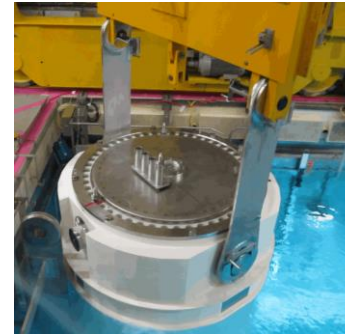
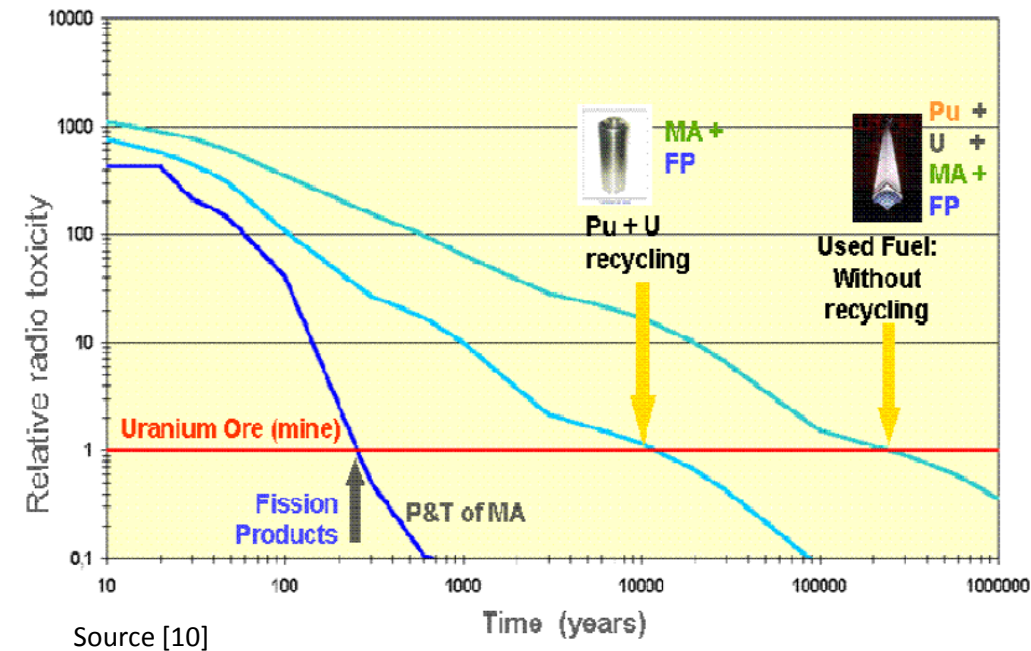
Reserves (2)

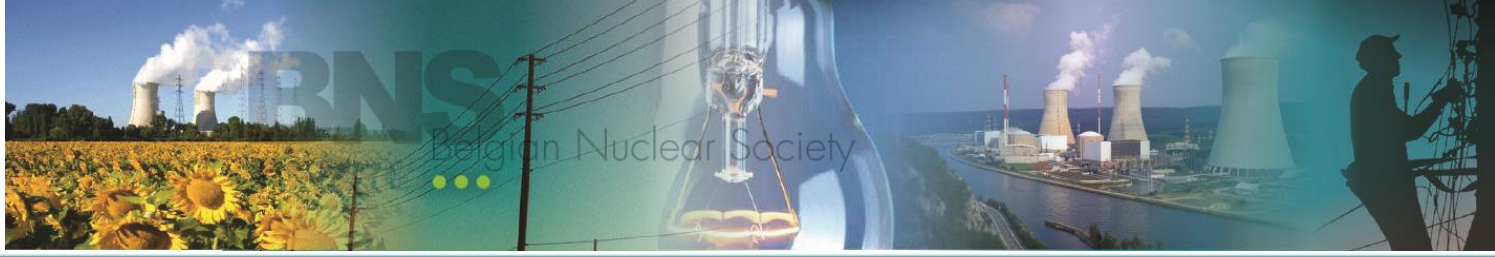
- Canada produces ~ 11.500 t/years
 - Australia produces ~ 6950 t/years
- } 50% of world production
- Niger, Kazakhstan, Namibia, Ouzbekistan, Russia, South Africa, ...
 - First supplier worldwide is now: Kazakhstan

⇒ Diversity of the supply



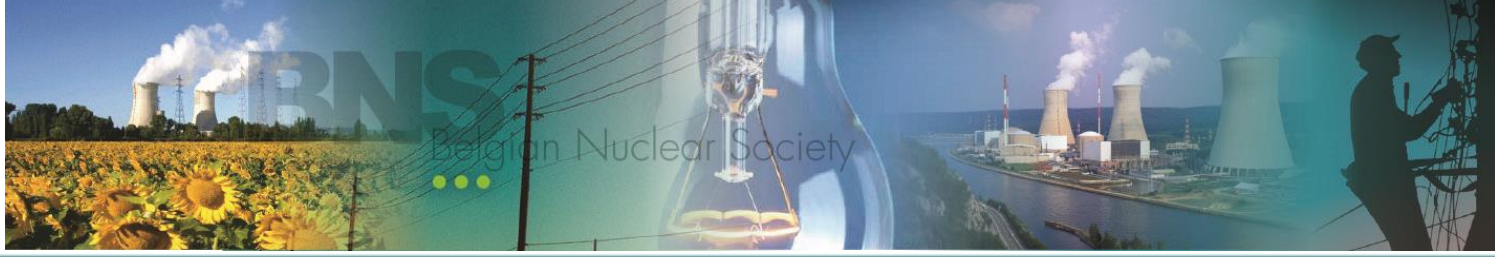
Wastes and (intermediate) storage



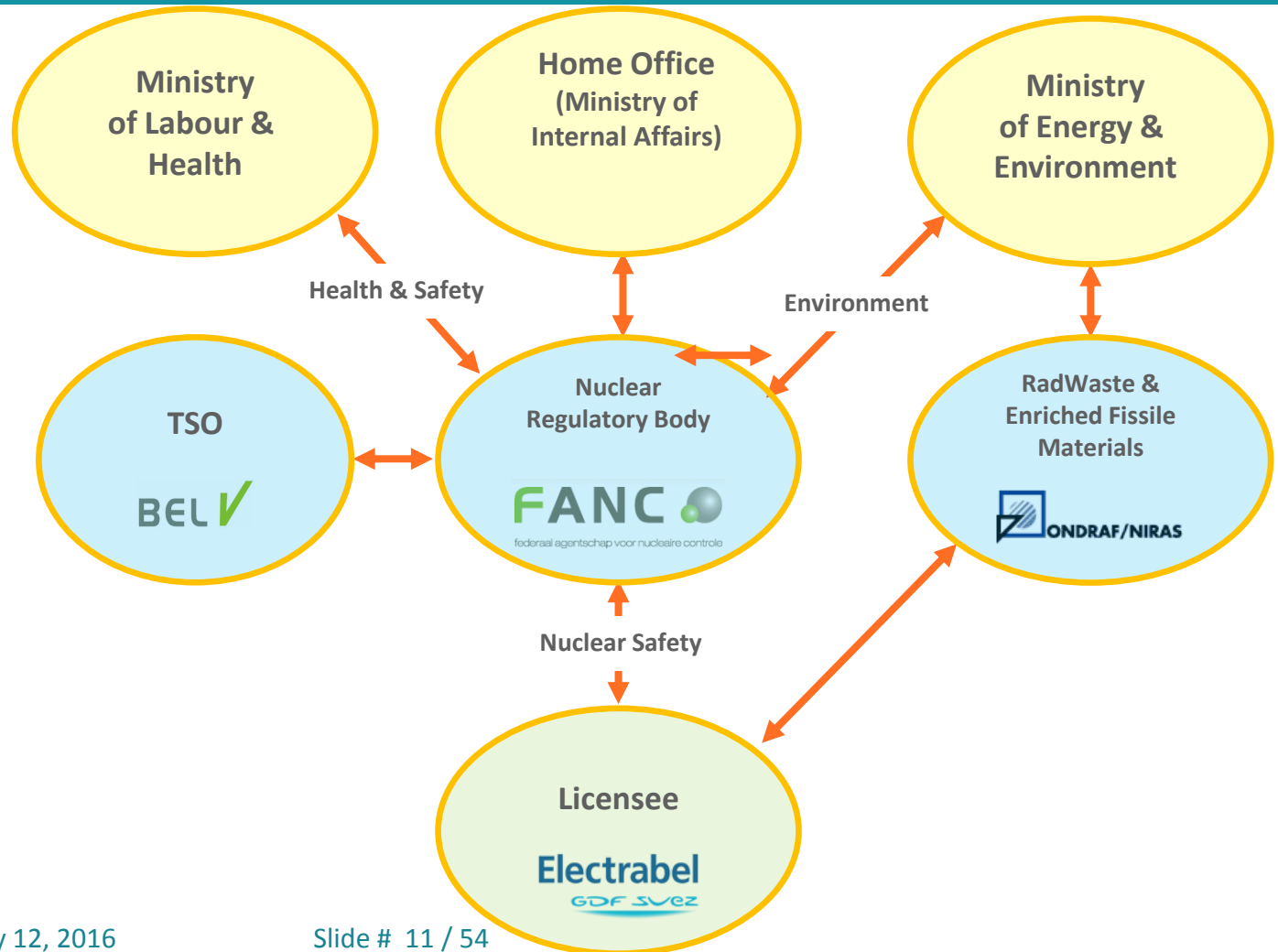


EURATOM

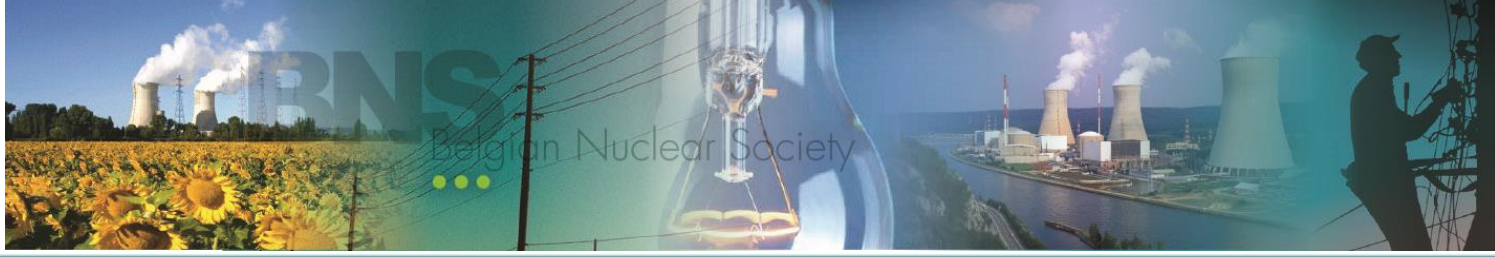
- All the sells have to be approved by Euratom
 - The buyers may rule the negotiations with the sellers but Euratom must accept the deal
 - Euratom may forbid a member to buy from a specific furnisher if it could lead to a dependency
- The head of Euratom is staffed by experts & Europeans officials
 - Great transparency researched



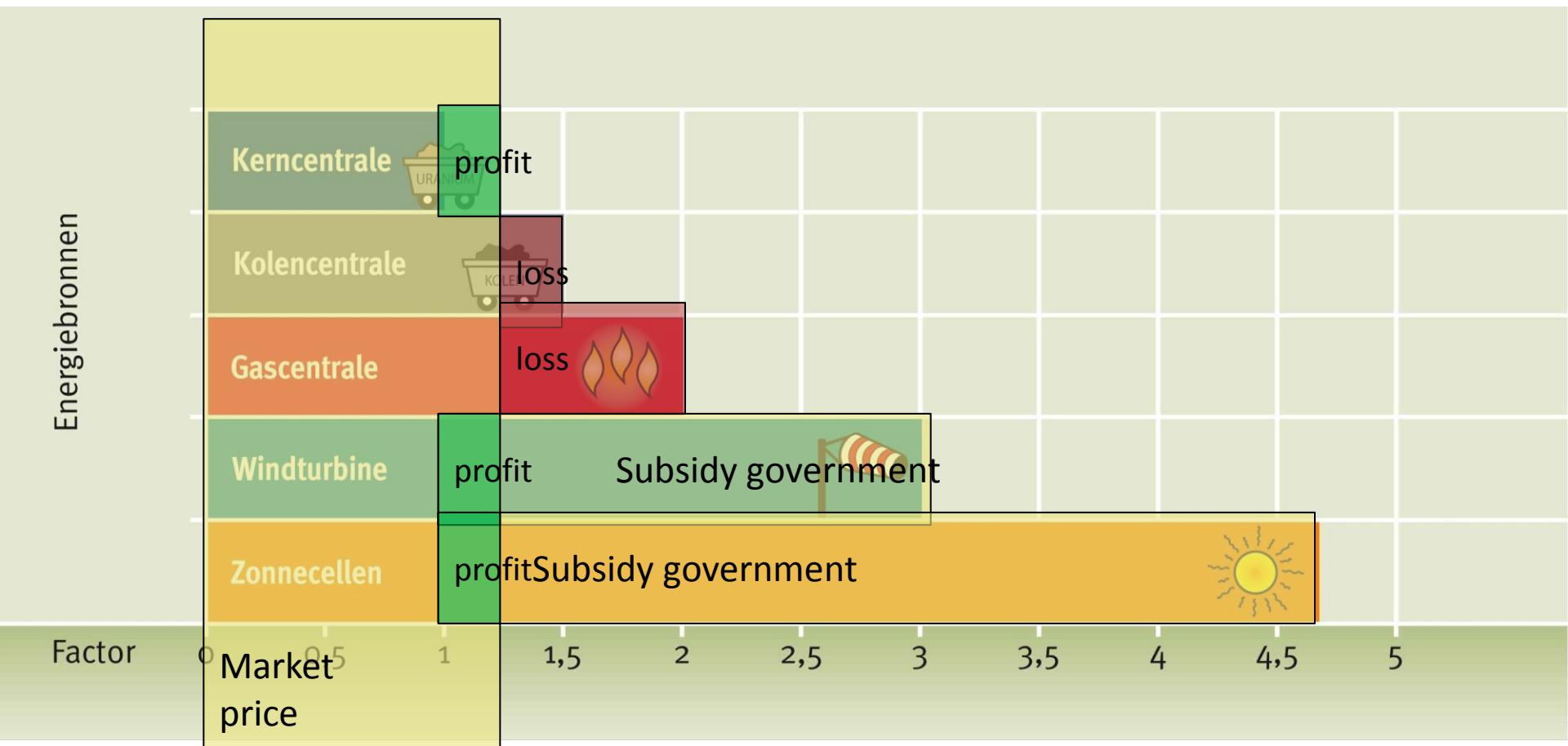
Belgian Regulatory Framework : The stakeholders



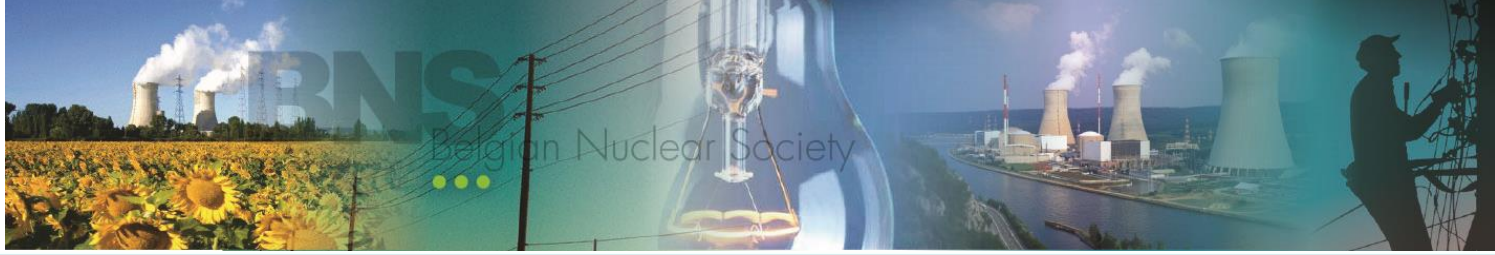
Source: [14]



State of the market



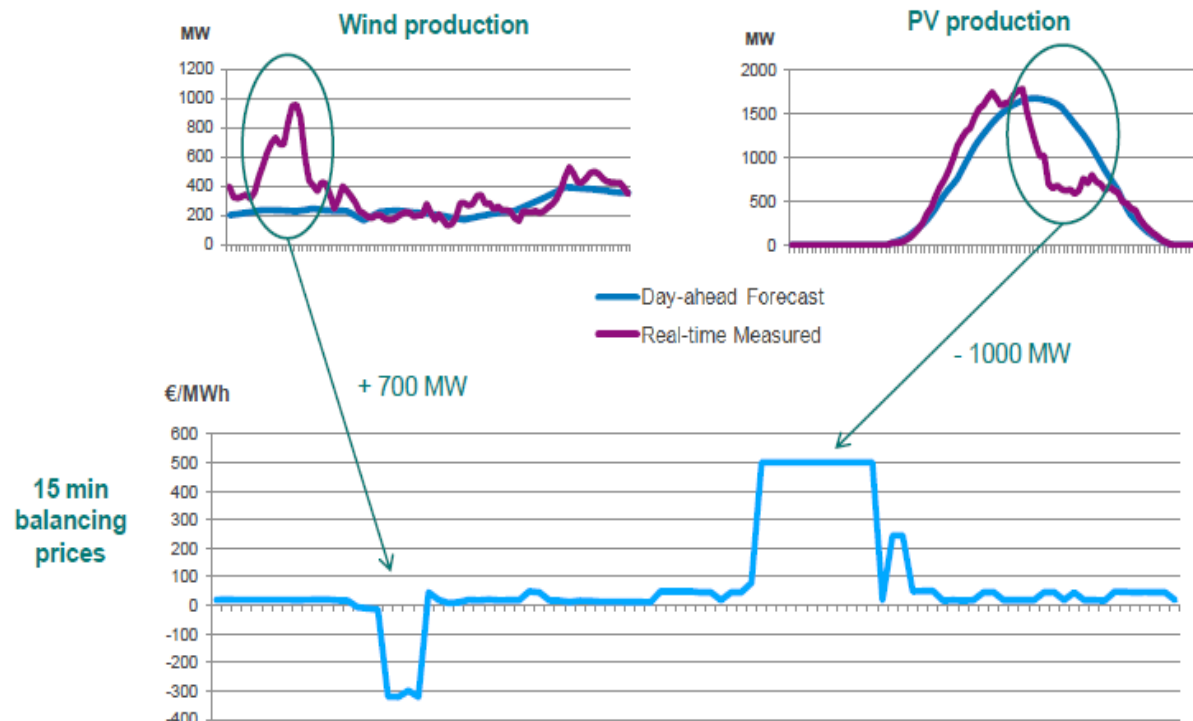
Source: [9]



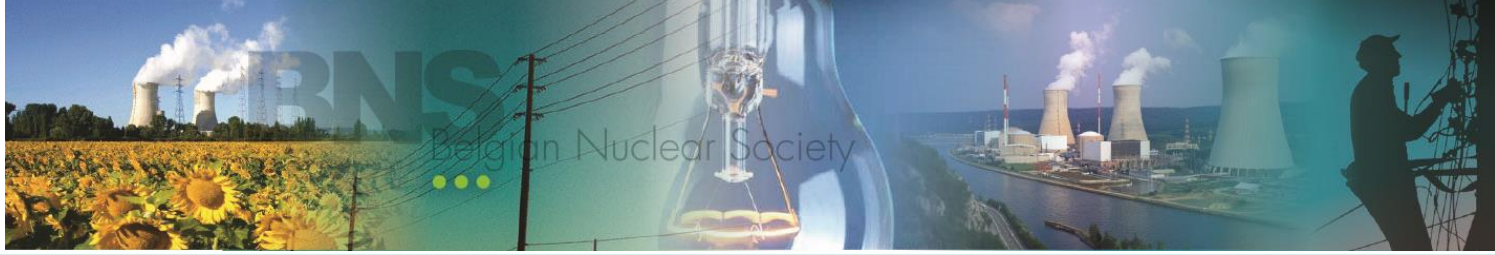
With more RES, flexibility need is growing

Discrepancy between RES production forecast and reality may create huge price fluctuations in the balancing market with negative prices up to -300€/MWh and +500€/MWh in the same day in case of lack of available flexibility.

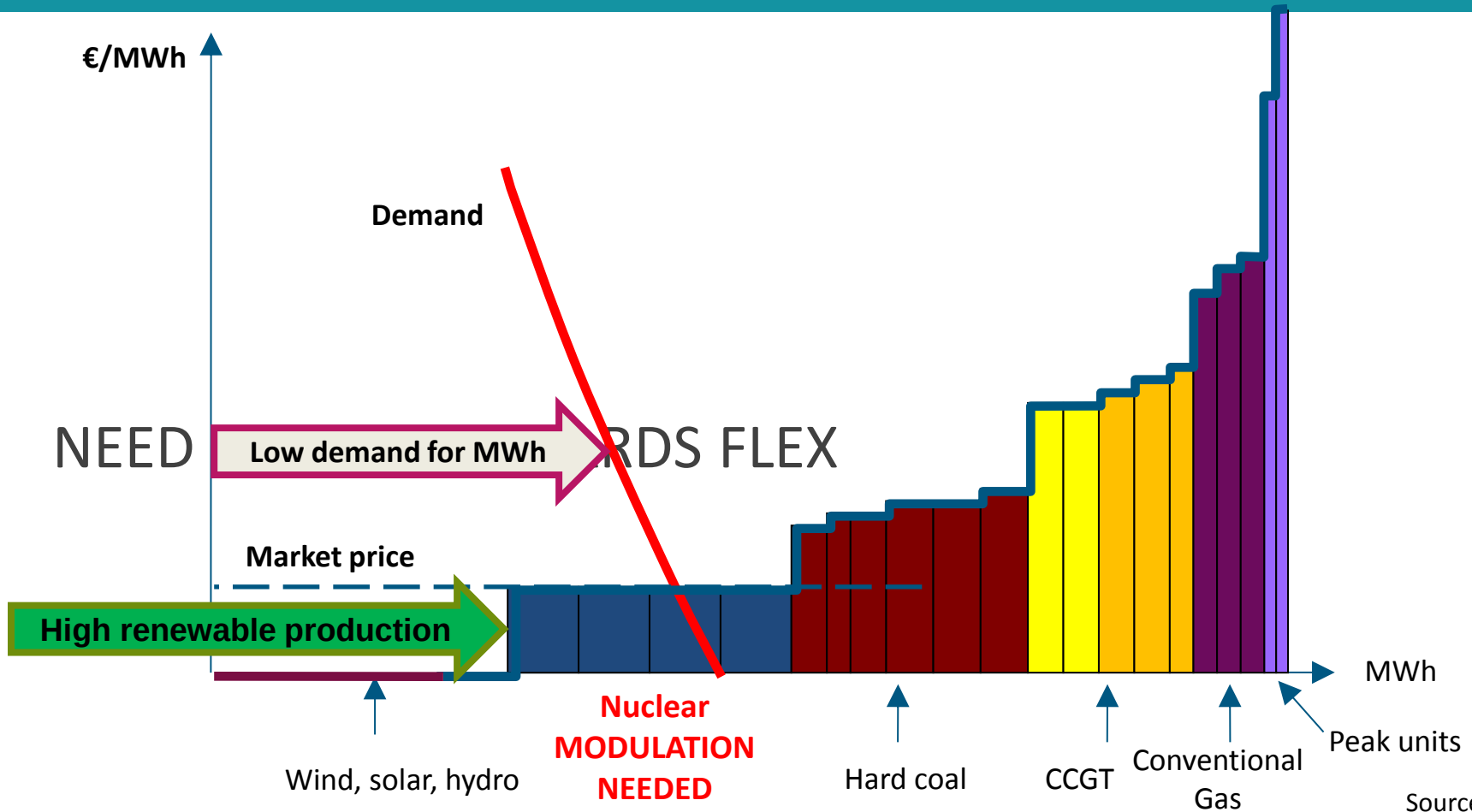
- An example for Tuesday 10/06/2014 in Belgium to see how RES is impacting the **balancing prices**



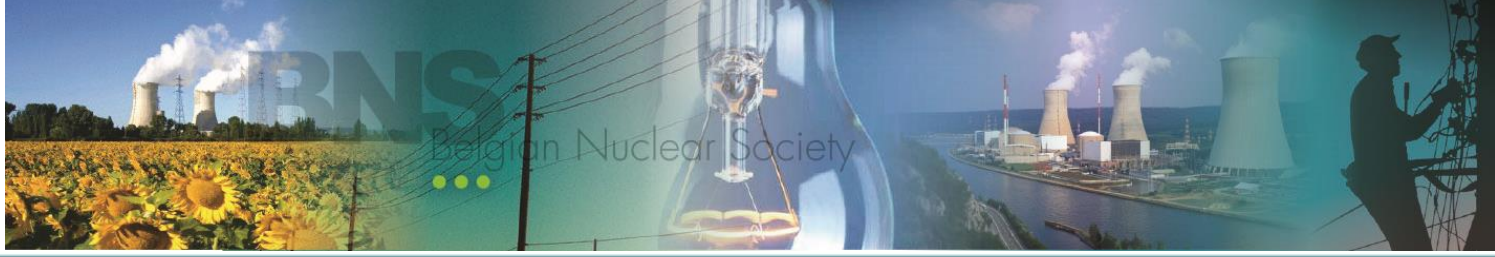
Source: [11]



In periods of low demand or/and high renewable production...



Source: [12]



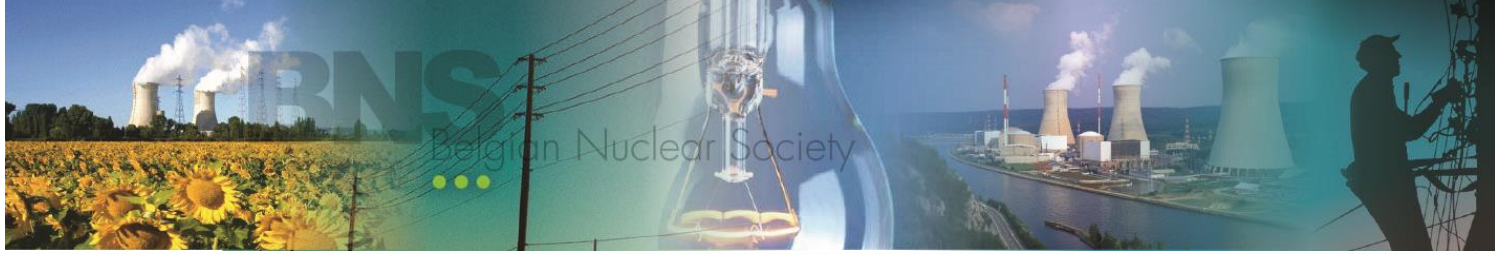
Part II

Climate change - from Kyoto to COP-21: place of the nuclear

What Kyoto protocol said (1997)...

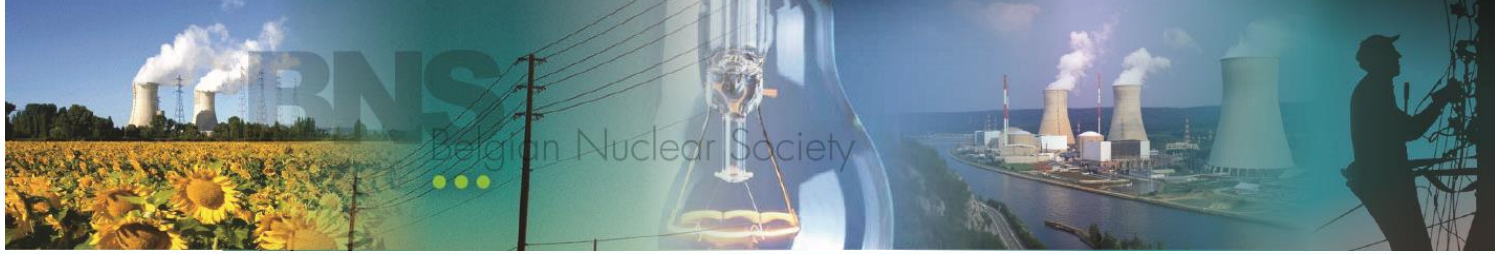
What COP-21 says (12/2015)...

What the nuclear industry says...



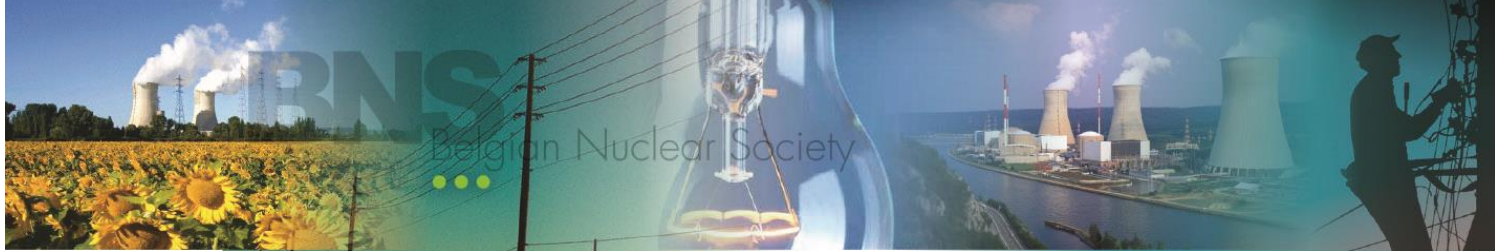
Kyoto

- Kyoto Protocol (KP) target (first commitment period 2008 – 2012)
 - global target -5,2% (for Annex 1 countries) compared to base year 1990
- Measures
 - direct actions ‘at home’ (reducing CO₂ emissions)
 - work through ‘flexible mechanisms’ (market-based mechanisms)
 - International Emissions Trading (CO₂ emissions trading between the country of Annex 1)
 - Joint Implementation (get credits by building clean technology in industrialised countries of Annex 1)
 - Clean Development Mechanism (get credits by building clean technology in Countries of Non-Annex 1 or developing countries)
- If not respected: sanctions possible (+30% reduction)



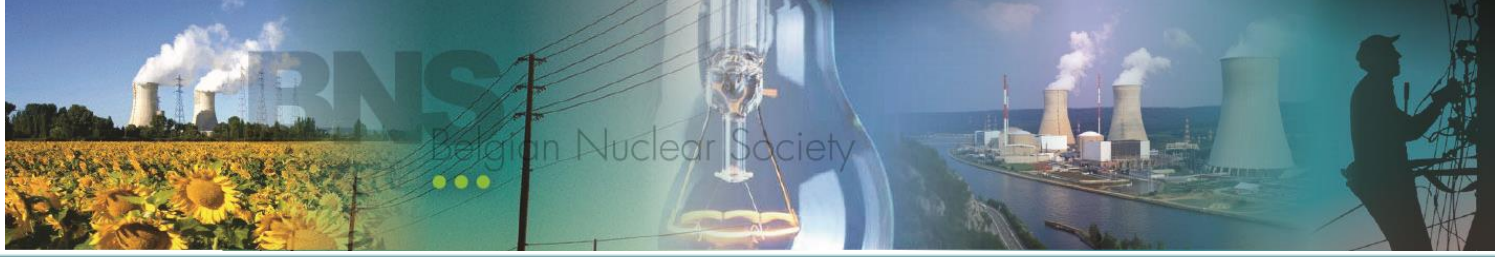
Nuclear in the climate change negotiations

- The KP states that
 - ‘parties should refrain from using nuclear technology within the clean development mechanism’: impossible to receive credits from supporting (new) nuclear in developing countries.
 - Symbolic exclusions, but...
 - does not affect industrialized and developing countries’ nuclear energy policies as such (CO₂ avoidances based on nuclear remain ‘valid’ under the KP).
 - important, as it complicates ‘rehabilitation’ of nuclear in future climate change agreements.
- Countries remained divided over the possible role of nuclear in future energy policies, but the issue has never been officially discussed in international negotiations.



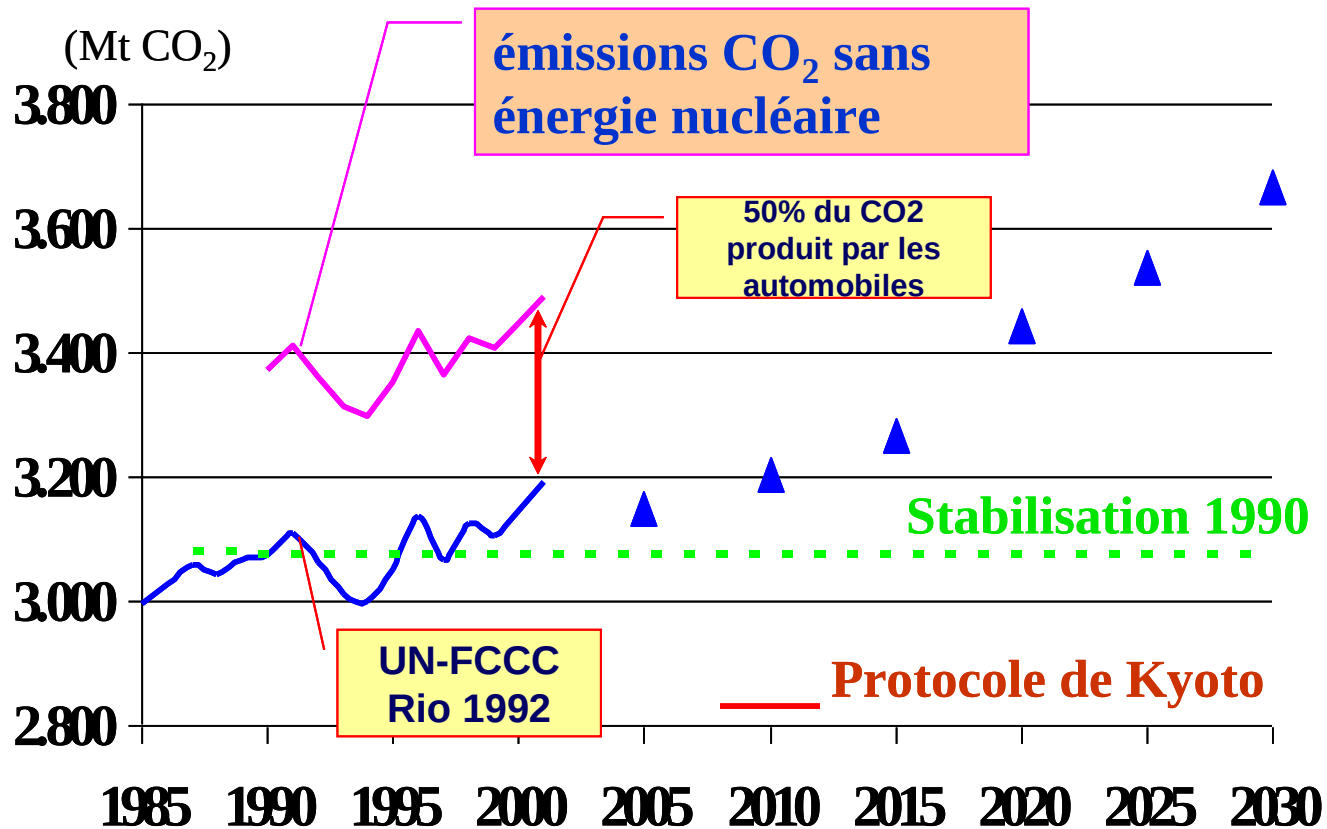
GHG Emissions of “CO₂ Free” Technologies

- Emissions of fossil-fired power plants
 - direct (fuel burning) + indirect emissions
 - **Direct** emissions can be measured
- Emissions of non-fossil Power Plants (nuclear, solar photovoltaic, wind...)
 - indirect emissions only
 - **Difficult to evaluate**
 - Many parameters to consider: construction/production, mining (nuclear and solar), transport, recycling, waste disposal, decommissioning (nuclear)...
 - Data not always available: approximations, models
 - Dependence on external parameters (solar panels emissions highly depend on insulation)
 - **Results vary significantly** (5-340 g CO₂-eq./kWh for nuclear)

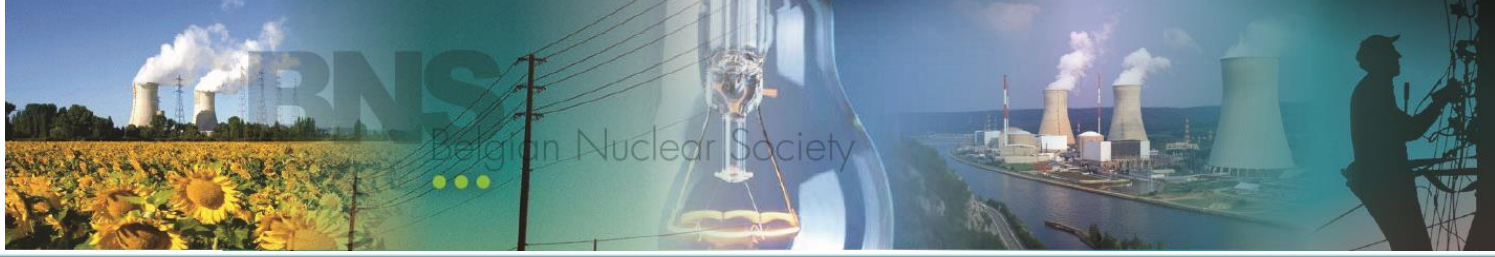


Situation at the time of Kyoto Protocol

Greenhouse gas (GHG) emission gain thanks to nuclear energy (UE-15)



Source: [1]

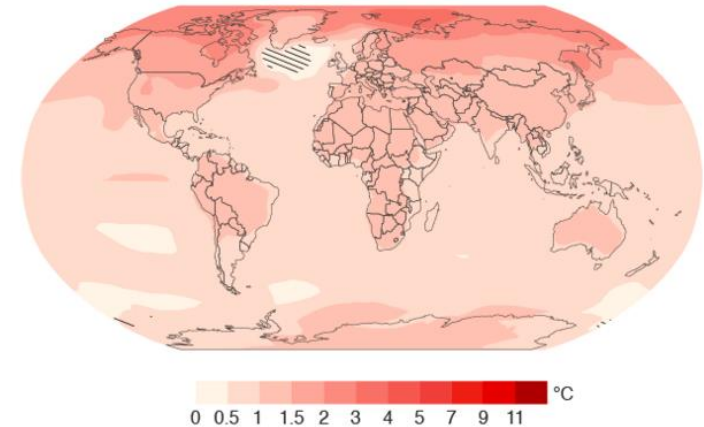


COP 21 outcomes

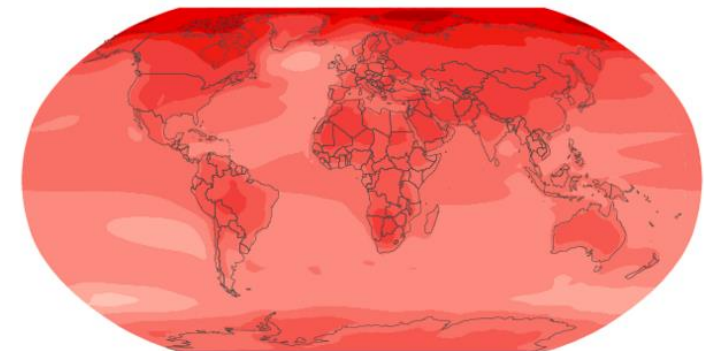
- The COP 21 conferences
 - joined the Parties in 12/2015 in Paris to pursue the finding of solutions against climate change and temperature changes.
 - It was agreed by 195 nations that they will attempt to cut greenhouse gas emissions to a level that will limit the global average temperature to a rise "well below" 2°C compared to pre-industrial levels.

Projected temperature change (1986–2005 to 2081–2100)

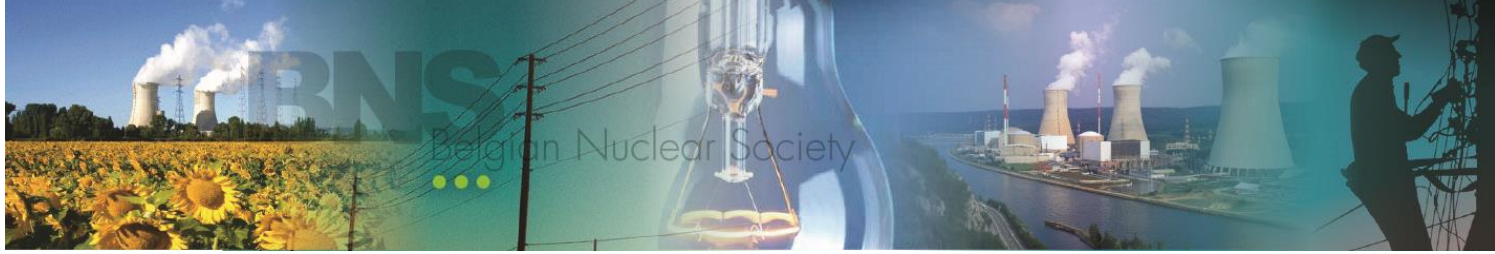
If greenhouse gas emissions peak between 2010 to 2020 and then decline substantially (RCP2.6).



If greenhouse gas emissions continue to rise throughout the 21st century (RCP8.5)



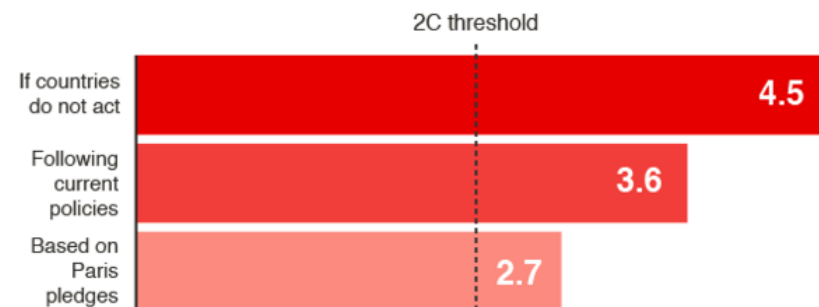
Picture extracted from [6]



COP 21 outcomes

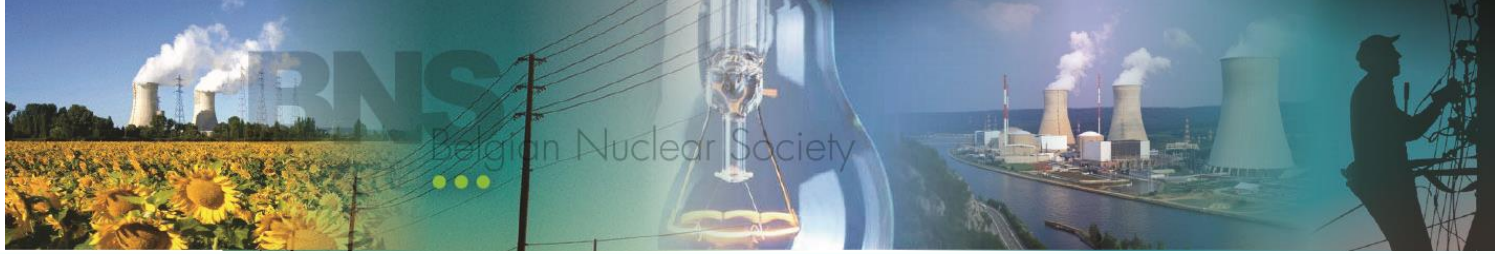
- The agreement presents, among others
 - some actions that are binding...
 - regular review and submission of emission reduction targets
 - helping the emerging countries by a \$100bn fund to decarbonize their energy mix - which means moving away from burning fossil fuels to clean energy sources, such as renewables and nuclear are binding.
 - ... and some that are not
 - But the emission targets are not binding...
 - “Observers have calculated that all of the targets, if delivered, will only curb warming by 2.7°C, well above, the 2°C goal of the Paris Agreement”.[6]. This could indeed change if new targets would be announced.

Average warming (C) projected by 2100



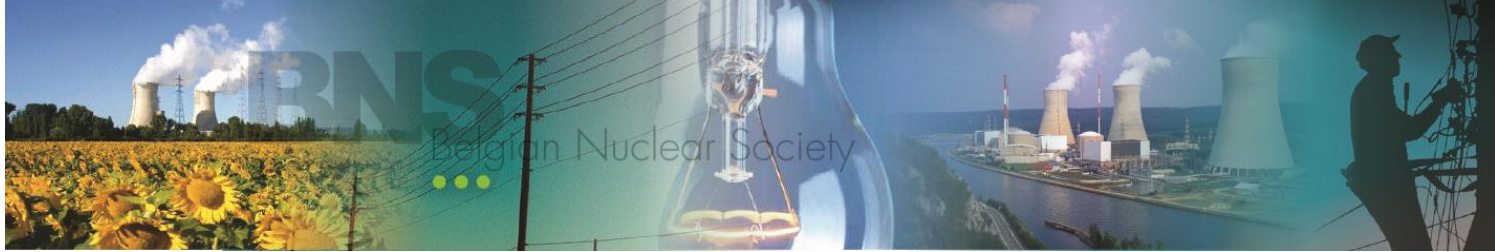
Source: Climate Action Tracker, data compiled by Climate Analytics, ECOFYS, New Climate Institute and Potsdam Institute for Climate Impact Research.

Picture extracted from [6]



COP 21 and nuclear

- The ambitions of the COP 21 agreement and the current level of engagement
 - Will force countries to proceed to massive decarbonation of their Energy Mix. All CO₂-free technologies are to be considered.
- The Paris Agreement neither defines energy technologies as low-carbon, nor specifies any energy technology*.
 - Instead, it describes “technology” in terms of research, development and demonstration, transfer, capacity building, needs assessment, action plans and project ideas, mechanisms, centers, committees and networks.
 - *: the word “CO₂” appears nowhere in Paris Protocol text. [22]
- All these are applicable to nuclear. **Consequently, all energy technologies, low-carbon and fossil, are on the table. [7]**
 - “Countries are free to specify nuclear to reduce their emissions in future updates of their Intended Nationally Determined Contributions”. [7]



The size of the climate challenge (1/2)

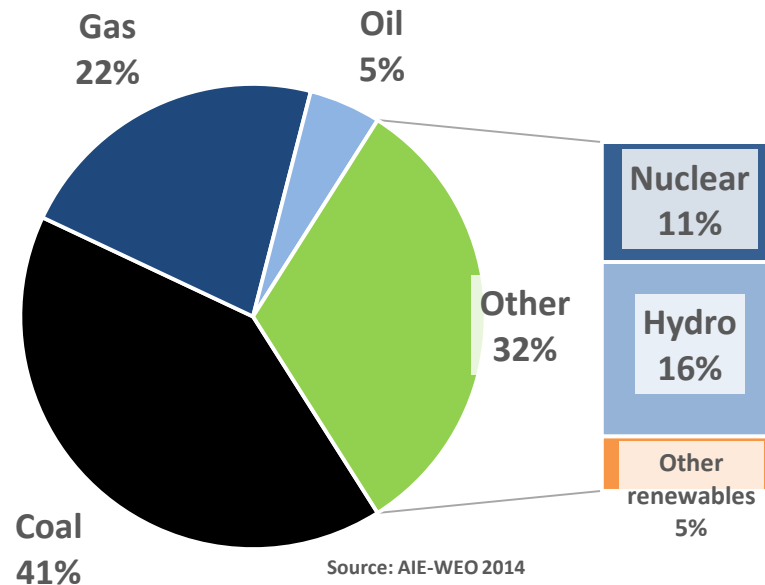
- To limit the temperature increase below 2°C in 2050..

..at least 80% of the world's electricity must be low-carbon by 2050.

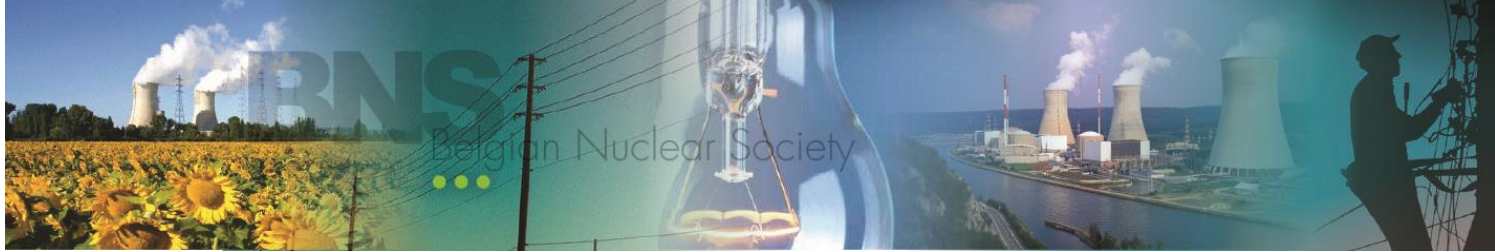
today, it is about 30%

Source: IPCC WG1 2014

2013 world electricity generation by source



This is a massive global challenge that requires the use of **all available low-carbon energy technologies.**



The size of the climate challenge (2/2)

- Major progress in energy efficiency will not be sufficient as the electricity demand is expected to double by 2050

By 2050

The world's population will be around 9.6 billion

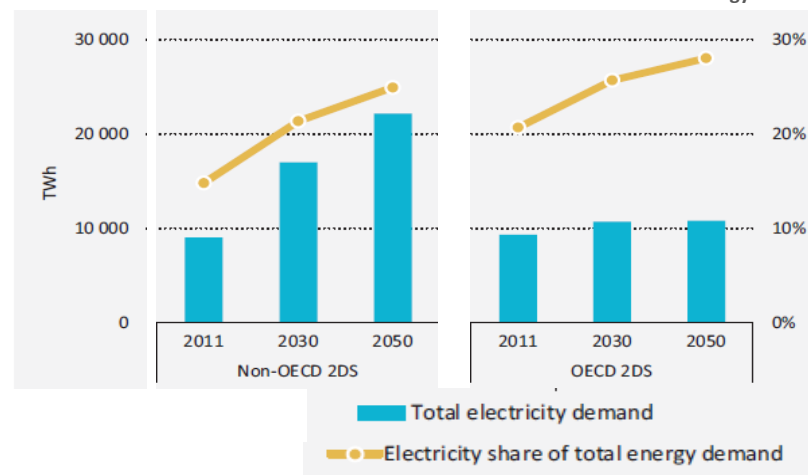
Today

1.2 billion people do not have access to electricity
2.8 billion use wood or other biomass products for cooking and heating

Source: UN, World Bank

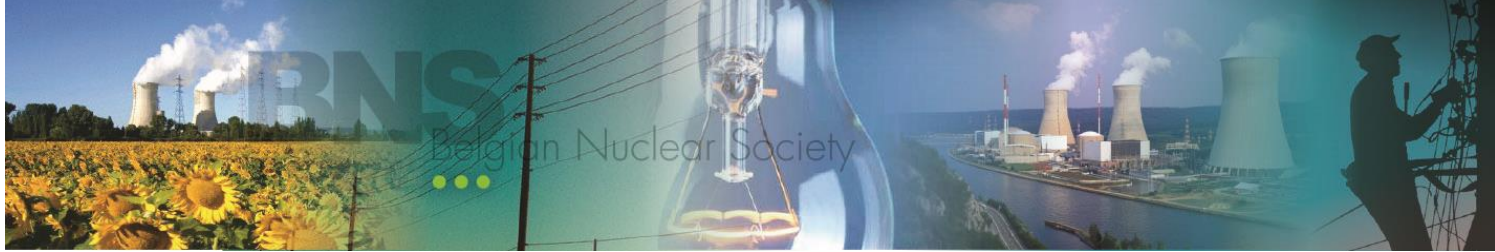
Electricity demand and share of electricity (IEA)

Source: AIE-AEN Technology roadmap 2015



- ✓ Strong demand from non-OECD countries
- ✓ Increased share of electricity in the overall energy mix, to decarbonize other sectors

- The fight against climate change should not jeopardize development

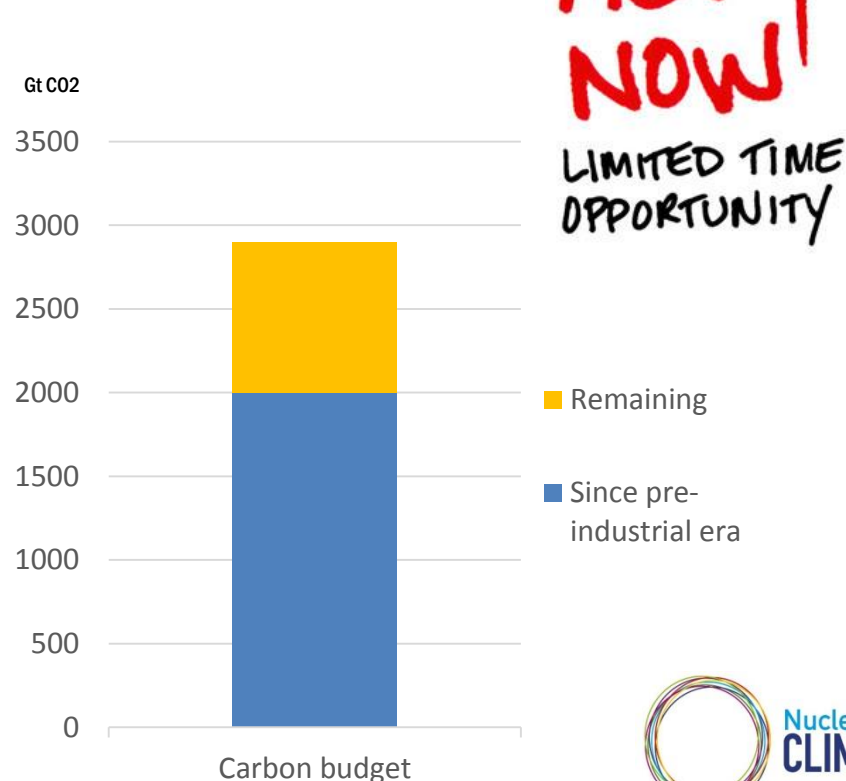


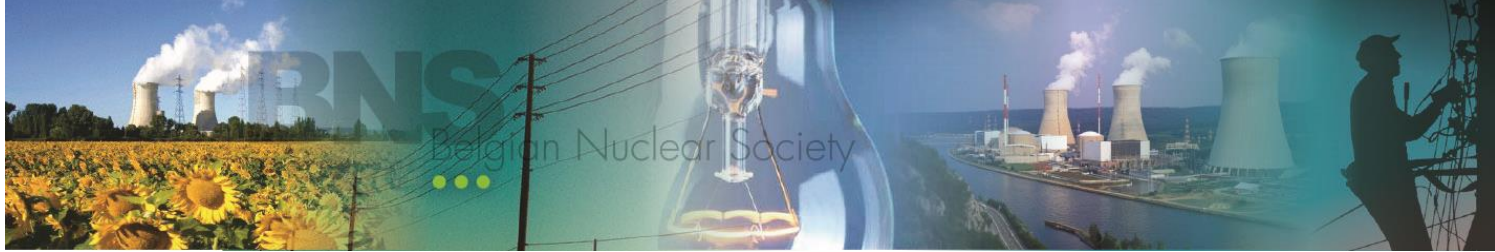
The URGENCY of the climate challenge

- It is urgent to use now all available low-carbon energy sources

- 70% of the carbon budget has been consumed
- Once released, CO₂ remains in the atmosphere for a long time.
- Carbon budget: cumulative CO₂ emissions that must not be exceeded if we are to contain average global warming to 2°C.

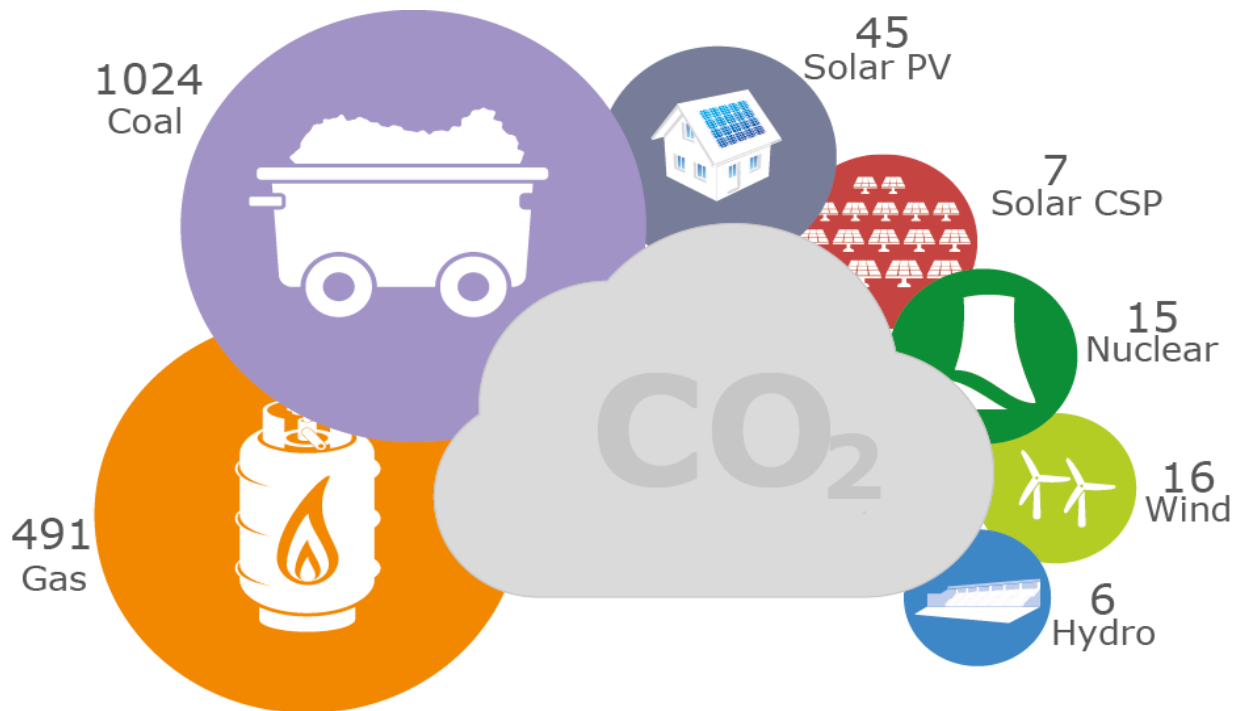
Source: IPCC





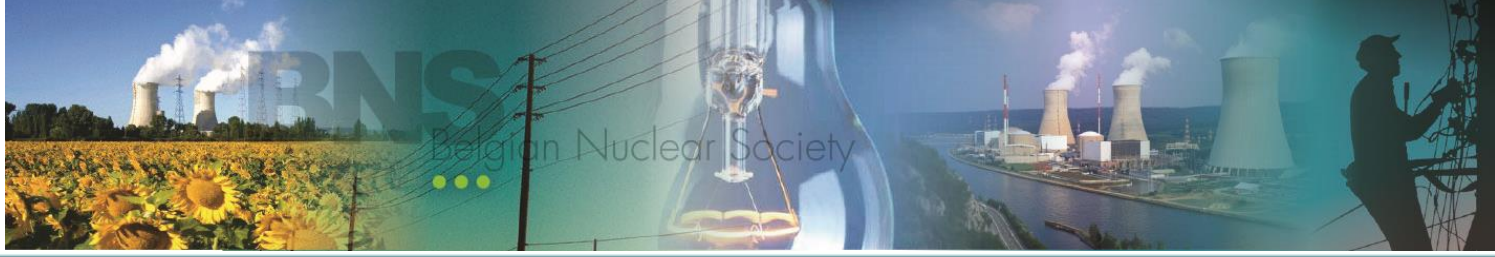
IPCC identifies 3 sources of low-carbon energies

- renewables, nuclear and CCS



Nucléaire et changement climatique – AIEA (2014)

- CO₂ emissions from nuclear energy are comparable to those of other non fossile/green energy sources.



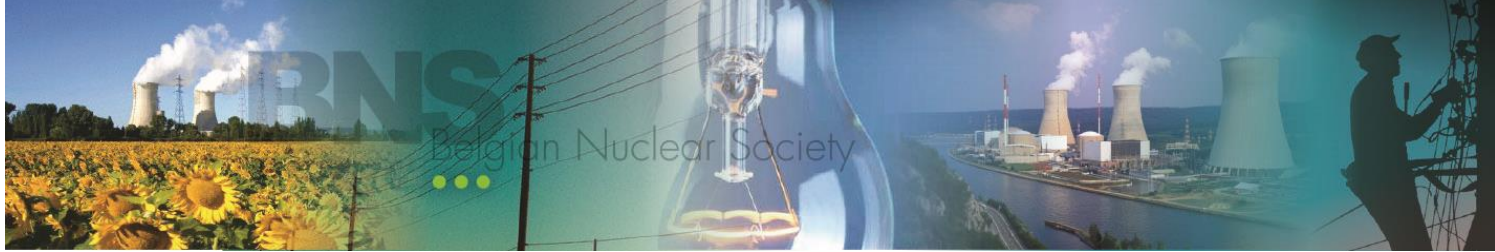
Part III

Presentation of 3 interesting studies

Reminder of some nuclear basic concepts used as assumptions for the studies to be presented

Presentation of the results of 3 interesting studies
([15])

Long Term Operation (LTO)
and CO₂

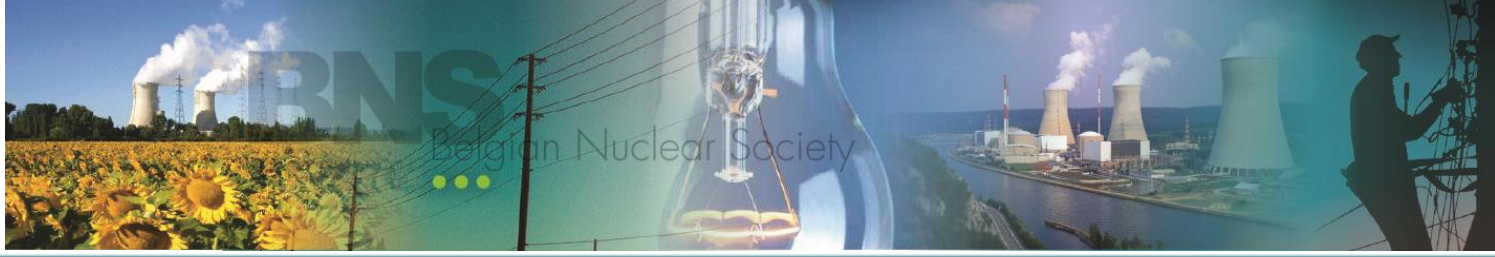


Some prerequisites needed to understand the assumptions of the studies presented

- The burnup
 - This is the combustion rate of the fuel assemblies used.
 - More the fuel is enriched, more energy may be released,
 - The longer it is used in the reactor (and as long as there are enough fissile material), the higher the burnup is,
 - But there are limitations to the enrichment and the energy released by the fuel rod (proliferation and mechanical resistance of the rod cladding)
- The yield
 - NPP are modeled by Rankine cycles.
 - Yield of the cycle is generally about 33%
- The Capacity Factor
 - is the ratio on a defined time period:

$$\frac{\text{actual output}}{\text{potential output if used at 100\% } P_{Nom}}$$

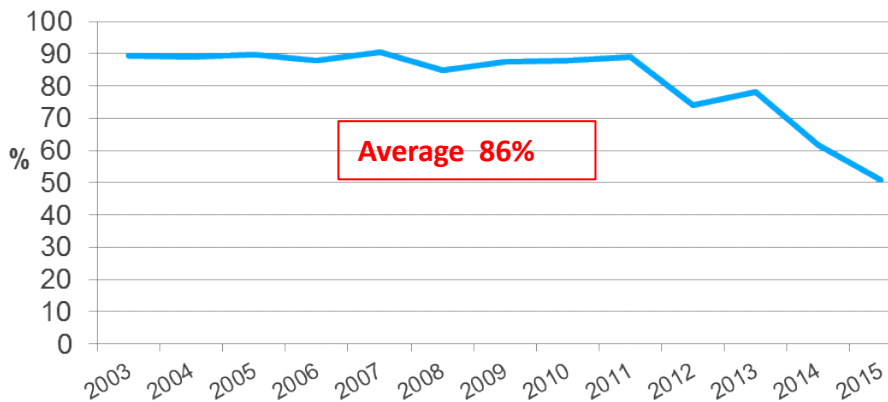
Sources: [18,19]



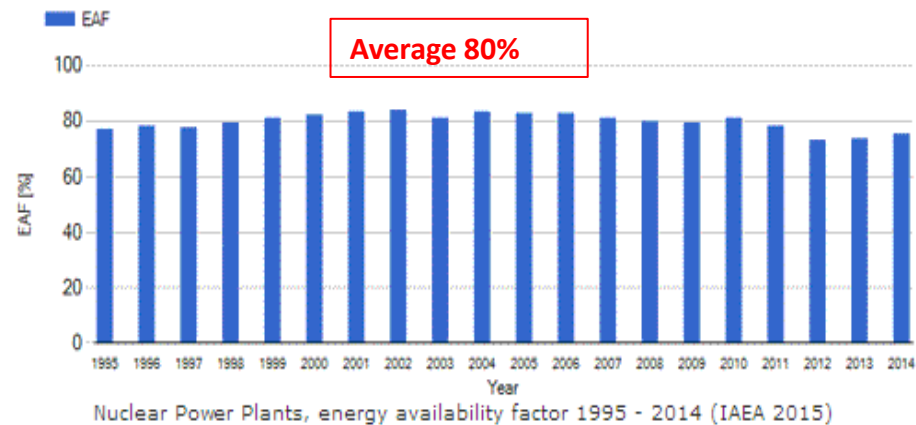
Remark: what is the Belgian availability factor ?

- Average Availability Belgian Park = 86%
 - Worldwide average availability factor <80%.

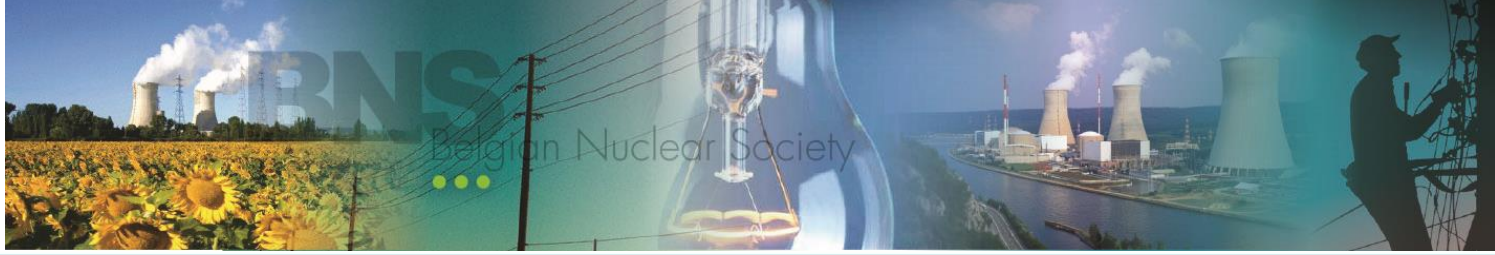
Belgian availability factor
(2003-2015)
Source: Electrabel



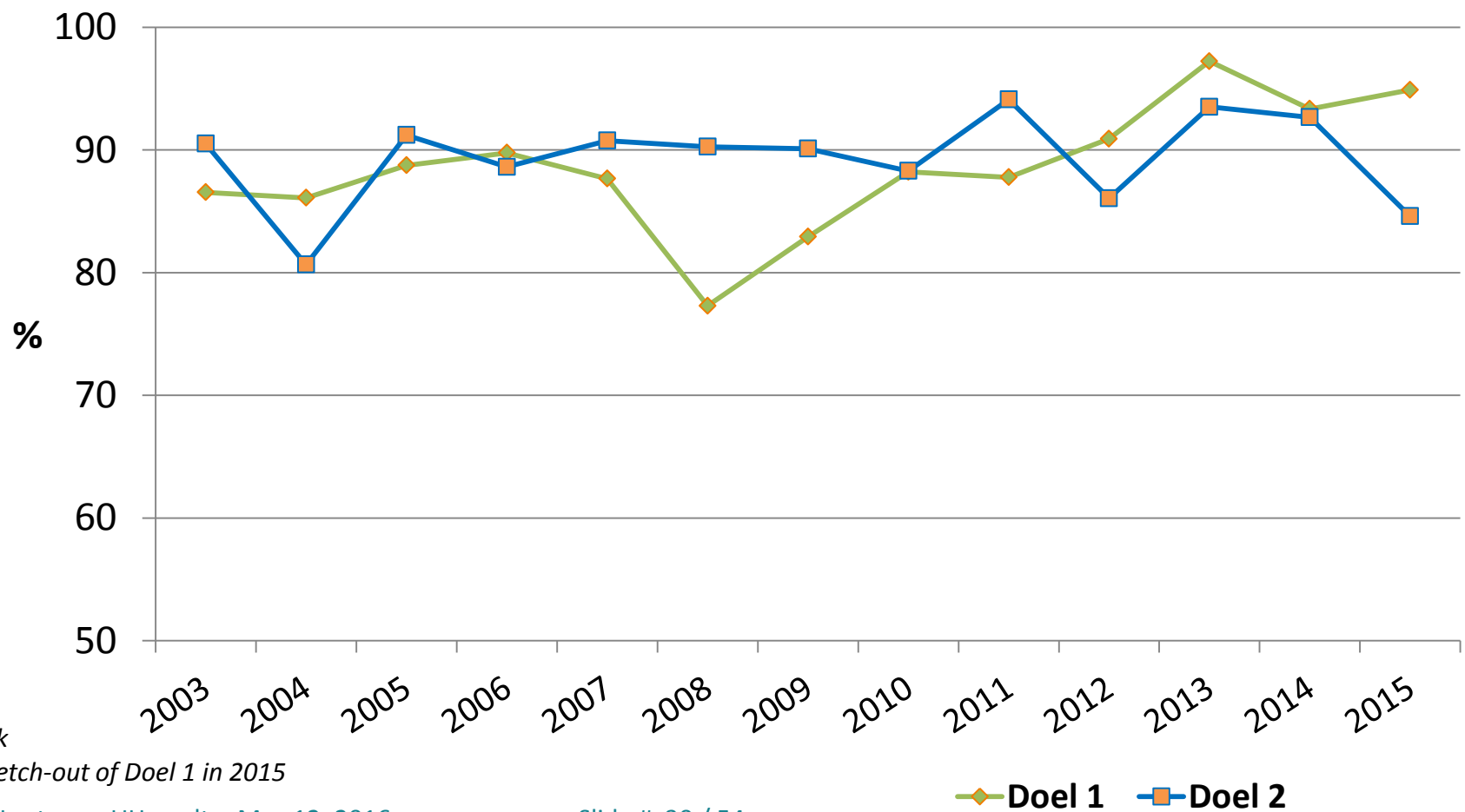
Worldwide average availability factor
(2003-2015)
Source: AIEA



Source: Electrabel

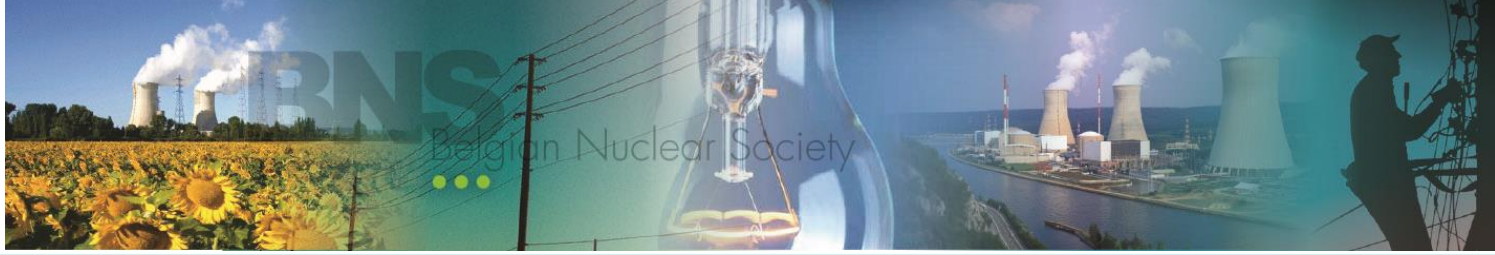


Backup slide - Availability of Doel 1 & 2

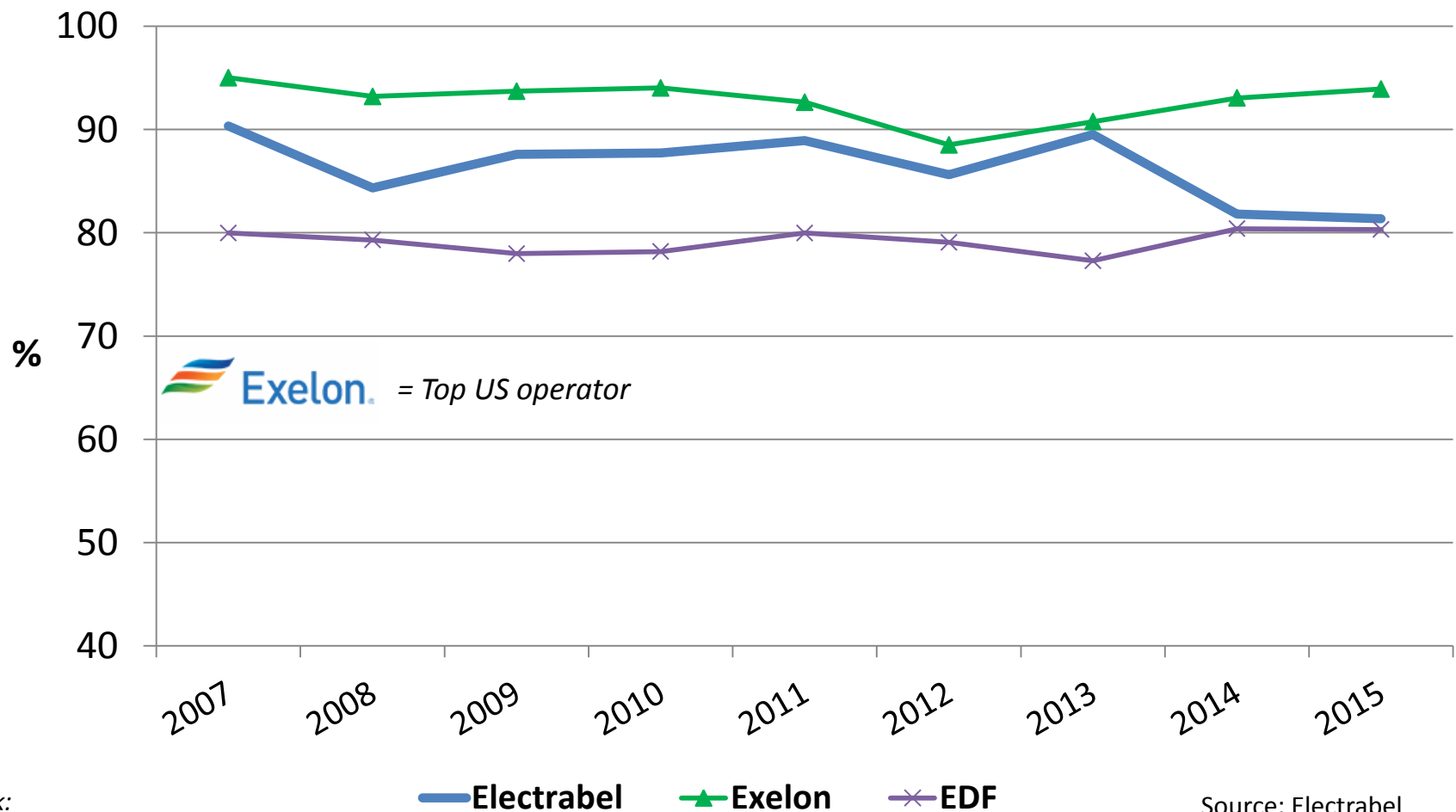


Remark

1. Stretch-out of Doel 1 in 2015



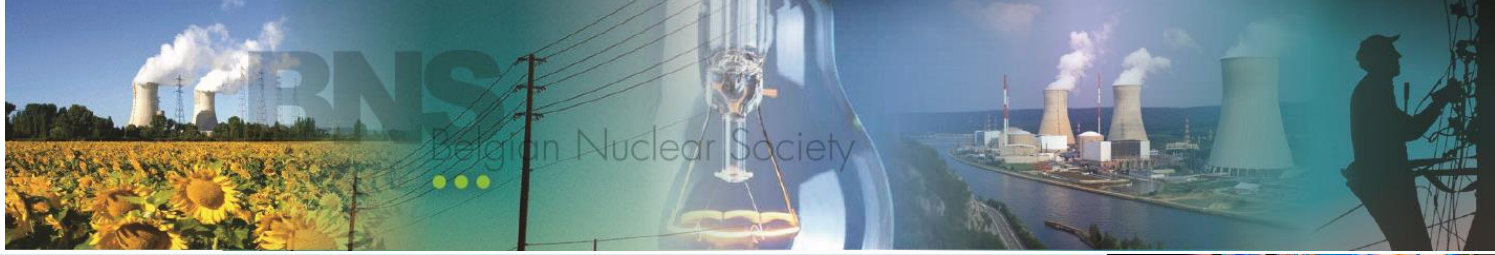
Comparison with top players



Remark:

1. Data Electrabel = Except shutdown D3 and T2 (DDH)

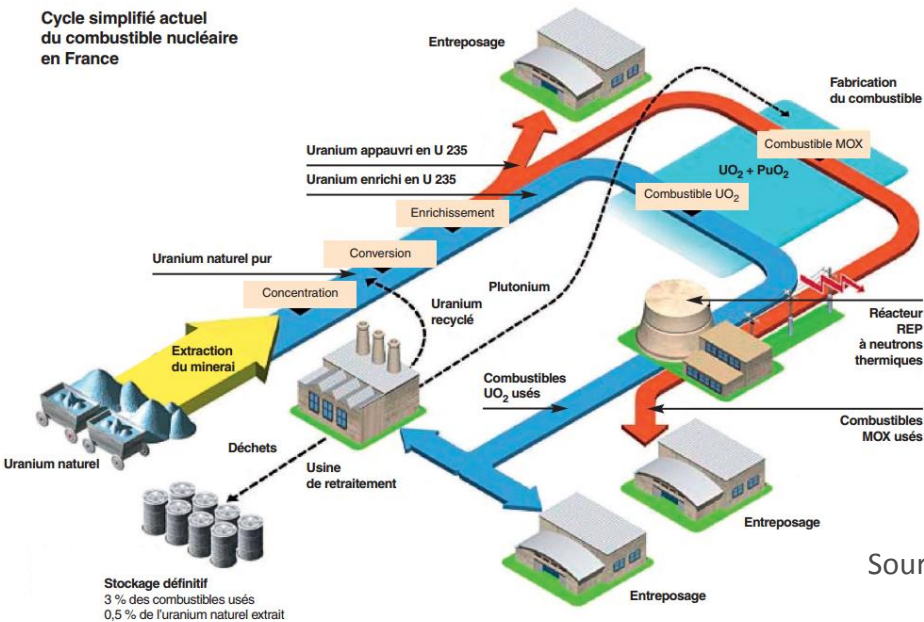
Source: Electrabel



Some prerequisites

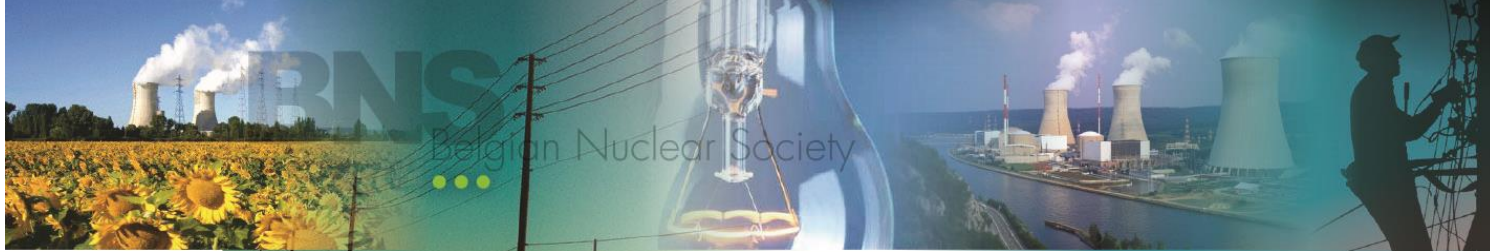
- Ore quality
 - The content in U_3O_8 in natural stones is about 0.1% (order of magnitude in the USA, [20], [21]).
 - The lower the content, the higher the extraction must be done to retrieve a sufficient quantity of the mill.
 - The content in natural uranium of ^{235}U is about 0.7%.
 - The product (UF_6) exiting the conversion chain and entering the enrichment process has the same content.
- But... enrichment is highly energy consuming!

Cycle simplifié actuel
du combustible nucléaire
en France



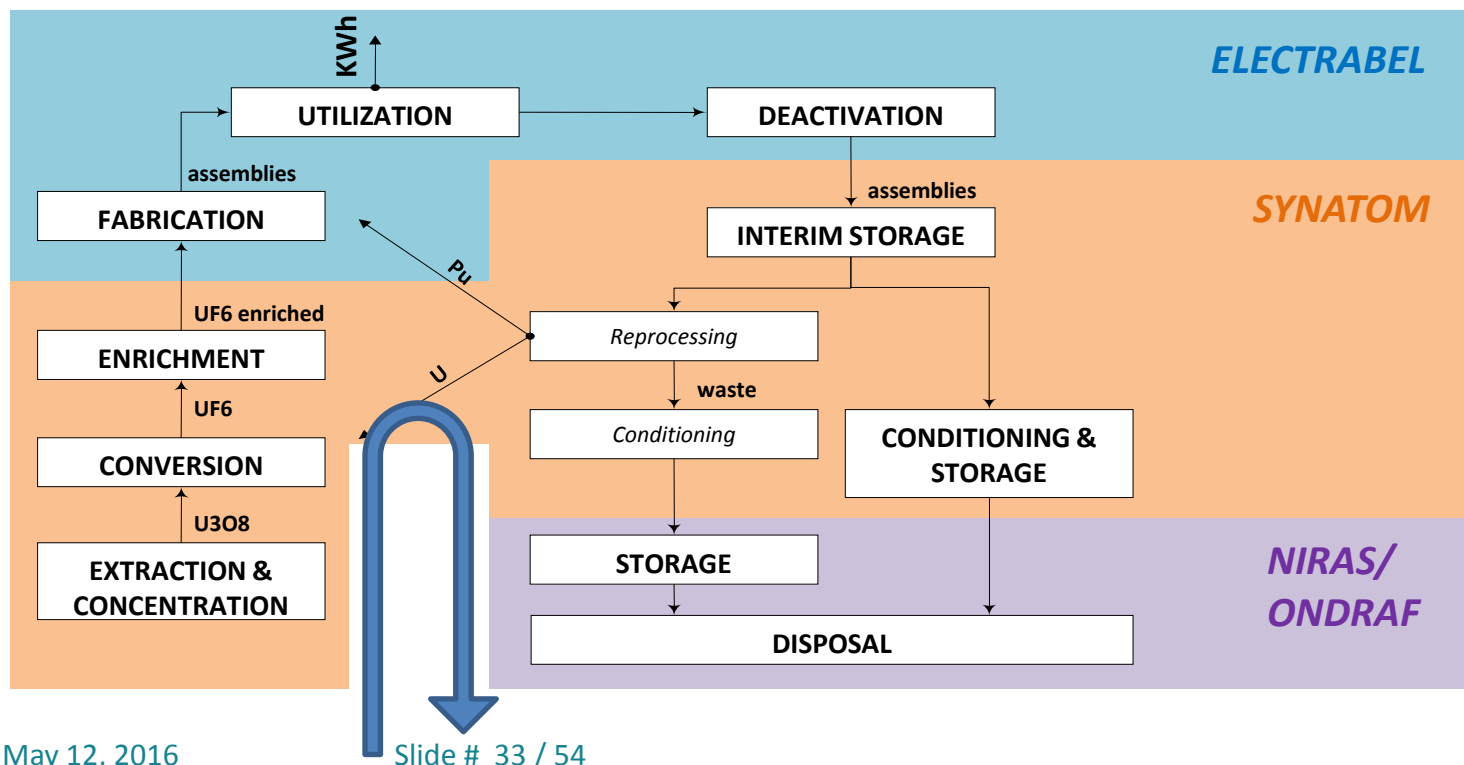
Source [8]



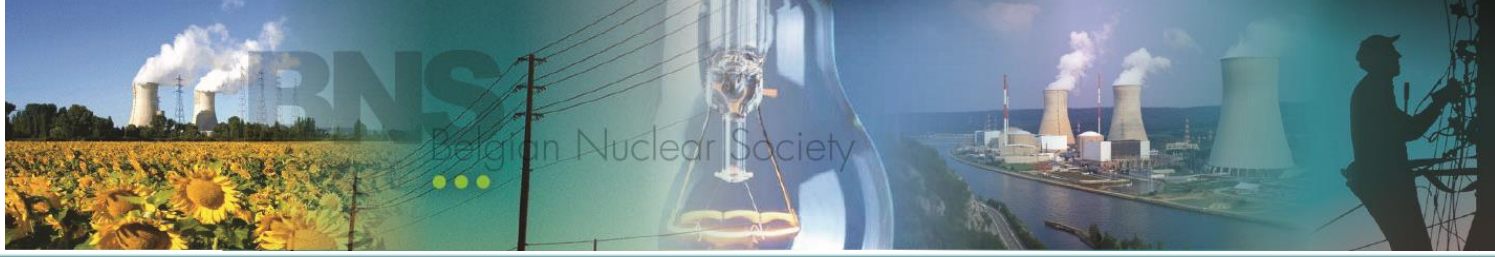


Backup slide - Responsibilities in the Belgian nuclear fuel cycle

- **ELECTRABEL** : Nuclear operator
- **SYNATOM** : Front- & Back-end management + Long term provisions
- **NIRAS** : National organization in charge of radwaste management



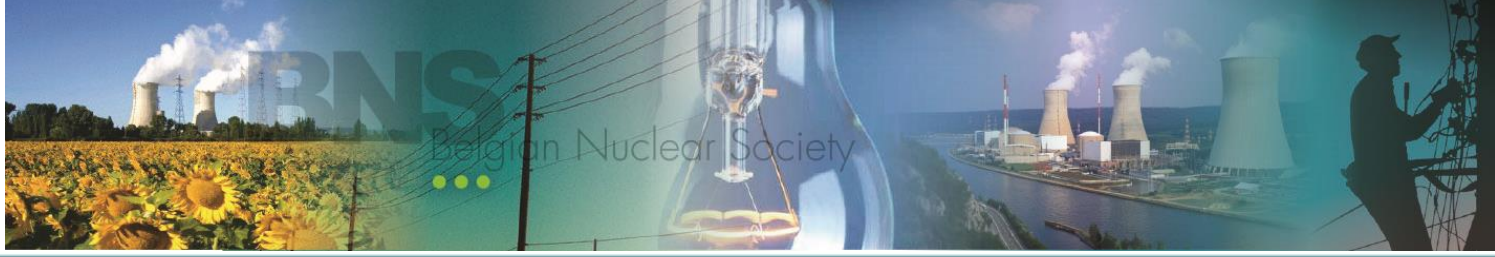
Source: [13]



VITO & KUL - assumptions

- Vito Study: ordered by Belgian electricity producers (Electrabel and SPE) [1998].
- KUL study: performed for the same research project
 - Both have been combined here
 - Main assumptions of the model

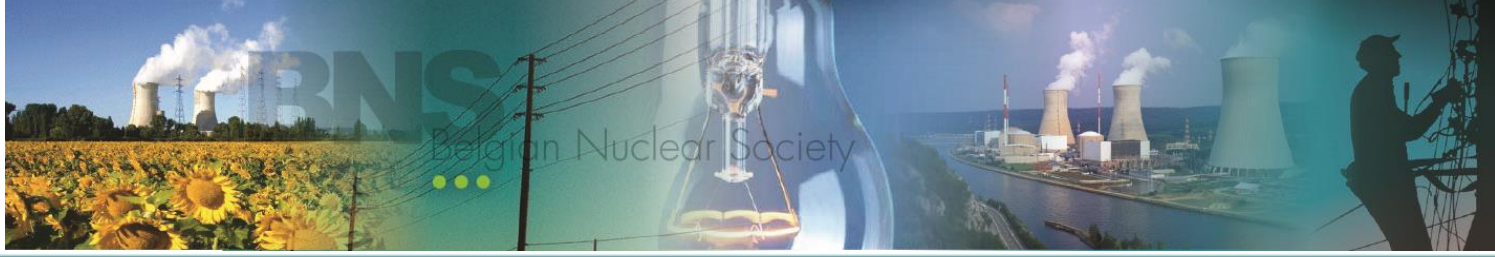
	Assumption
Burn up [<i>MWd/kg U</i>]	45
Yield of the NPP [%]	33
Capacity factor [%]	85.4
Life time of the plant	40
Ore quality [% U_3O_8]	0.2



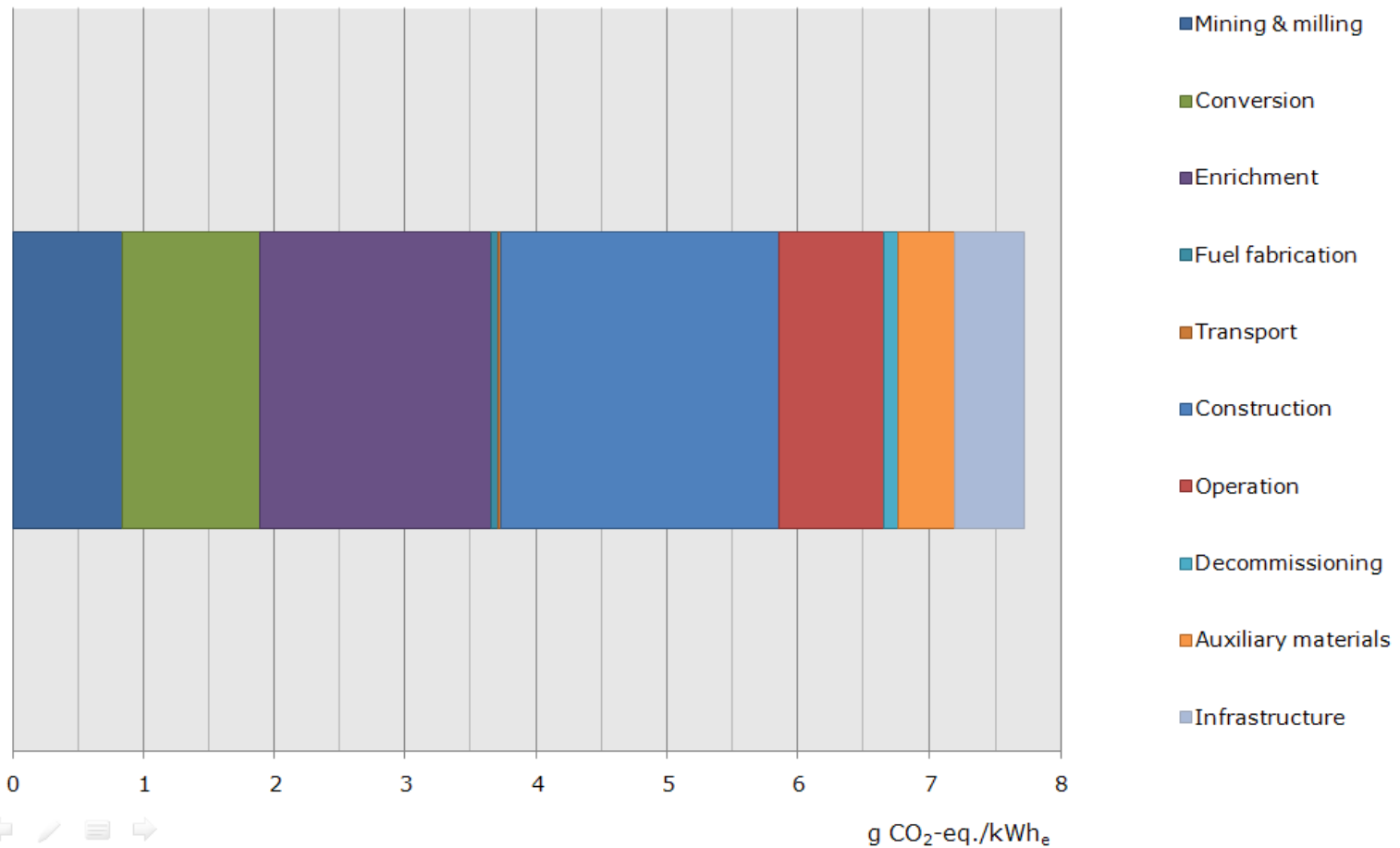
VITO& KUL goals and main result

- The purpose of the study was the evaluation of
 - Greenhouse and acid gas emission and the energy consumption from the starting up to the decommissioning [Vito]
 - Electricity generation units as final customer [Vito]
 - Indirect emissions coming from electric power plants during their life time (Construction, Operation and decommissioning of so called 'emission-free' power plants) [KUL]
- Main result for NPP
 - 7,7 g CO₂-eq./kWh_e
 - Range: 5,9 - 16,5 g CO₂-eq/kWh_e

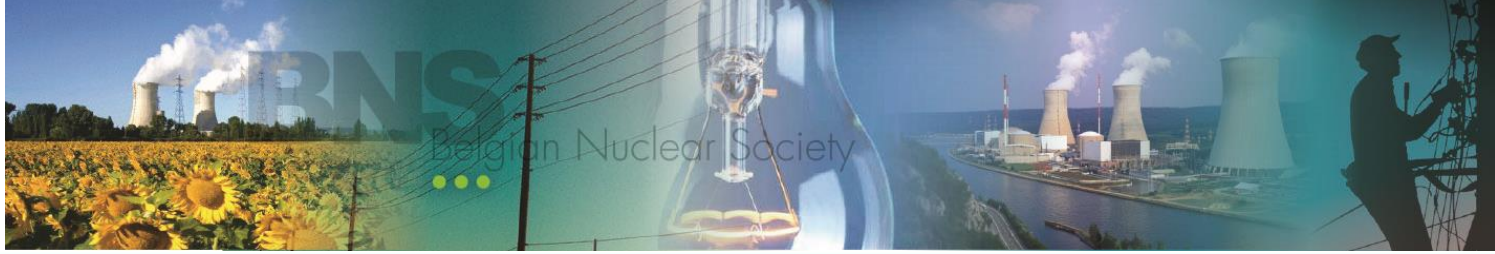
Source: [15]



Synthesis VITO/KUL study



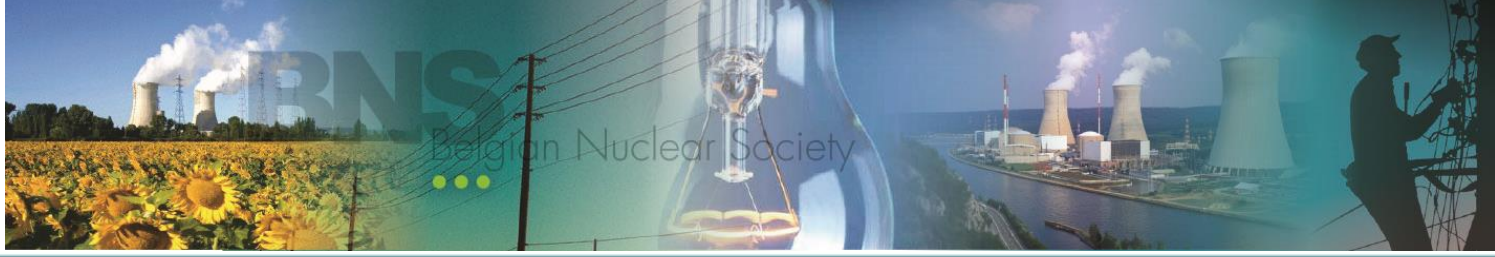
Source: [15]



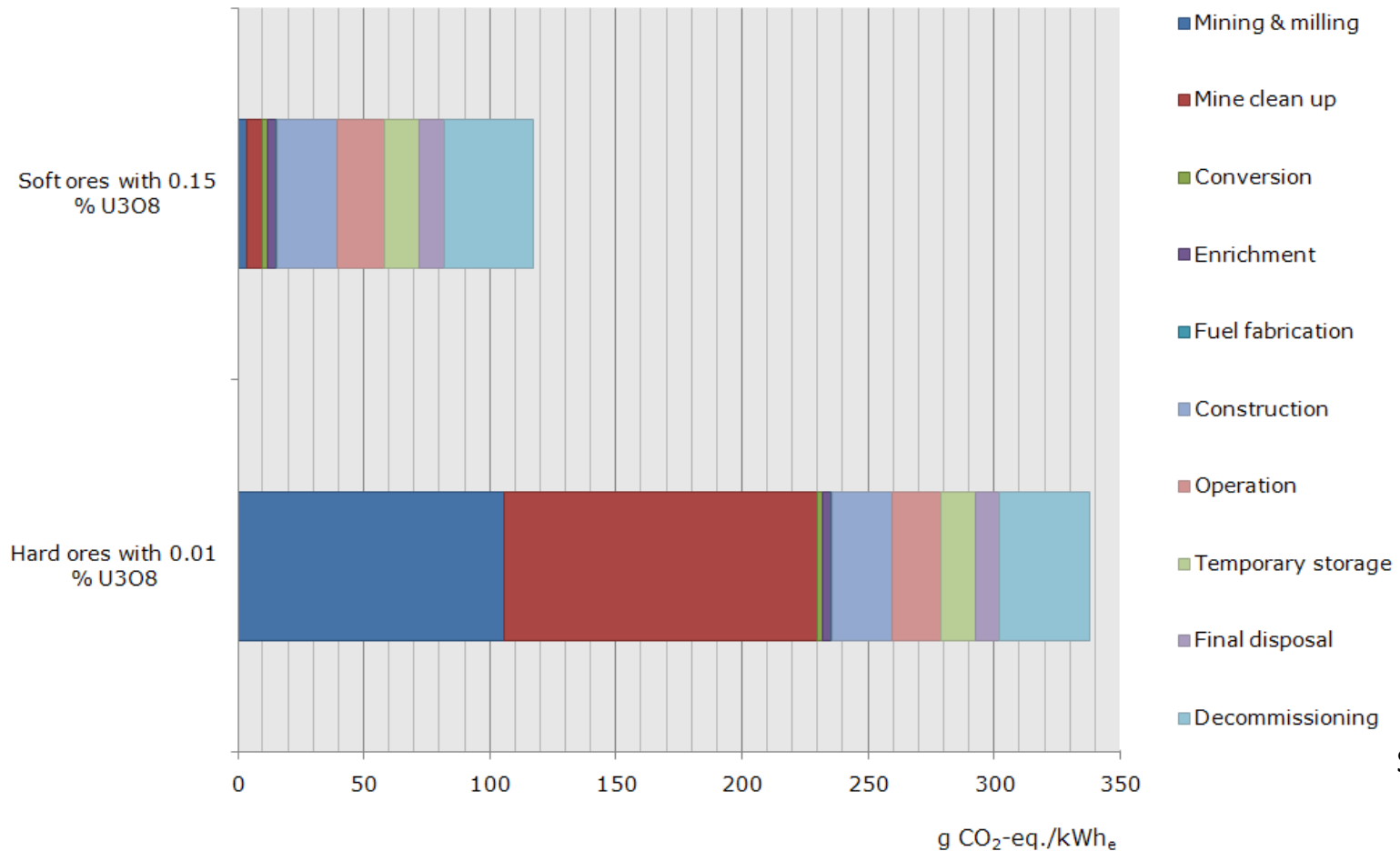
Study of Storm van Leuwen and Smith

- Study ordered by the green parties in the EU parliament
- Results range from 110 to ~340 g CO₂-eq./kWh
 - To be compared with the 5,9 to 16,5 g CO₂-eq./kWh of the KUL-VITO study
- The study considers two scenarios
 - One corresponding to the current situation
 - Uranium ore corresponding to world average (0.15% U₃O₈)
 - Result: 110 g CO₂-eq./kWh
 - One assuming a decreasing Uranium quantity
 - Mining of lower quality ores (0.01% U₃O₈)
 - Result: 340 g CO₂-eq./kWh
- Second study
 - nuclear not a long term solution, as Uranium availability decreases

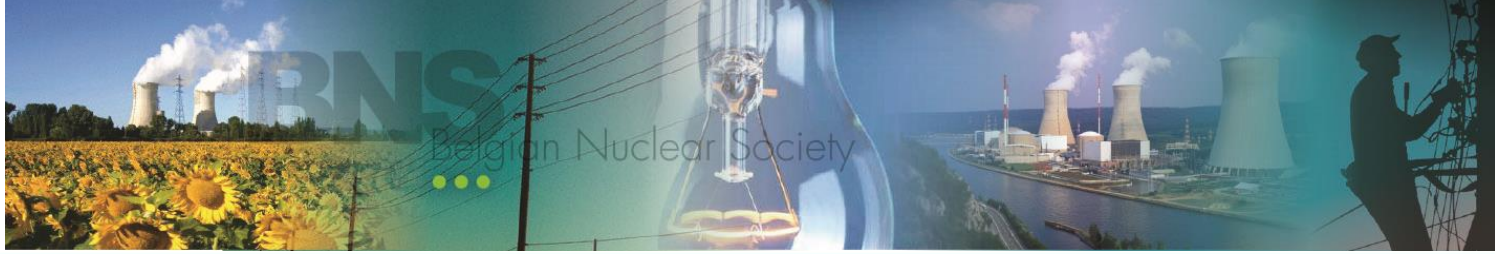
Sources: [15,17]



Study of Storm van Leeuwen and Smith - Overview



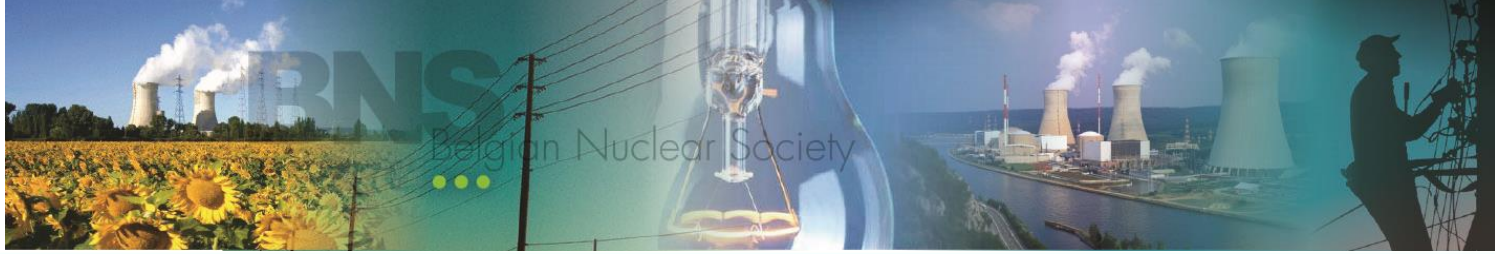
Source: [15]



Study of Storm van Leeuwen and Smith - Comments

- The main difference between the results comes from:
 - Mining and milling
 - Mine clean-up
- Mining and milling
 - Highest estimates used for mining
 - Fact that other materials can be mined at the same time (with splitting of energy costs) not taken into account
 - No consideration of “G4” reactors
- Mine clean-up
 - Only study taking this step into account
 - Based on an hypothetical model
 - Difficult to validate the model due to the lack of data

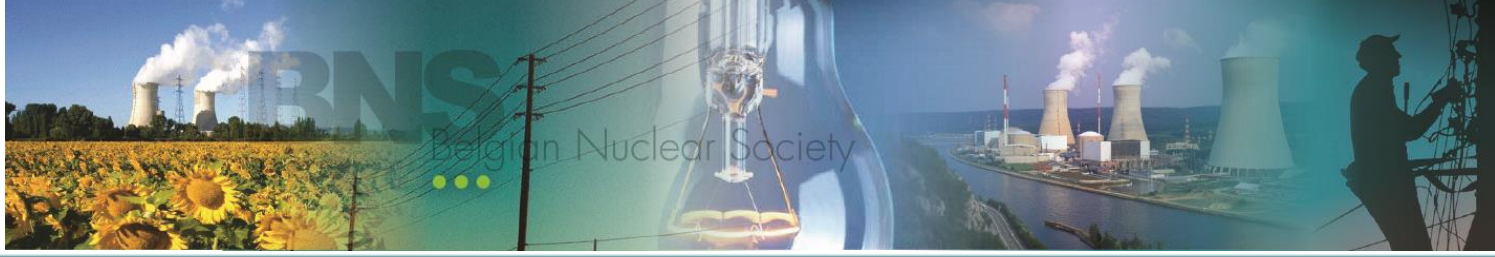
Sources: [15,17]



Study of Storm van Leeuwen and Smith – Comments (2)

- For the current situation scenario, one of the main GHG costs is the construction
 - Estimation based on the monetary cost of the construction in the US
 - Large range (1.4-6G\$[1982] / GW)
 - This cost is then multiplied by “energy spent per dollar spent” factor corresponding to the construction sector
 - Many factors not taken into account, as for example the fact that the cost depends also on administrative tasks and licensing
 - Much larger results than the two other studies

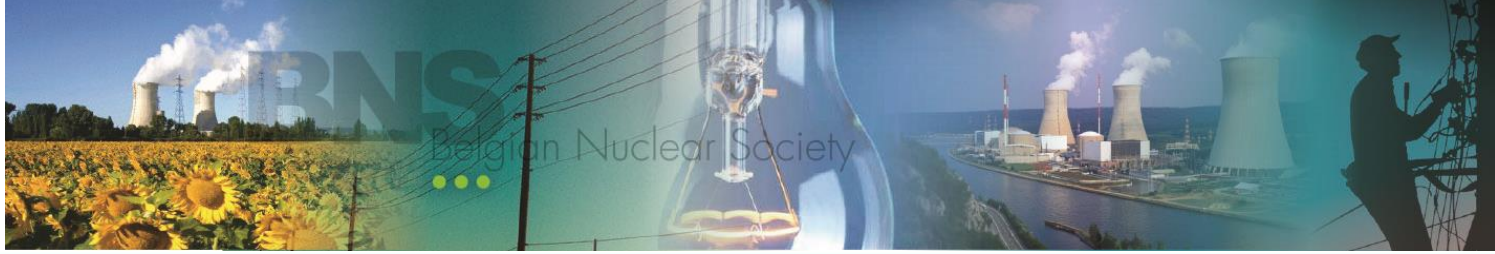
Source: [15]



Study of Storm van Leeuwen and Smith – Comments (3)

- Very high estimates used for the energy expenditure of the construction
- Overall impact on the final result
 - Decommissioning and Final Disposal energy expenditure related to construction costs
 - For the current situation scenario, construction and decommissioning amount to $\sim 50\%$ of the total
- Assumed lifetime (29 years) has consequently a great impact on the final result

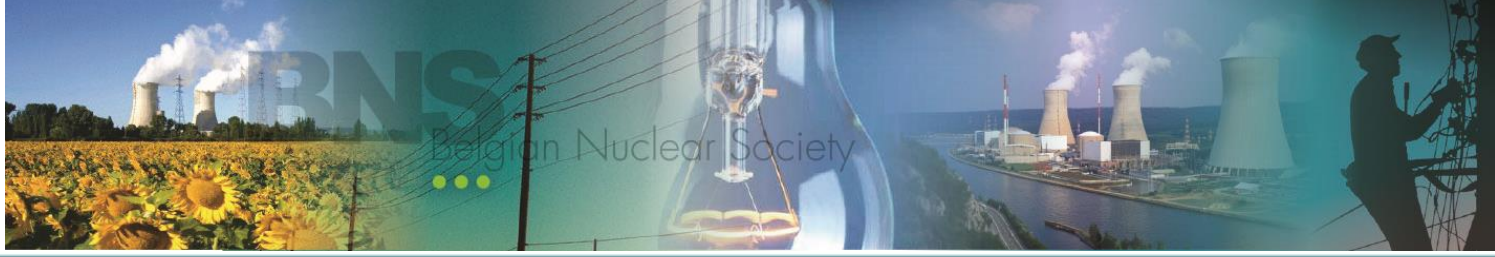
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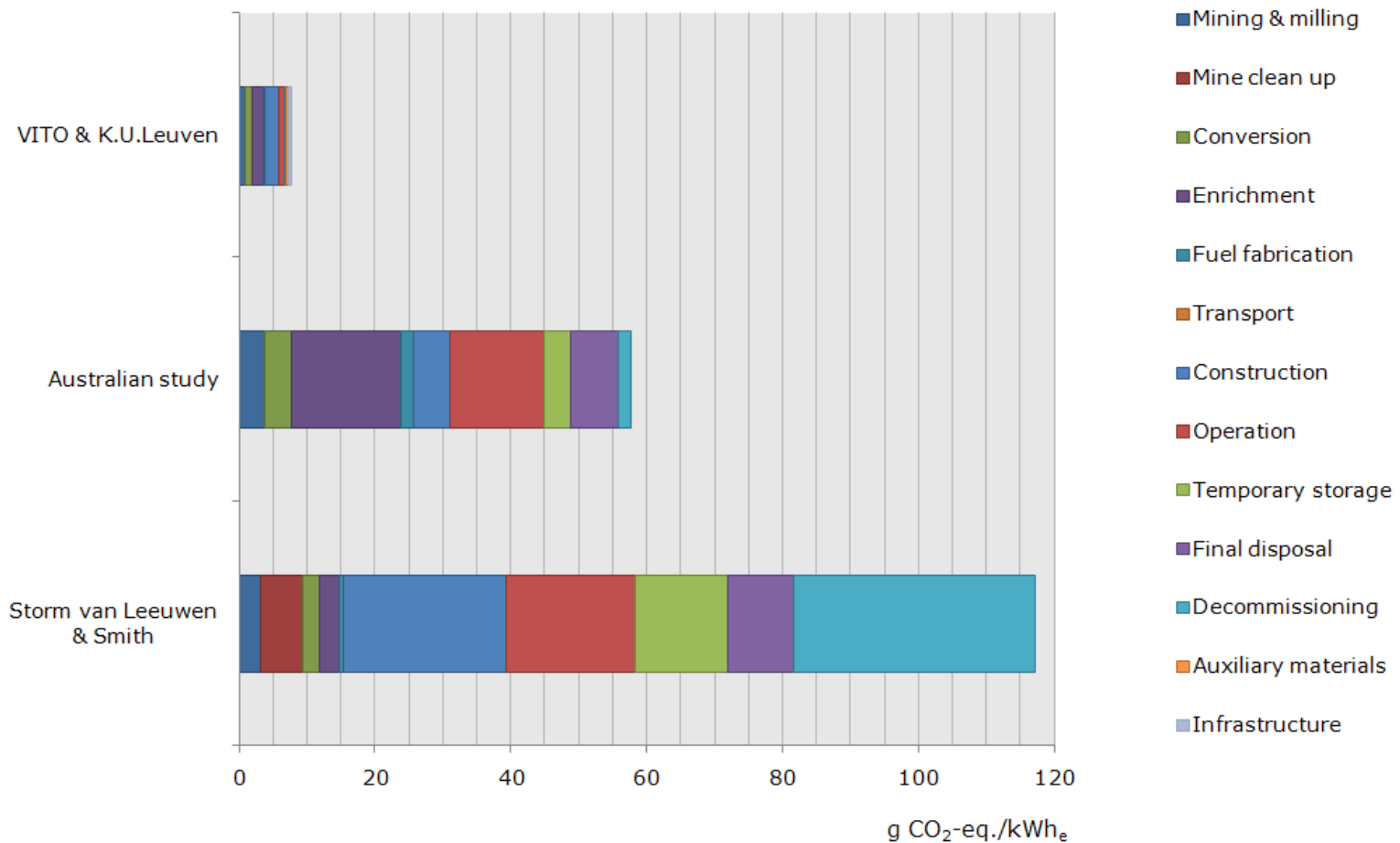
Australian study (Lenzen et al.)

- This study (2006) ordered by Prime Minister of Australia
 - Goal: evaluating the nuclear option for decreasing GHG gas emissions
- Large range of values
 - 10-130 g CO₂-eq./kWh
 - 57.7 g CO₂-eq./kWh as a best-estimate for Australia
- Results in between those of the two previously discussed studies
 - KUL-VITO: 5,9 - 16,5 g CO₂-eq./kWh
 - Storm Van Leeuwen, Smith: 110 - 340 g CO₂-eq./kWh
- Mine clean-up not taken into account

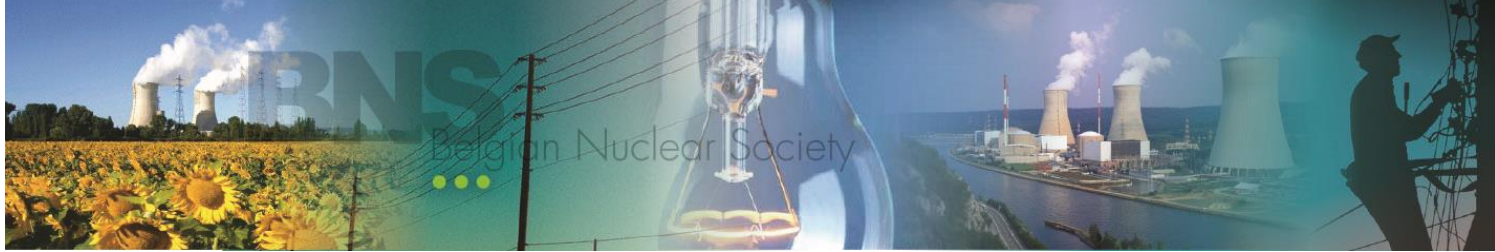
Source: [15]



Overview of the three studies for current situation



Source: [15]

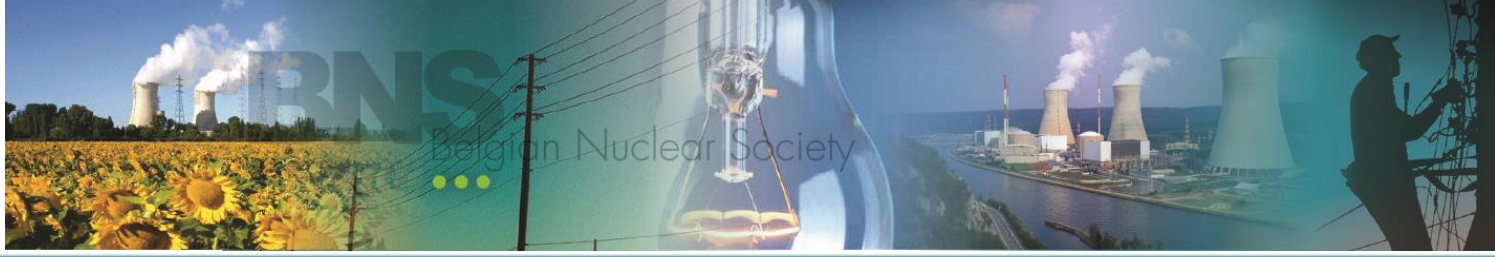


Long Term Operation (LTO) & CO₂

- As it has been shown, several assumptions have been made for the life time of the NPP and for energy used in the construction/dismantling:

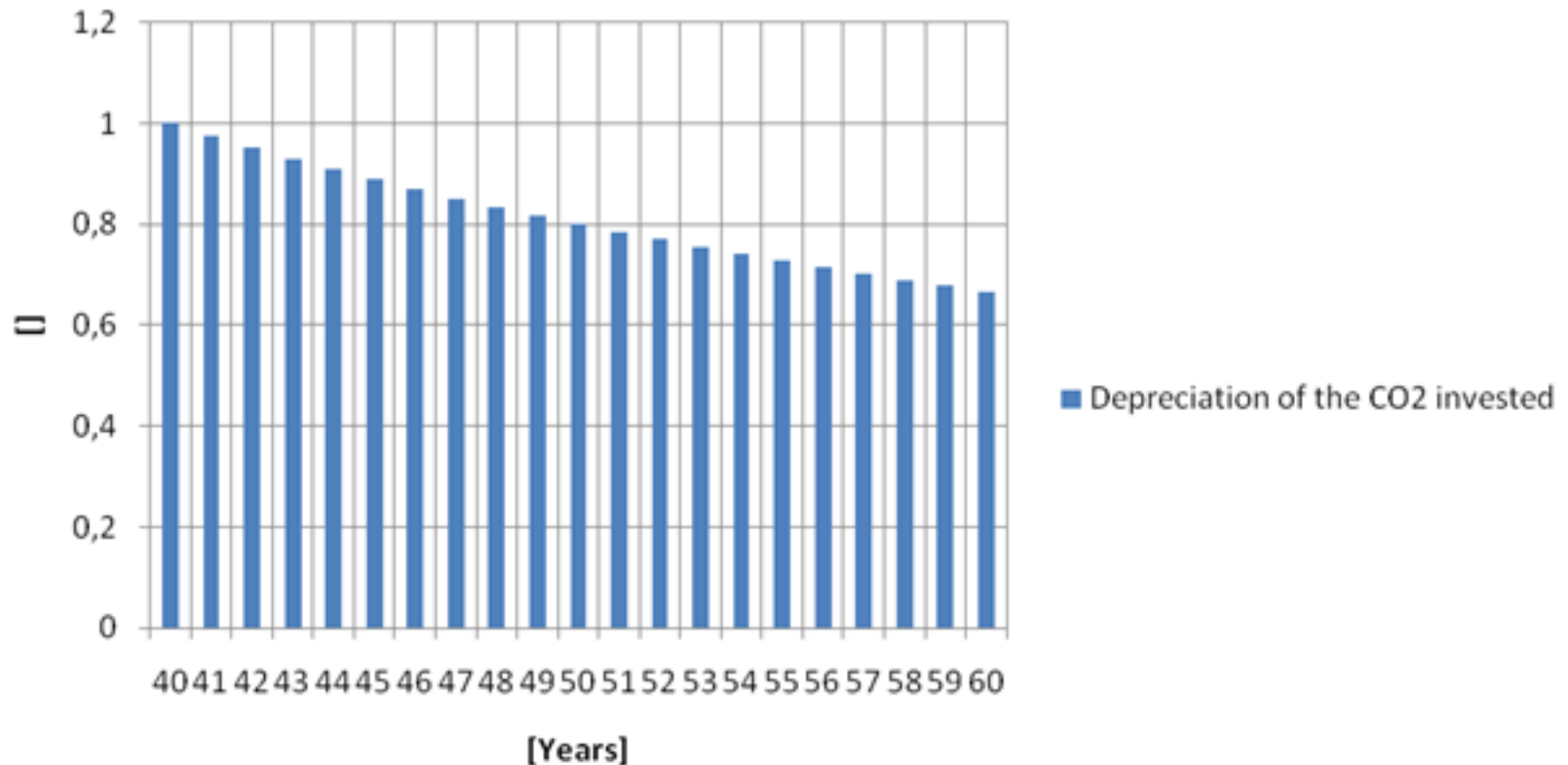
Study	NPP life time [years]	Energy for the construction [GWh _p /GWh _e]	Energy for the decommissioning [kWh _p /kWh _e]
Vito & KUL	40	1500-3972	0.0004
SvL&S	29	28854	0.2060
Australian study	35	4100	0.0058

Source: [17]

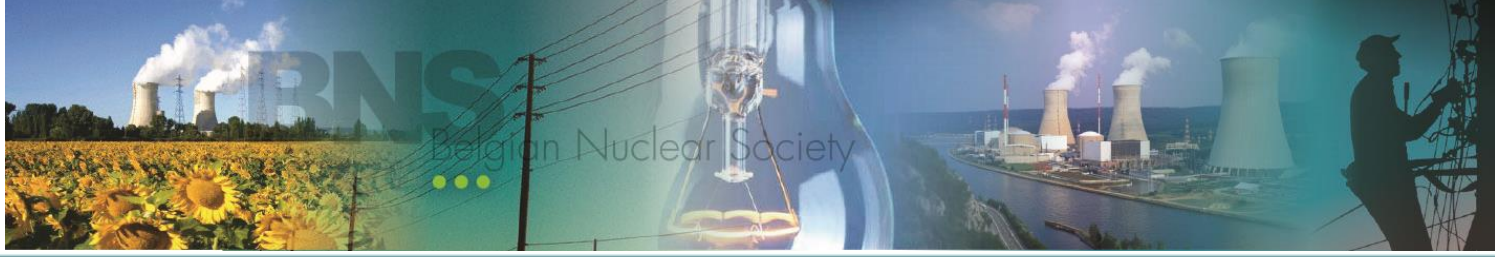


Ratio Energy used for the construction / years

LTO and Energy used for the construction

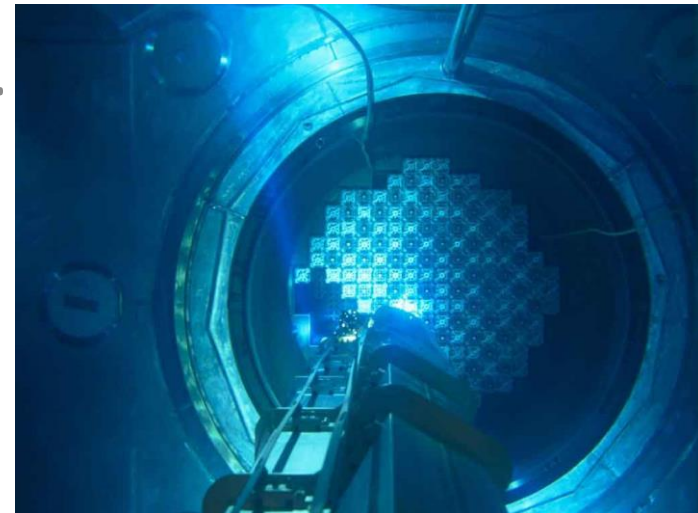


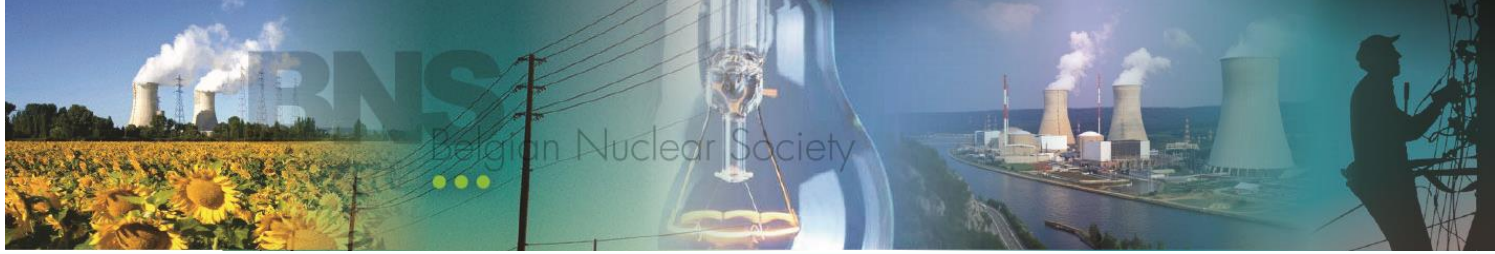
Source: [17]



Part IV Conclusion

Conclusion
Question Time...

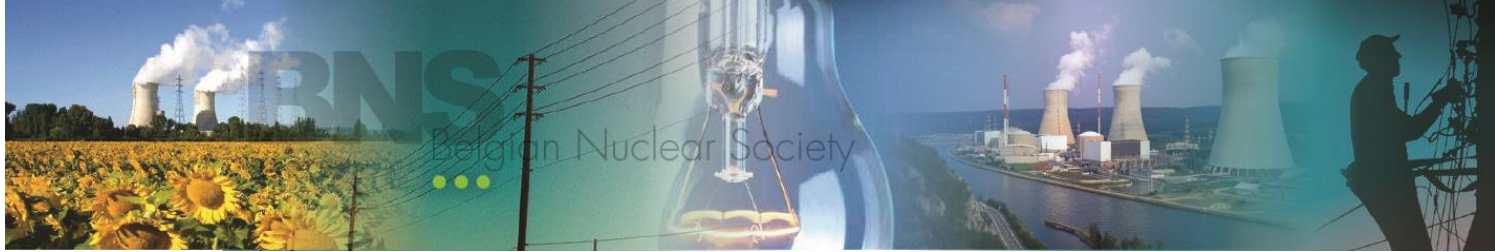




Conclusion

- Evaluating indirect emissions is difficult
 - Depends on the assumptions, models used, data available
 - Many steps taken into account
- The three studies have weaknesses
 - Most pessimistic study corresponds to prospective scenario, which uses excessively high estimates
- For current situation studies, most pessimistic one leads to results far below those of fossil-fuel fired Power Plants
 - Green Energy as solar photovoltaic have also high CO₂ costs
 - Results get better with a higher lifetime

Sources: [15,17]

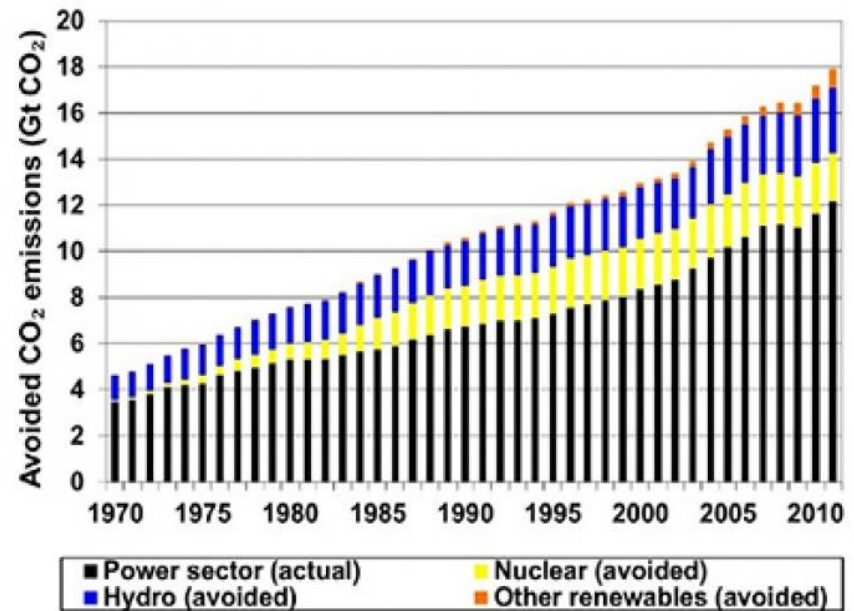


Nuclear energy is an available, low-carbon and efficient industrial solution, that has been proven efficient

- 438 nuclear reactors in operation, nuclear energy is available in 30 countries.
- Today, only 6 countries above 80% goal of low-carbon electricity, 4 of them have nuclear.

	Sweden	40% nuclear
	Switzerland	40% nuclear
	France	75% nuclear
	Brazil	2 nuclear reactors

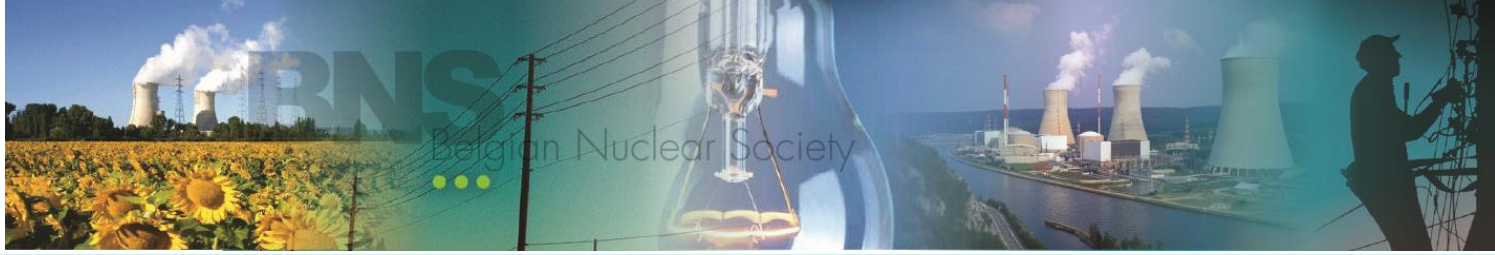
Source: IAEA, IEA



Source: WEO 2014

Since 1971 nuclear power has avoided the release of the equivalent of **2 years of CO₂ emissions**.

By 2040, nuclear power should save the equivalent of **4 years of CO₂ emissions**.



Excluding any low-carbon technology (such as nuclear) undermines climate mitigation efforts



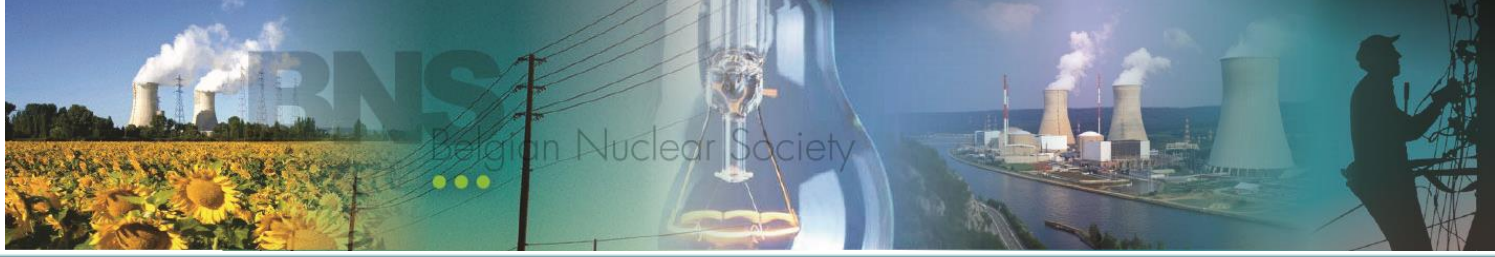
IPCC WG3: only **8** scenarios out of **1 200** allow limitation below 2° and **nuclear phase-out**.

Very few scenarios enable to limit global warming below 2° without nuclear

"There is no credible way to climate stabilization that does not include an important role for nuclear energy....we cannot afford to turn our back on any technology".

*Open letter from environmentalists,
Washington Post, Oct 2013*

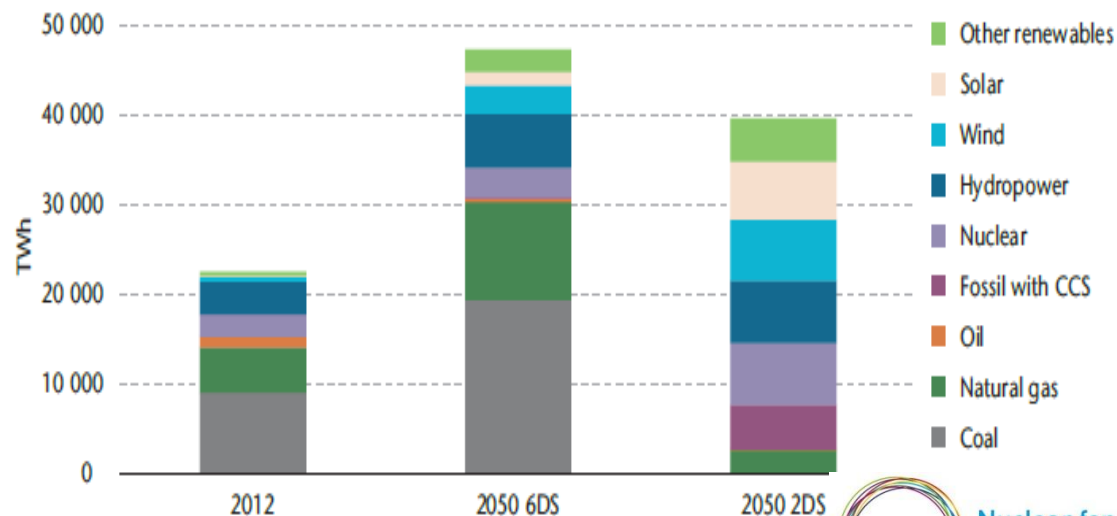
UNFCCC Protocols must allow countries who wish to use nuclear energy to have access to climate change financing, as is the case for other low-carbon energy sources.

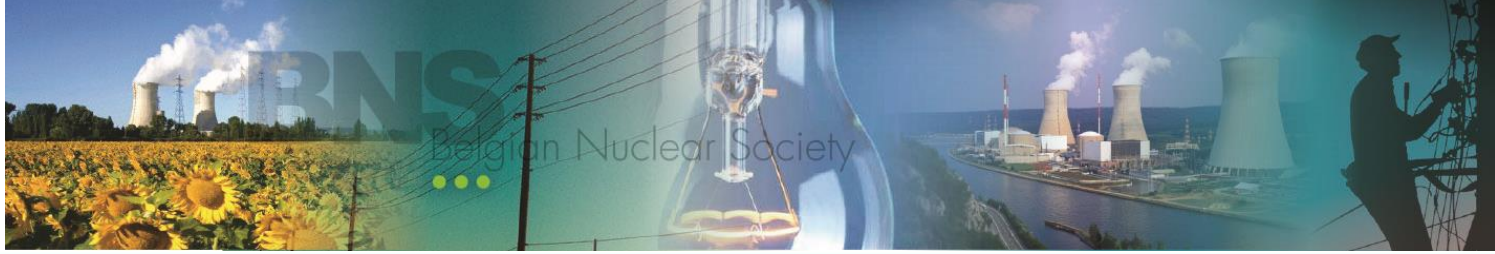


IEA forecasts a doubling of nuclear capacity by 2050

- The 2DS scenario
 - most efficient way to remain below 2°C
- IEA forecasts nuclear capacity would increase by 2050
 - from 400 GW to 930 GW
 - The share of nuclear energy in the electricity mix would increase from 11 to 17 %

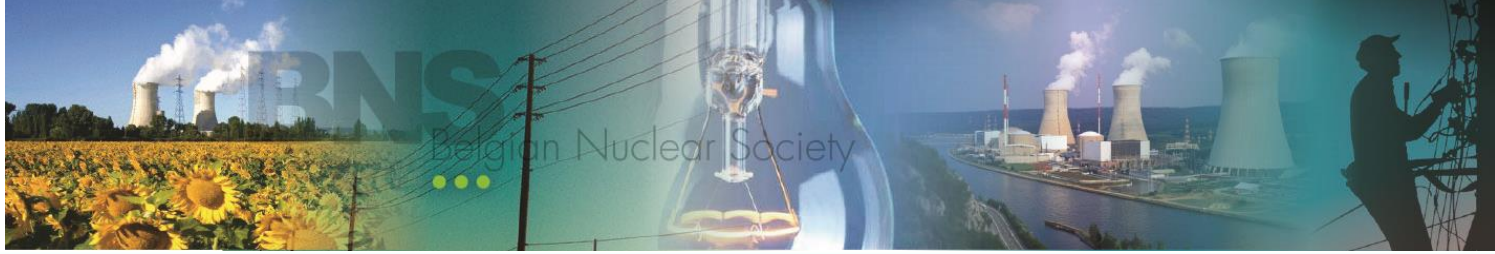
Figure 3: Electricity production by technology in the 6DS and the 2DS





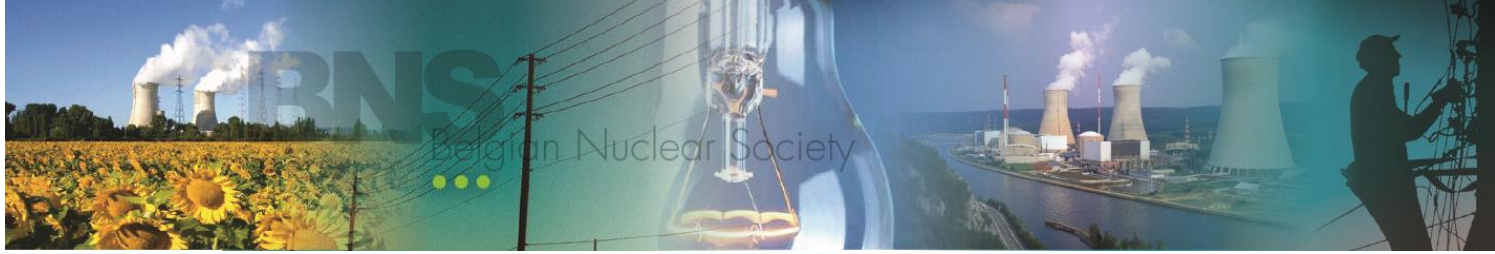
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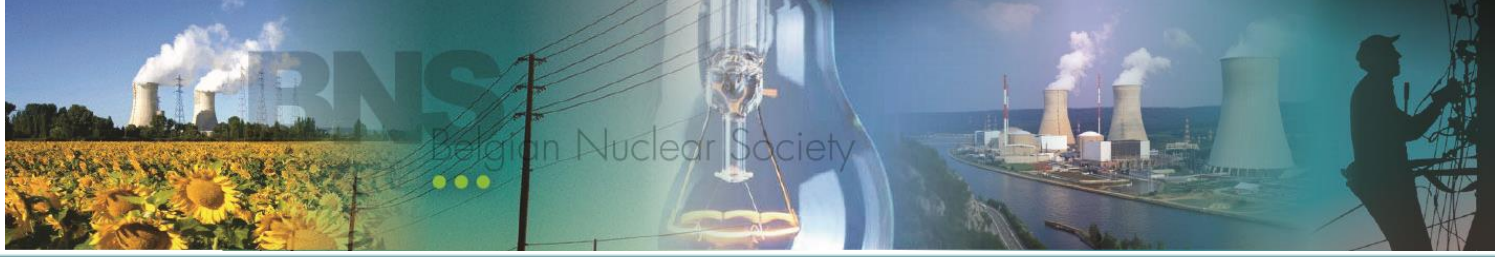
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Thank you for your attention!

Questions?