Centro de Altos Estudios Nacionales

Colegio de Defensa del Uruguay
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"SUSTAINABLE FUSION / FISSION DEPLOYMENT SCENARIOS ON THE LONG TERM FOR PROPER ADDRESSING OF CLIMATE CHANGE"

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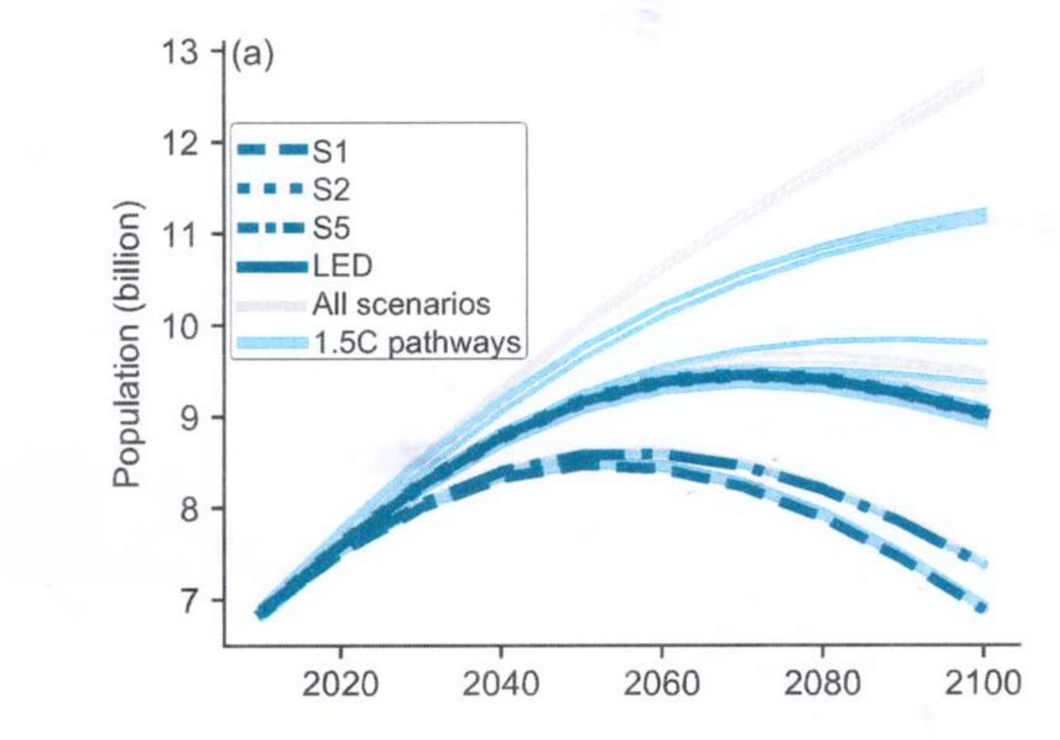
World Top Social and Environmental Challenges

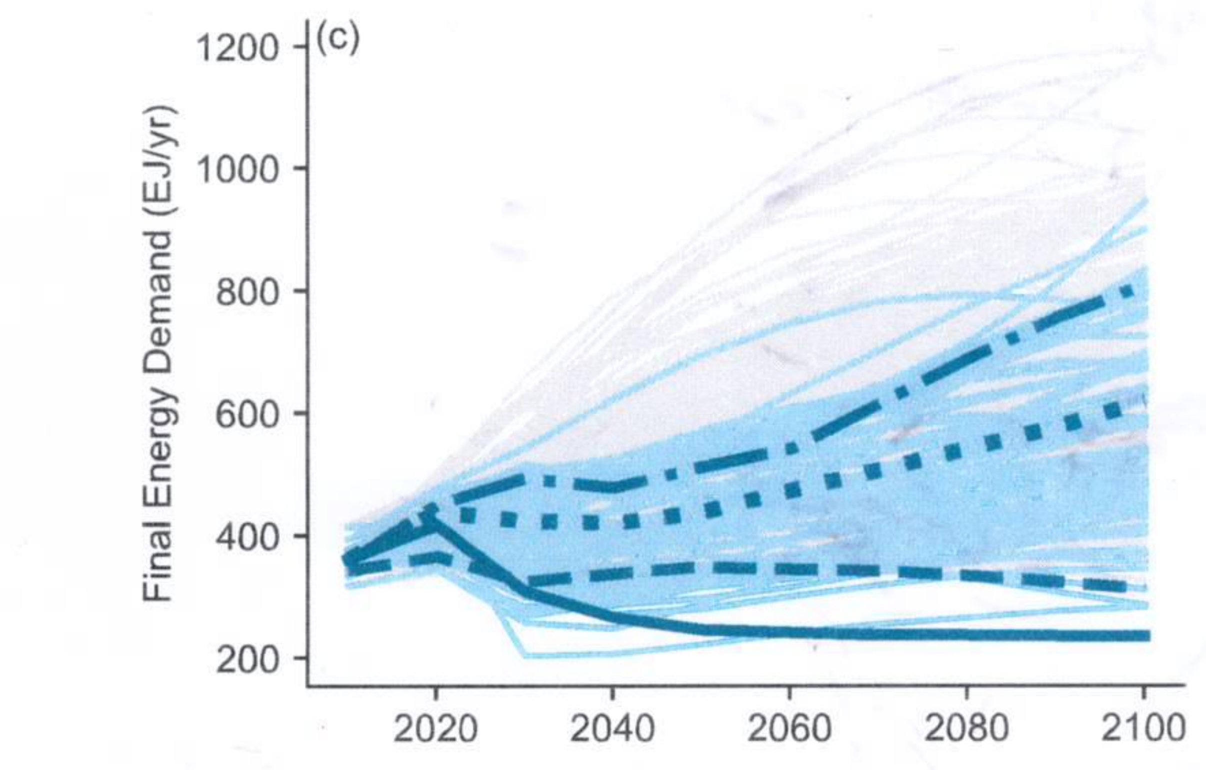
- **The SDGs:**
  - Sustainable Development Goals (SDGs, 2015) are a global commitment essential for the urgent need of lifting more than **800 million people** out of poverty and famine.
  - Meeting the SDGs, will stabilize world population, but probably not before 2050. This growing population, added to rising consumptions per capita related to Human Development, will require from 2020 to 2050 huge amounts of power, as main (≈60%) final energy carrier, to meet SDGs .

- **The Climate Change Threat:**
  - On the other hand, Climate Change is the current worst global environmental menace, that, unless properly mitigated, by 2100 would trigger:
  - **>100 million people** exposed to sea level rise (1).
  - **>1,500 million people** vulnerable to water/heat stresses and/or crop yields changes (1). Not accounting for millions exposed to widespreaded tropical diseases and trillion dollars of economic losses as well as other social and environmental effects.

- **Mitigating Climate Change:**
  - Reducing CO_2 emissions from fossil fuels burning is the key way to keep global temperature rise around 1.5 ºC.
  - Accounting for growth in energy consumption, **unabated** thermal power emissions must plummet to **0** by 2050, from current **60%** of total power, in order to have a chance for 1.5 ºC.

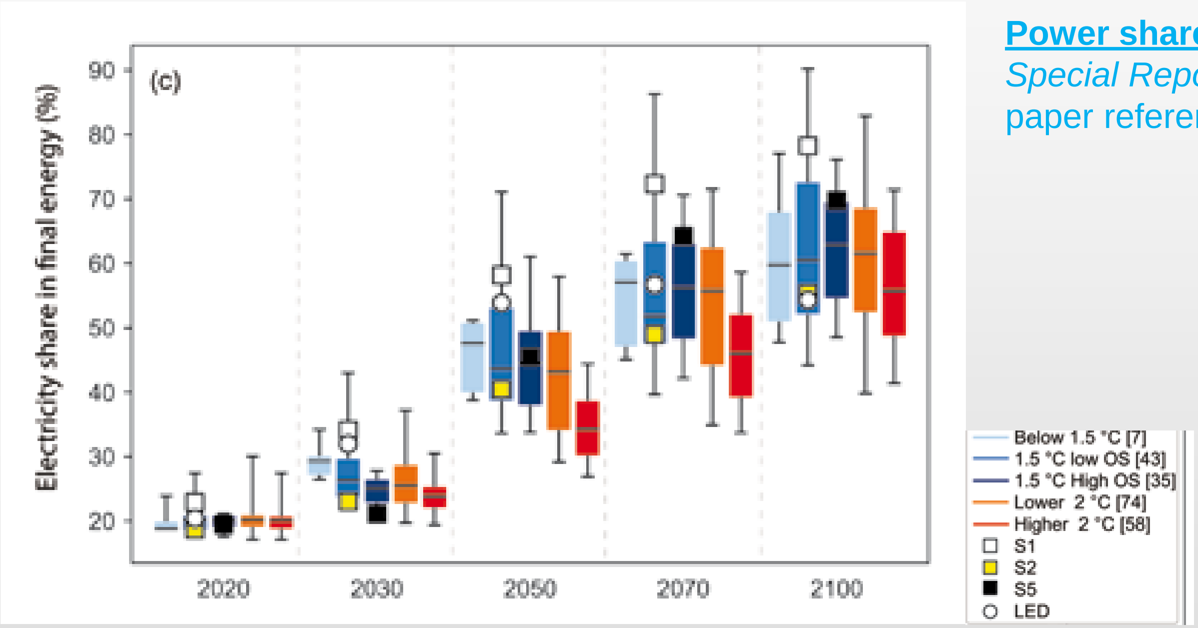
Social, energy consumption forecasts and climate requirements



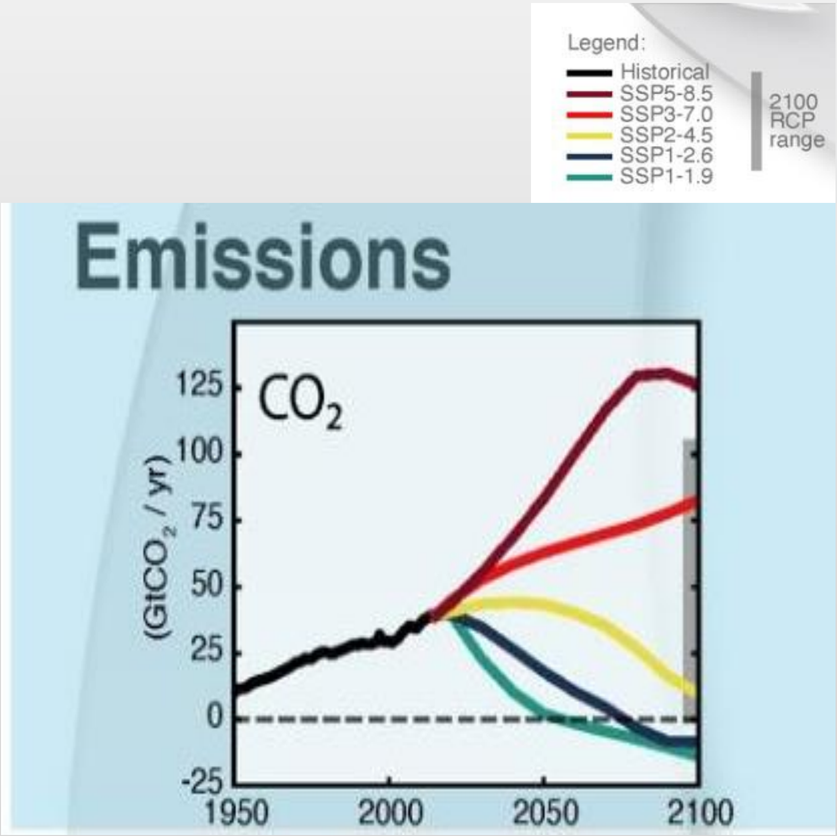


Figures from *IPCC 2018 Special Report on impacts of global warming of 1.5 ºC* (see paper references); Chapter2, Fig. 2.4

Social, energy consumption forecasts and climate requirements



Power share in total final energy. Figure from *IPCC 2018 Special Report on impacts of global warming of 1.5 ºC* (see paper references); Chapter2, Fig. 2.14



Emissions trajectories consistent with diverse climate scenarios. Figure from *IPCC Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (see paper references); Fig. TS.4

Proposal of sustainable scenarios by 2050 to address SDGs and Climate

- **Addressing the challenges:**
  - Any sustainable proposal, must include firm baseload and flexible, low carbon power sources, enough to meet the skyrocketing demand, even if Carbon Capture and Storage (CCS) could be widely developed.
  - Also, these sources must be sustainable from the standpoint of mineral resources demand, land use and/or land affectation. Requirements of technical infrastructure, must be attainable, too.

- **Our past Proposal:**
  - At 2019 IAEA *International Conference on Climate Change and the Role of Nuclear Power*, we suggested (2) an energy portfolio that could meet those requirements. This portfolio, for a high Human Development case and 1.5 ºC (with overshoot) scenario is resumed in next Table.

- **Challenges ahead:**
  - It must be highlighted that even if such portfolio is attainable by 2050, it also poses huge challenges for nuclear industry, uranium mining, energy planners, nuclear regulators.
  - Use of fast/breeder reactors, shift to thorium cycle, plutonium reprocessing, were mentioned to «*at least to some extent, unavoidably required*» options, in the long term, even if nuclear Fusion becomes widely available before 2100.

Proposal of sustainable scenarios by 2050 to address SDGs and Climate

- Energy portfolio suggested in 2019:
  - 1.5 ºC –HIGH- OS SCENARIO (assumptions: 215 ton Natural Gas/(GW*hr); 2.8 (ton CO_2/ton NG)).

	NUCLEAR GENERATION (TW*hr/yr)	RENEWABLES GENERATION (TW*hr/yr)	RENEWABLES PORTFOLIO	GROSS EMISSIONS FROM ELECTRICITY ($GtCO_2$/yr)
32% nuclear – 32% renewables	22,300	22,300	-8% HYDRO -15% WIND/SUN -9%BIOMASS/OTHR	15.1
32% nuclear – 35% renewables	22,300	24,400	-11% HYDRO -15% WIND/SUN -9%BIOMASS/OTHR	13.8
32% nuclear – 40% renewables	22,300	27,900	-16% HYDRO -15% WIND/SUN -9%BIOMASS/OTHR	11.7
32% nuclear – 43% renewables	22,300	30,000	-16% HYDRO -18% WIND/SUN -9%BIOMASS/OTHR	10.5

- Challenges forecast:
  - In the event of use just current Light Water Reactors for such nuclear expansion:
  - 22,000 TW*h/yr nuclear, would consume 300,000 ton Uranium/yr. Uranium proven reserves would be depleted before 2070.
  - Global enrichment capacity would be surpassed by 2050.

Nuclear Fusion Promise

- **Energy aplenty:**
  - Fusion power has potential of raw resources for probably much longer than humans could need power.
  - 1% of seawater contains enough deuterium to power the world for 10^9 years, at current consumption rate.

- **Clean power:**
  - No major chemical or radioactive residues, except minor amounts of activated items.
  - No impact on land use of afforestation.
  - Ignition accidents hindered by design.

- **Worldwide deployment:**
  - Very sophisticated technology, but once stablished, raw materials available everywhere; even if deuterium recovery is a somewhat complex industrial process, could be faced by clusters of developing countries.
  - Strategic limitations for developing countries could be less than there are today for nuclear fission, provided reactors supply and maintenance are ensured.

The Path to Fusion Power

- **In progress:**
  - Fusion power is awaited from long ago, some 60 years.
  - Currently, 96 facilities worldwide are achieving results that bring the controlled, commercial fusion power reactor closer and closer.

- **Achievements forecast:**
  - DEMO reactors are expected (3) to start operation by the 2040s in Europe and Far East.
  - Commercial fusion reactors delivering power would be the next step, but no clear calendar is available.
  - Some reports (3) expect first fusion power in grids by 2070, and sharing 20% of total power by 2100. We considered this as a base case and optimist/pessimist ones for our analysis of sustainable climate and social scenarios.

- **Our proposal of scenarios:**
  - BAD SCENARIO FOR FUSION: begins by 2100, 20% of total power in 2130.
  - BEST SCENARIO FOR FUSION: begins by 2060, 20% of total power in 2080.

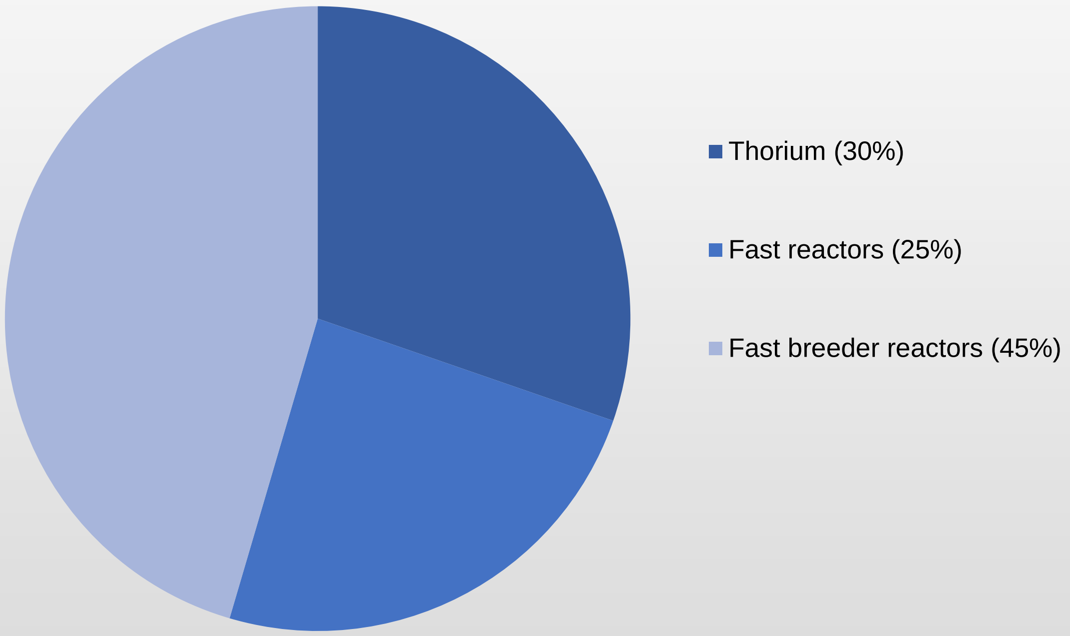
Global power in the considered scenarios

- **Power demand:**
  - According to results of (2), for this analysis we assumed that global power demand peaks in 2060, at 75,000 TW*h/yr and remains stable to 2100.
  - Power generation until 2050 is as per (2): 32% nuclear and 43% renewables, balance power is from natural gas and coal abated by CCS and/or afforestation.

- **Nuclear power:**
  - To cope with mentioned challenges related to a high nuclear share of a very high power demand, we assumed as realistic a hard case that in the 2040s, achieves 15% of nuclear power from advanced designs, a proposal for shares of diverse designs is shown in Fig. 1.
  - This hard, but probably doable case, also assumes that by 2070s, besides eventual Fusion arrival, advanced nuclear Fission reaches 40% of total nuclear and is, in part, flexible (fast flexible reactors). Fusion reactors could, then replace baseload sources, and Fission, also baseload and some flexible power sources.

Global power in the considered scenarios

Nuclear advanced shares



- *FIG 1.- Example shares of advanced cycles within nuclear power.*

- These shares are mantained in our scenarios for 2070s, but then, some fast reactors become also flexible (4).

Roles of power sources in the diverse scenarios

- In any event, commercial Fusion will came when power demand has peaked, according to targetted social scenarios. So, its fate will be to replace large baseload -as Fusion probably is to be- sources, typically coal-CCS, conventional nuclear, biomass and some hydropower.
- Small Modular Reactors (SMRs) for local power in remote locations and for industrial heat/railway transport are not likely to be immediatey replaced by Fusion. Natural gas stations and most hydropower, probably not, either.
- Replacement by Fusion of conventional nuclear, biomass and hydropower would ease the challenges related to massive use of these sources (2).

- Baseload power:
  - In the climate and social scenario we suggested in (2), conventional nuclear is the main baseload source until 2050, followed by biomass, hydro and, probably, scarce coal-CCS.
  - As nuclear Fusion arrives, it goes its way to become the main (20%) baseload source around 2080, 2100 or later, according to the case.
  - In such events, some baseload nuclear power is replaced by Fusion, as well as part of biomass and hydropower. Other part of nuclear, becomes partly flexible and could reduce need for flexible sources as some NG-fired and hydro power.

Roles of power sources in the diverse scenarios

- **Fusion fate scenarios:**
  - We suppossed that any new GW*h of Fusion power, replaces a before-existing mix comprised of **0.73 GW*h nuclear**, **0.2 GW*h biomass** and **0.07 GW*h hydro**.
  - This replacement pattern is based upon energy portfolios mentioned in (2), excluding intermittent sources and accounting for just 20% of hydro working as baseload.
  - Replacement of nuclear by Fusion, will be, mainly, replacement of conventional Light Water Reactors, the oldest replaced first. This will solve ageing problemas of many nuclear fleets, besides reliefing supplies troubles related to nuclear fuels, enrichment, etc.
  - Advanced nuclear (fast reactors), besides becoming part of flexible sources, could help to burn actinides from nuclear waste of shutted LWRs and these advanced nuclear are likely to remain in grids by 2100, as well as the mentioned non-electrical fission applications.

Impacts and Needs of diverse Fusion Scenarios

- Enviromental impacts and raw materials needs:
  - As said, Fusion baseload power is likely to have minor impacts and footprints. Its deployment, so, will reduce impacts of other (nuclear LWRs, biomass, hydropower) sources that are replaced by Fusion.
  - We have done a preliminar assessment of those impacts in diverse scenarios of Fusion deployment.
  - Base case is as follows:

Fusion power by 2100 (TW*h/yr)	Uranium for nuclear power (million ton U, accumulated)	Land area for biomass power (million Ha)	Land area flooded by hydrpower (million Ha)	Crops land area seized by power needs (million Ha)
15,000	10.1	-no needed-	168	168

Impacts and Needs of diverse Fusion Scenarios

- Fusion optimist scenario:
  - As said, in this scenario, Fusion power comes in 2060s and reaches 20% of total grid power by 2080. We suppossed further linear deployment until 2100.

Fusion Power (TW*h/yr)	Uranium for nuclear power (million ton U, accumulated)	Land area for biomass power (million Ha)	Land area flooded by hydropower (million Ha)	Crops/ forest land area seized by power needs (million Ha)
15,000 (2080)	6.7	-no needed-	168	168
22,000 (2090)	7.5	-no needed-	154	154
30,000 (2100)	8.8	-no needed-	137	137

Impacts and Needs of diverse Fusion Scenarios

- Fusion bad scenario:
  - In this scenario, Fusion power appears in grids by 2100, requiring wide use of natural resources to fuel other sources until that date. Such impacts are summarized below:

Fusion Power by 2100 (TW*h/yr)	Uranium for nuclear power (million ton U, accumulated)	Land area for biomass power (million Ha)	Land area flooded by hydropower (million Ha)	Crops land area seized by power needs (million Ha)
3,000	13.2	98	194	292

  - Depletion of currently proven and even reasonably assured Uranium reserves and persistence of other sources´ impacts are clear in this scenario, unless nuclear Fission is fully turned to advanced designs and grows more, additionally replacing more baseload renewables.

Key findings from assessment of the scenarios

- We think that the following remarks from above data, must be highlighted:

- **Early deployment of Fusion:**
  - Coupled with a hard, but probably achievable shift to advanced Fission cycles, it may limit global use of uranium along this century, to around the level of currently proven reserves, some **8 - 9 million tons U** (5).
  - Thorium reserves (**6 million tons Th**, as a minimum, for a consumption estimated at **2 million tons Th**) would be more than enough, although global infrastructure for reprocessing/fuel manufacture should be assessed in the long –after 2050- term, as well as uranium enrichment capacity.
  - This early deployment, also may recover **130 – 160 million Ha**, enough to feed 23 million people, otherwise flooded or used for energy crops.

- **Climate, Energy Security and Land Use:**
  - In the event of no Fusion until 2100, sustainability of these three key issues, would be strongly dependent on a huge capacity of thermal power fitted with CCS/U (very unlikely) or massive use of advanced nuclear fission.

Concerns and Opportunities of the global Transition Phase to Fusion

- **Uranium Enrichment capacity:**
  - Abovementioned use of fast reactors by 2050, could require some 10 – 30 million SWU/year. This capacity may be globally available, but must be fitted for high-enrichment, 20% ^{235}U or more, depending on reactor type.
  - Stockpiling low-enriched uranium and plutonium, with current capabilities, from 2020s on, could relieve these issues, as use of these materiales for LWRs would see a sharp drop by 2060. Additional capabilities (including reprocessing of minor actinides) if installed by 2040s, could close the gap.

- **Nuclear Fission around the world:**
  - Global deployment of nuclear Fission until Fusion surges as baseload source, is likely to have different shapes across diverse regions.
  - Large deployment of advanced Fission cycles could be achievable by countries with great expertise in the nuclear field. This, in turn, would let developing coutries rely –at first stage- mostly on moderns LWRs for which operational experience and regulaton criteria (6) is widely available, to ease their transition.

Conclusions

- Nuclear Fusion:

  - *On the long term, it is the promise for sustainable power.*

  - *Along 21ST Century, its deployment as early as operationally possible, synergized with nuclear Fission (that gradually transitions to advanced to the end of Century), would allow to address Climate Change and universal Human Development, the most critical environmental and societal global matters.*

  - *This can be done in a really demanding, but probably achievable way.-*

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Thanks a lot for your attention!

CALEN Headquarters at Montevideo, Uruguay