Technical Workshop On Nuclear Fuel Cycle simulation (TWoFCS)
EDITION 2021

From RESEARCH to INDUSTRY

Modeling the low-carbon electric transition of a fictitious emerging country with external constraints.

19/05/2021

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Aim of the study : Model the energy transition of a fictitious emerging country, which anticipates growth in demand but wishes to minimize its impact on the environment.

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2 procedures for modelling the scenario: simulation or optimization

→ optimization: return the best possible configuration of the system that favors specific criteria

$$(P_{EI})\begin{cases} inf_x\, f(x) & \\ c_i(x) = 0, & i \in E \\ c_i(x) \leq 0, & i \in I \end{cases}$$

The criterion to be minimized is the scenario cost among the whole considered period:

$$Cost = \sum_{year} \frac{\sum_{tech}[CRF_{y,t} \times CAPEX_{y,t} + FOM_{y,t} + VOM_{y,t} + GHG_{y,t} * Tax_y]}{(1+r)^y}$$

The supply-demand balance = constraint of equality between electricity production and expected consumption.

LEAP

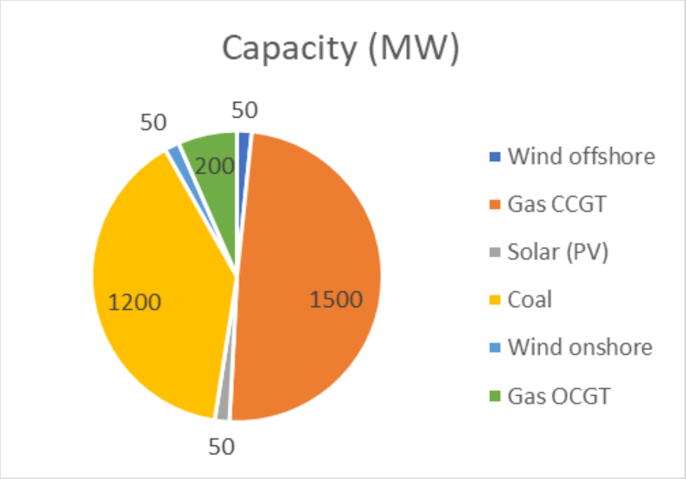
The calculations presented below were performed with the **Low Emissions Analysis Platform** (**LEAP**) and the OseMOSYS and NEMO tools.

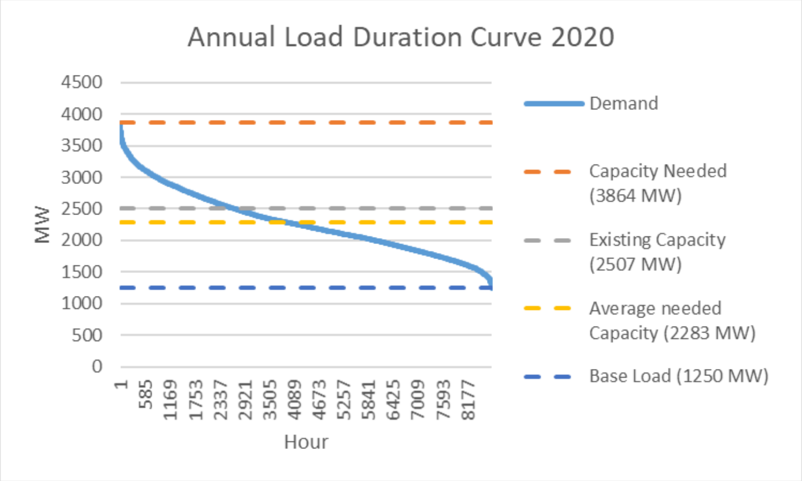
→ Seasonal sampling : 96 hours/year (hourly accuracy cannot be achieved)

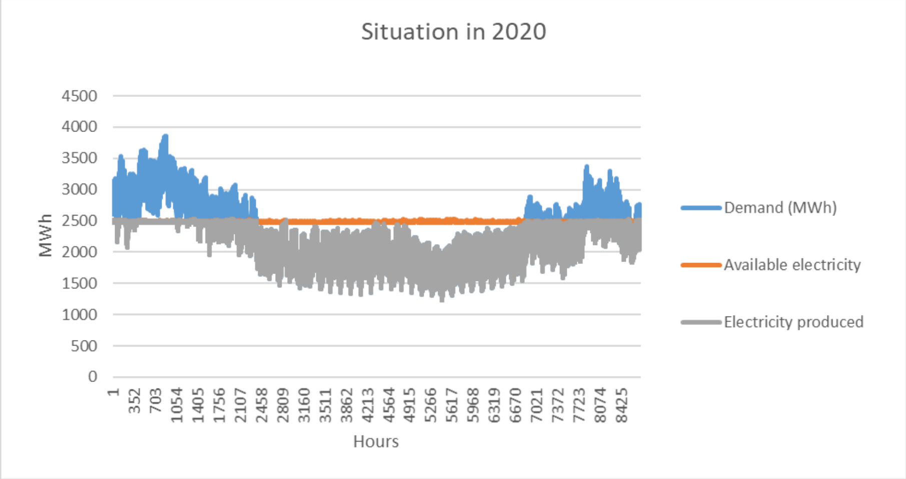
Electricity supply in 2020: 6 production technologies (Coal, Gaz CCGT/OCGT, Solar PV, WindON, WindOFF)

→ 3050 MW installed wich can produce in theory 21,8 TWh

However with consideration to the annual load duration curve and the hour-by-hour availability of RVE : peak demand is not met 32% of the time.





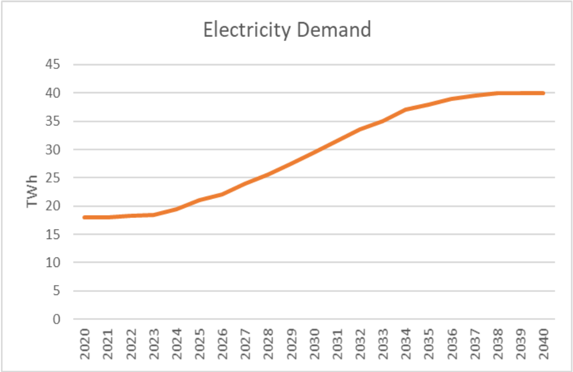


The h/h variability of RVE used are those of an African Equatorial country (Satellite data processing by RenewableNinja).

GHANA	Solar PV	WindON	WindOFF
Average Availability (%)	16.6	11.3	12.6

→ <u>Doubling electricity production and meeting the demand of its 30 million inhabitants</u> :

An increase **from 18 TWh to 40 TWh** has been assumed, which follows an S-shaped curve

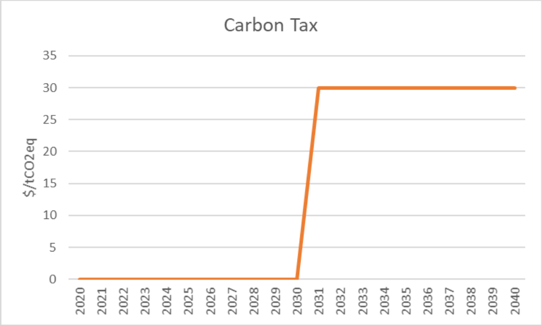


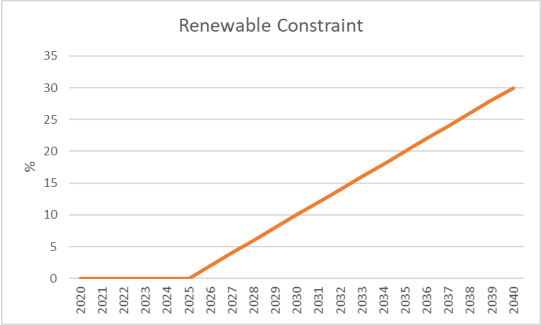
→ <u>Limiting its impact on the environment :</u>

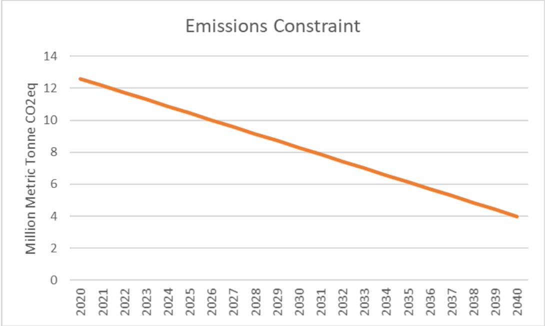
Ladonia is considered to have adopted **a 3-part "climate plan”**

The following indicators were also considered:

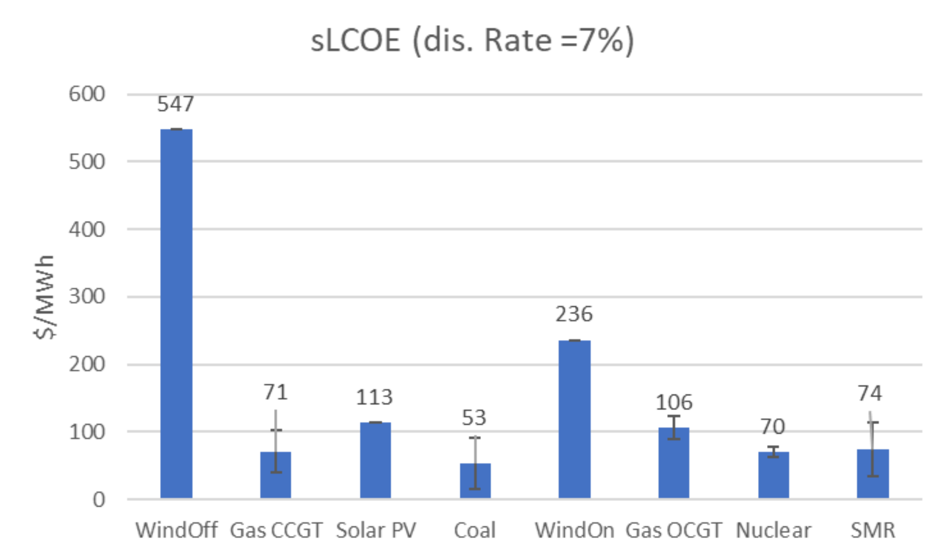
Total and per MWh CO2eq emissions / Land use / Use of structural raw materials/ Water consumption / Impact on human health

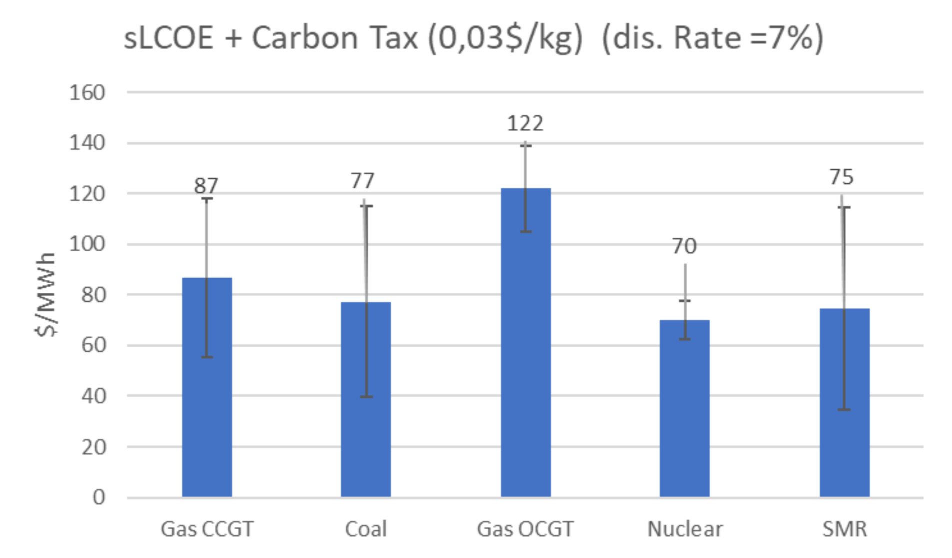






Constraints based on the 'Climate Plan'

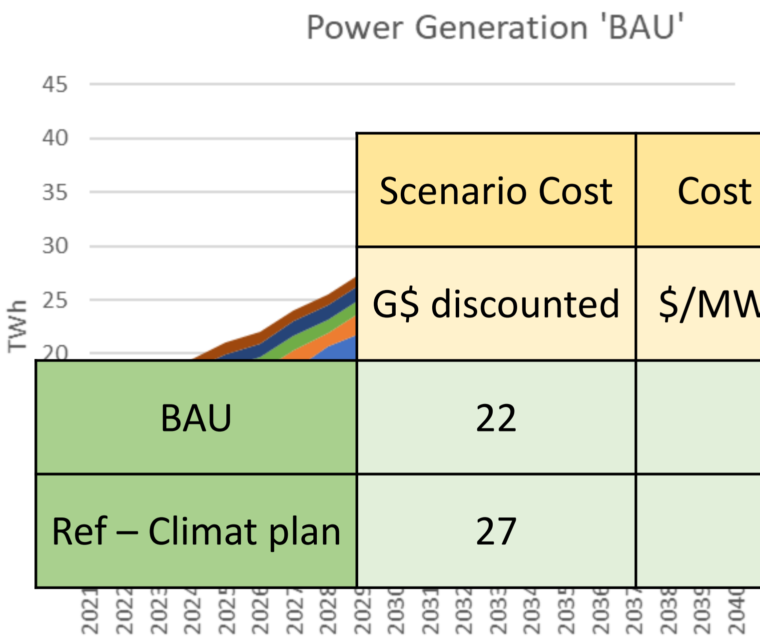


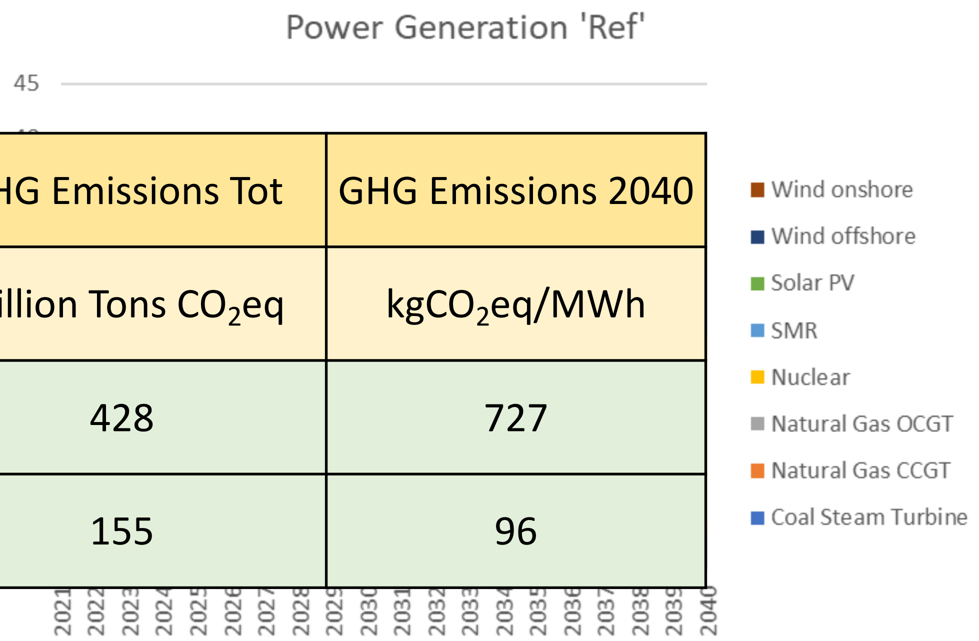


$$sLCOE = \frac{CAPEX \times CRF + FOM}{8760 \times Av.} + VOM$$

The reference data are taken from OECD, IAEA, CEA documents (they are debatable because of the variability linked to the geographical position, the evolution of the markets, etc.)

Modeling Results



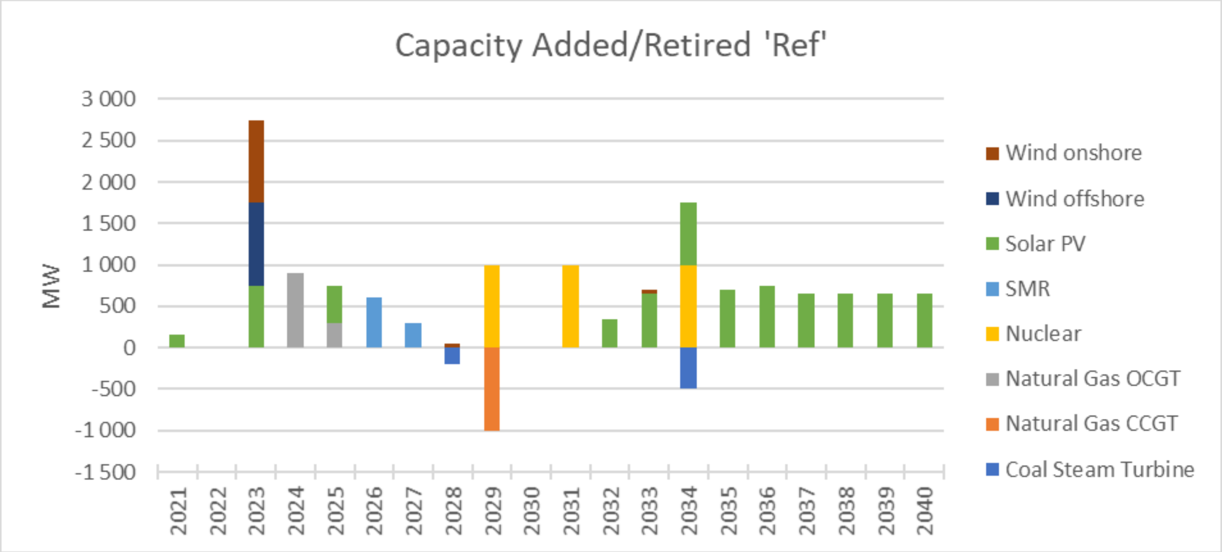


	Scenario Cost	Cost of Elec 2040	GHG Emissions Tot	GHG Emissions 2040
	G$ discounted	\$/MWh discounted	Million Tons CO_2eq	kgCO_2eq/MWh
BAU	22	18.45	428	727
Ref – Climat plan	27	28.45	155	96

<u>'BAU' :</u> **massive use of coal** throughout the modeling period. In 2040, 86% of electricity production is provided by coal combustion (8 new 500 MW coal units).

<u>'Ref' :</u> In 2040, **60%** of the production is based on **conventional nuclear and SMR** (46%-16%). The share of renewable energy is driven by solar photovoltaics at 24% of the mix.

Power Plant addition to the electricity generation fleet



The following generation plants are installed:
- 1200 MW of OCGT (12 units)
- 3000 MW of LNPP (3 units)
- 900 MW of SMR (3 units)
- 7150 MW of PV (143 units)
- 1000 MW of WindOff (4 units)
- 1100 MW WindON (22 units)

2040 : 17 250 MW installed

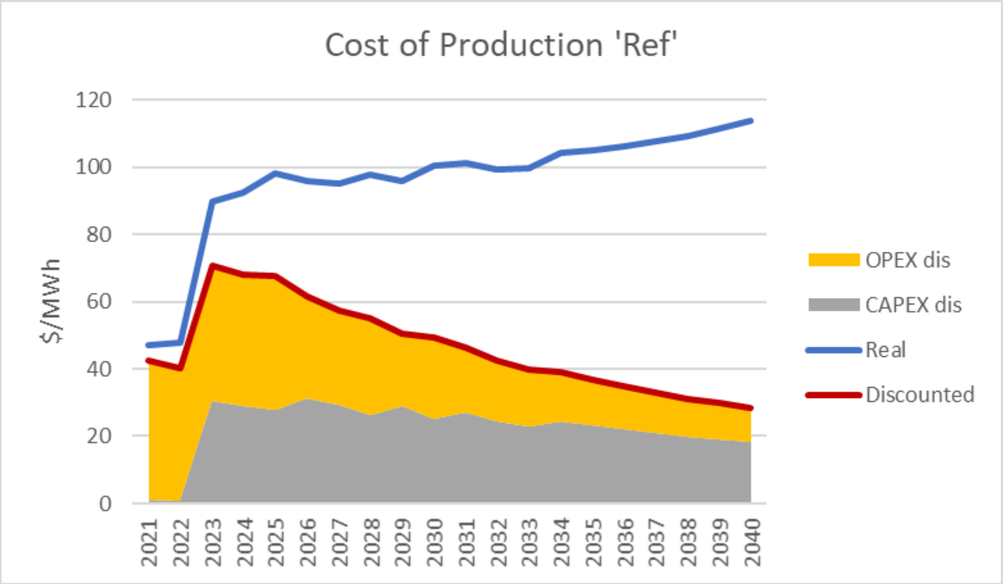
2022 = Reference year of construction (start of building)

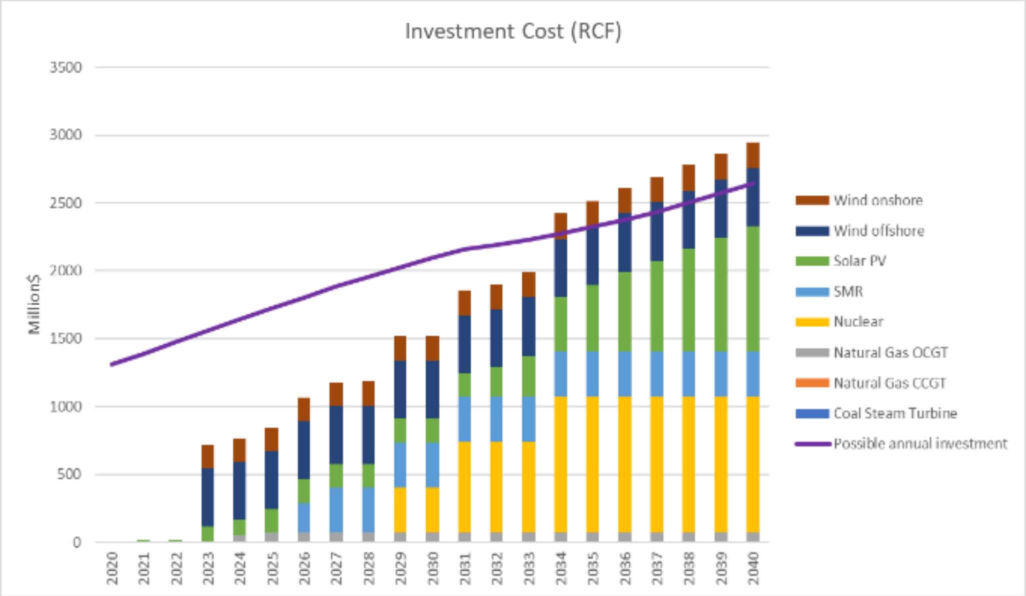
Installation of many RVE in 2023: to compensate for the power outages experienced in Ladonia in 2020, and only RVE have a compatible construction time.

Coal and CCGT gas plants can be dismantled in 2028/2029

II. SCENARIO BUSINESS AS USUAL VS 'CLIMATE PLAN

2. Scenario Cost





The total cost of the scenario is $27 billion dis. (area under the red curve).

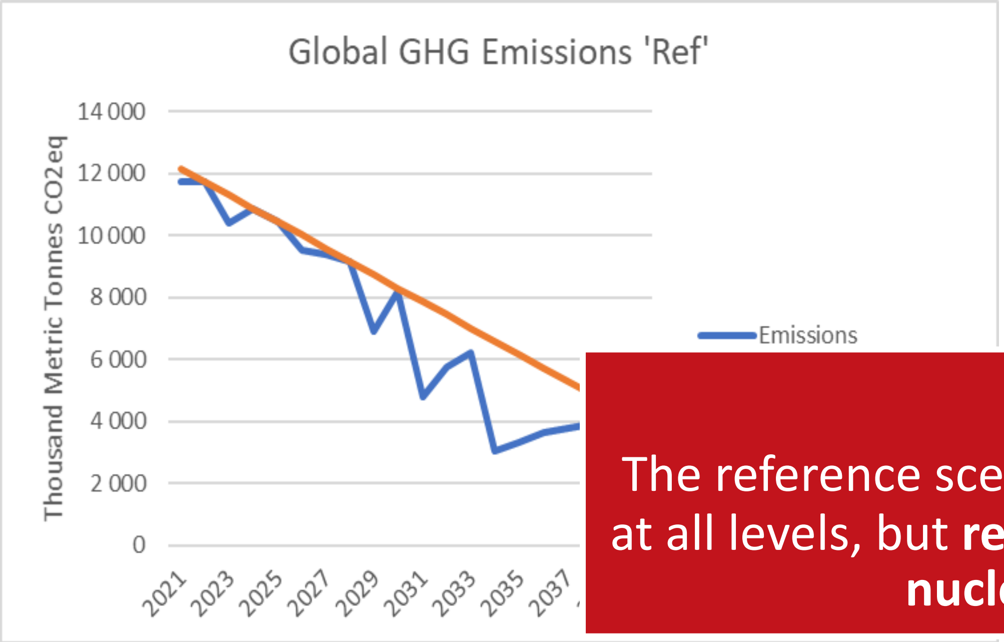
LCOE starts from 42 $/MWh and decreased down to 28 $/MWh dis. in 2040.

- Before 2023 → OPEX only
- After 2023 → OPEX + CAPEX

The total investment cost is 38 billion real (33 billion CRF).

Economic feasibility of the scenario:

- 2020-2034 : necessary investment curve below the annual limit of national investment + possible private contributions
- 2034-2040 : the overinvestment lower than the "savings" made before 2034.



The scenario respects the GHG emission limit, and emits less than the amount allowed over the whole scenario period (174-155 = 19 million tonnes).

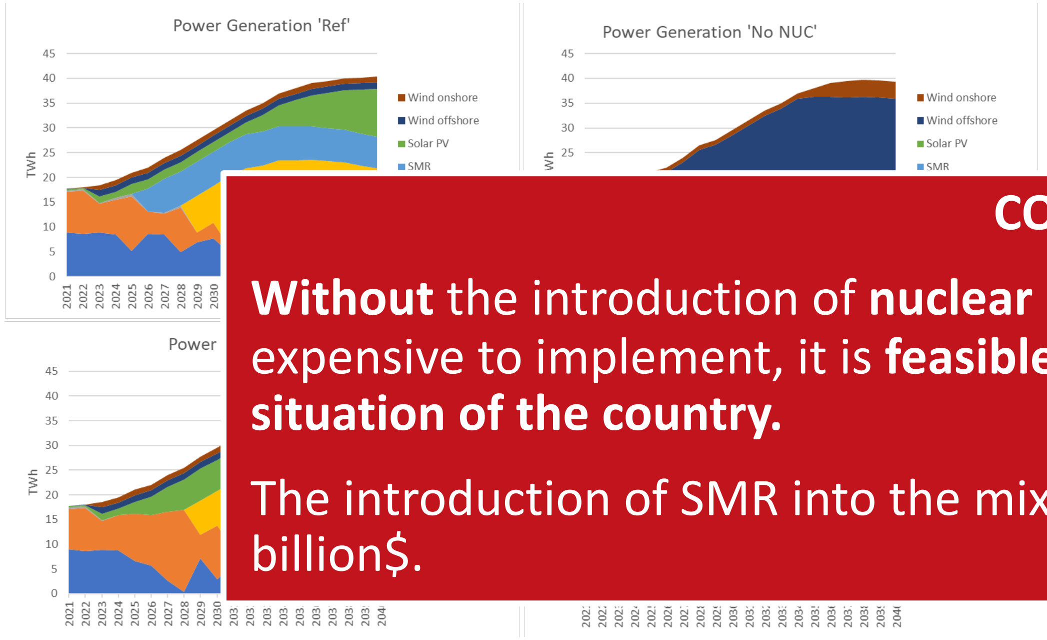
CONCLUSION

The reference scenario (i.e. Climate Plan) is **feasible** at all levels, but **requires the massive introduction of nuclear** power in Ladonia.

		2020	Ref - 2040
	eq	/	155
		652	96
		9,09	3,29
		0,82	1,65
		1,6	1,6
Human Health Impact	DALY/MWh	2,43E-04	6,10E-05

On all the indicators considered the progression is positive, except for the necessary structural materials (cement, aluminium, copper, iron).

The 'Ref' scenario is compared with a 'No NUC' scenario, a 'LNPP' scenario without SMR, and finally a 'SMR' scenario with only SMR.



No nuclear scenario : 84% of the production provided in 2040 by RVE, 16% left by CCGT

→ Scenario with higher GHG emissions than 'Ref'

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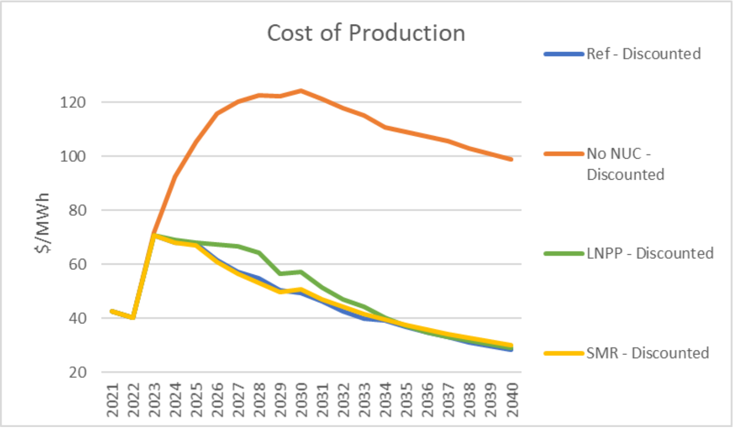
→ Scenario cost ~ 'Ref'

CONCLUSION

Without the introduction of **nuclear power**, the climate plan is extremely expensive to implement, it is **feasible but inconsistent with the economic situation of the country.**

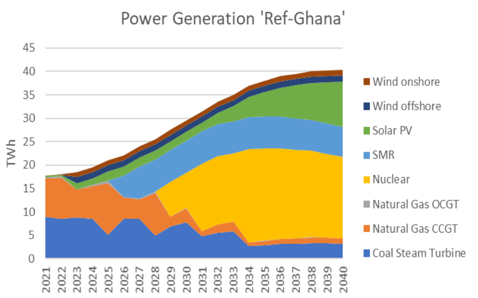
The introduction of SMR into the mix reduces the cost of the scenario 'Ref' by a 2 billion$.

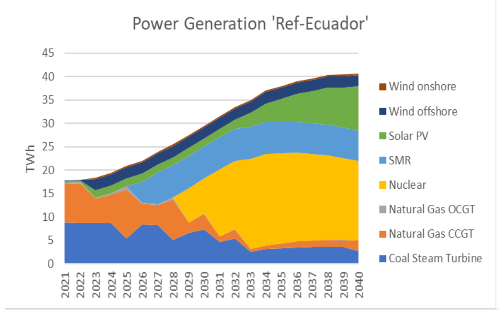
	Units	Ref	No NUC	LNPP	SMR
	G$ dis	27.0	64	29.0	27.3
GHG Emissions total	Millions Tonnes CO2eq	155	165	168	171
GHG Emissions 2040	kgCO2eq/MWh	96	100	90	100
Land Occupation 2040	m2/MWh	3.29	2.4	3.24	2.68
Material Use 2040	kg/MWh	1.65	4.37	1.65	1.66
Water consumption 2040	m3/MWh	1.6	0.22	1.93	0.72
Human Health Impact 2040	µDALY/MWh	61.0	57.0	80.0	92.6

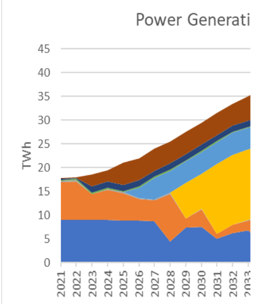


IV. IMPACT OF GEOGRAPHICAL POSITION ON THE 'REF' SCENARIO (I.E. CLIMATE PLAN)

The influence of geographical location on the scenario is assessed: 4 world regions GHANA, ECUADOR, FRANCE, KENYA







'Ecuador' scenario: Very similar to the 'Ref' scenario

- Solar = 20/25% of production in 2040
- Roughly the same cost

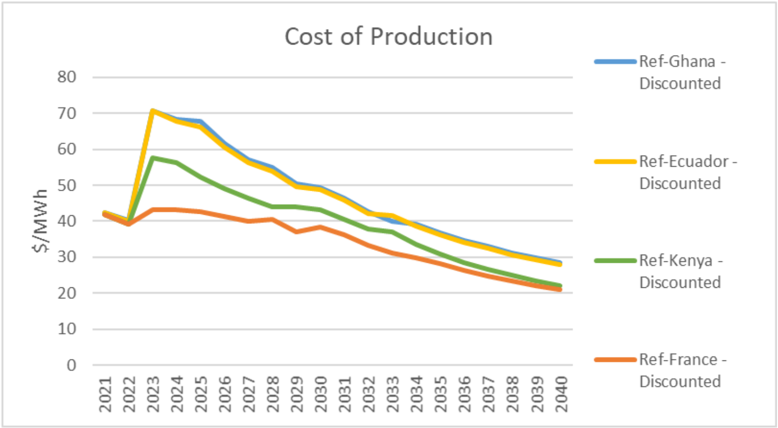
'France' scenario:

- Favoured onshore wind = 20/25% of production in 2040

CONCLUSION

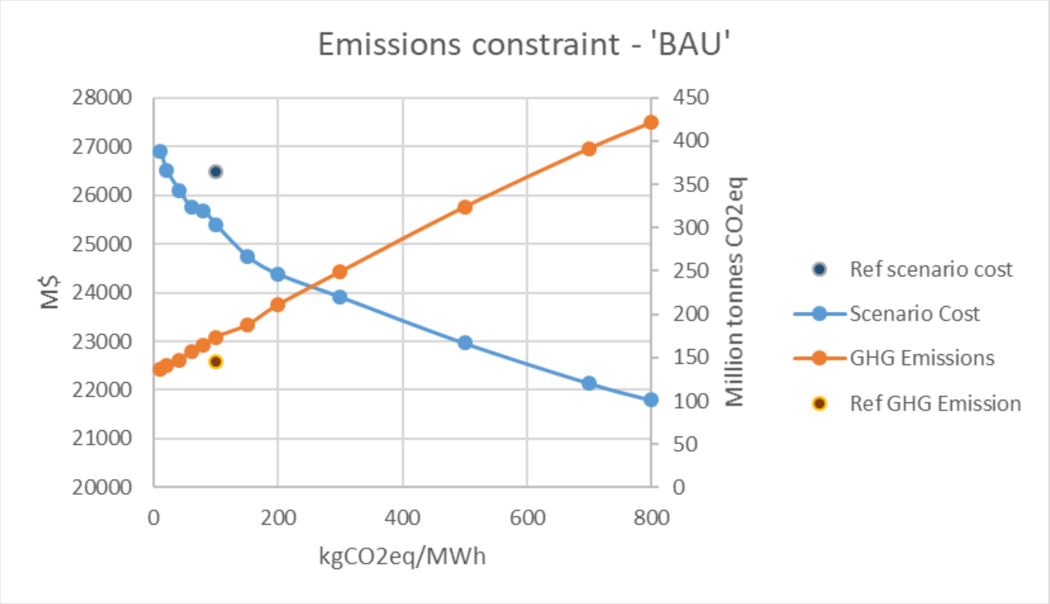
The constraint of introducing RVE in the mix, up to 30% in 2040, foreseen in the 'Climate Plan', does not impact in the same way the countries according to their geographical position (meteorological conditions - availability of RVE).

- A little more expensive than the 'France' scenario



Average Availability %	GHANA	ECUADOR	FRANCE	KENYA
Solar PV	15	16	15	18
WindON	11	6	30	47
WindOFF	13	15	40	36

▶ Emission Constraint : On ‘BAU’ scenario and ‘Ref’ scenario



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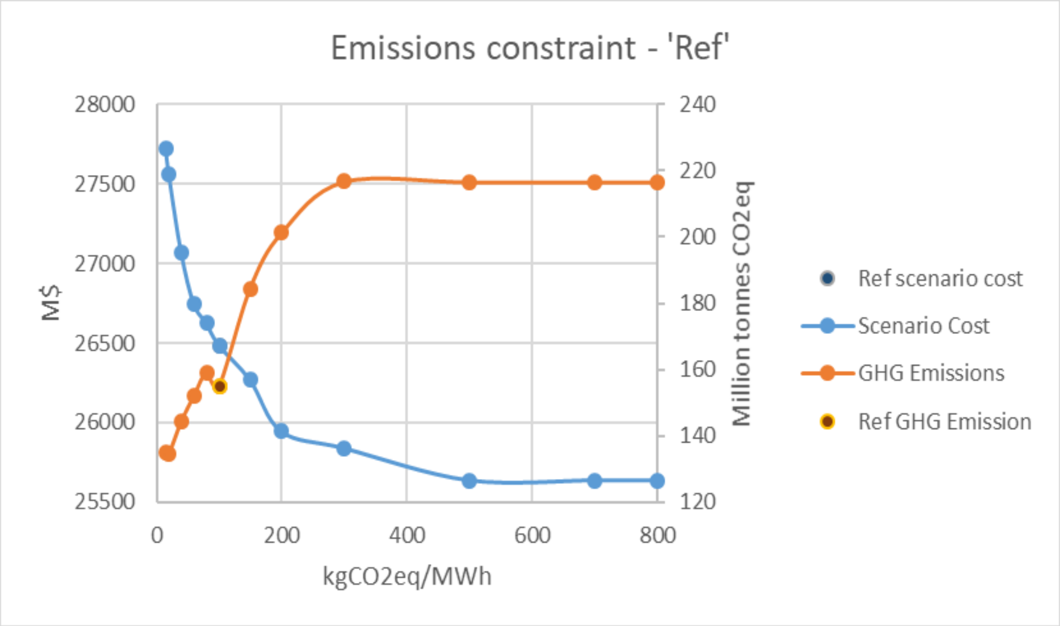
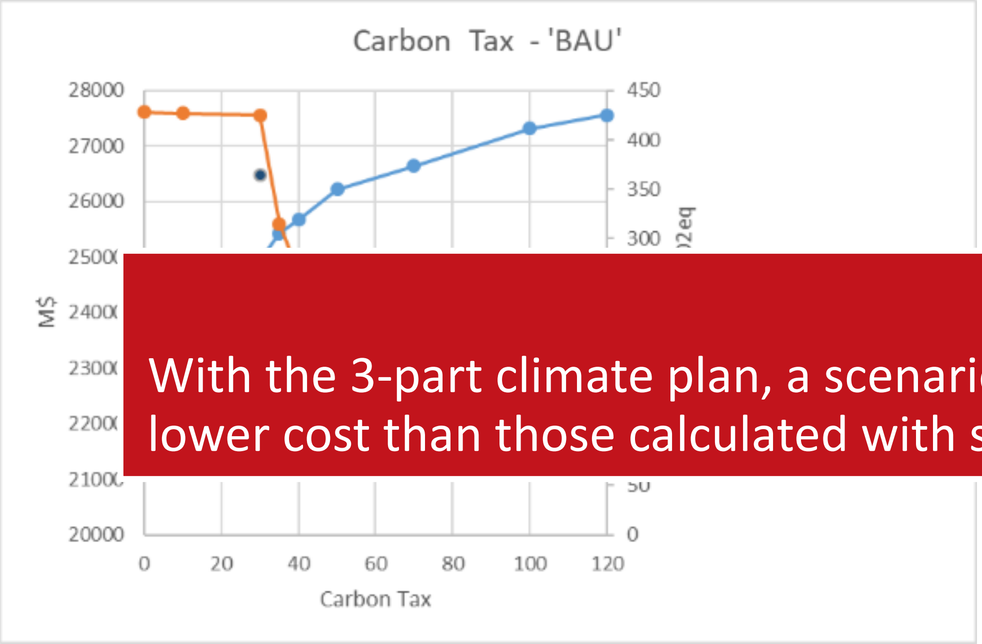
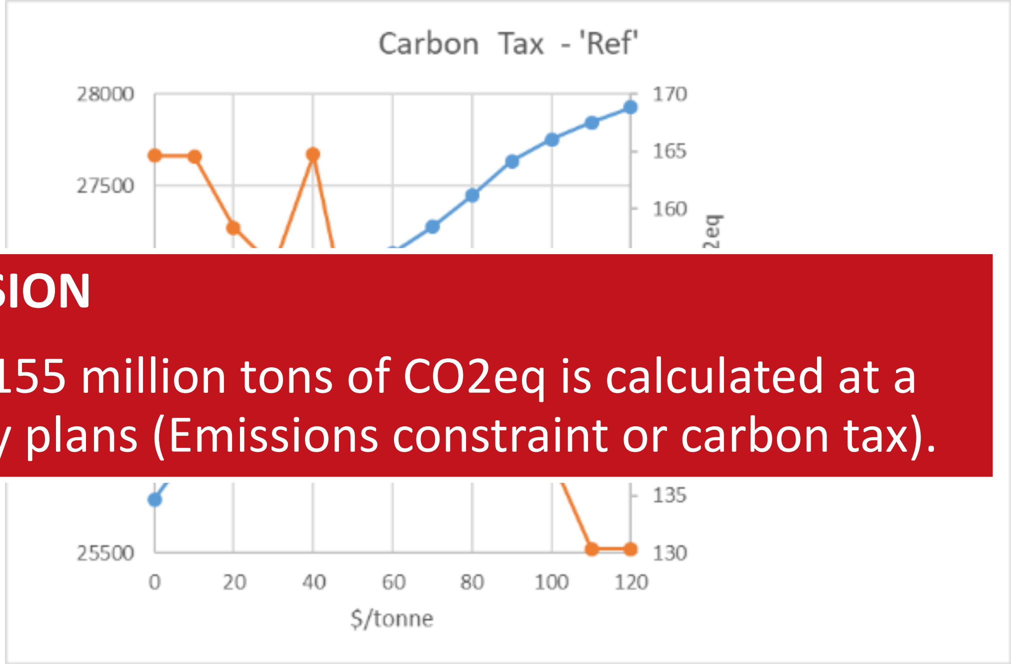


‘BAU’ : The cost increases sharply with the restriction (22 G$ to 27 G$) but strong impact on emissions wich decreases linearly (450 to 137 m.tonnes).

‘Ref’ : No or little impact on the scenario before 300 kgCO2eq/MWh: the other constraints of the Climate Plan have a greater weight on the mix, plateau of 220 Mtonnes of CO2eq emitted.
From 300 kgCO2eq/MWh onwards, the cost of the scenario increases to 27.8 B$ and emissions decrease to 115 Mtonnes.

▶ Carbon Tax : On 'BAU' scenario and 'Ref' scenario





CONCLUSION

With the 3-part climate plan, a scenario emitting 155 million tons of CO2eq is calculated at a lower cost than those calculated with single-policy plans (Emissions constraint or carbon tax).

'BAU': increase in the cost of the scenario with an increase in the price of the tax (22 B$ - to 27.6 B$). Emissions actually decrease when the tax is raised and reach 130 Mtonnes - $120/tonne: with a stall at $30/tonne.

'Ref': Impact of tax variation on the Ref scenario more complex to analyse. The cost increases linearly with the increase in the carbon tax (about $1.7M per $/tonne) but raising the tax gives an unstable result on emissions.

Conclusion of the study:

→ The 'Ref' scenario (i.e. Climate Plan) possible but implies the introduction of conventional nuclear and/or SMR

→ Non-nuclear scenario expensive (no fewer emissions)

→ Sensitivity to geographical location: France location more advantageous than Ghana/Ecuador

→ 2 techniques to limit GHG emissions:

- A more restrictive emission constraint
- A higher tax per tonne of CO_2eq emitted

The Climate Plan in 3 parts more interesting from a cost point of view to limit GHG emissions

To go further (work not presented/in progress + ideas):

→ Sensitivity to uncertainties on economic values

→ Development of a modelling tool underway (POEM - Proposals of electricity mix)

→ Introduction of storage technologies

Thanks for your attention

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Annex 1 - Baseline Data

TECHNOLOGY	Coal	Gas CCGT	Gas OCGT	LNPP	SMR	Solar PV	Wind Onshore	Wind Offshore
Typical Unit Size (MW)	500	500	100	1000	300	50	50	250
Construction duration (y)	4	2	2	7	4	1	1	1
Techn. & Econ. Lifetime (y)	40	30	30	60	60	25	25	25
Average Availability (%)	85	85	85	85	87	16	11	13
Overnight Cost (M$/MW)	2.2	1.1	0.7	4.7	5.2	1.6	2.0	5.0
Fixed OM cost (k$/MW.y)	37	26	20	100	120	36	62	175
Variable OM cost ($/MWh)	25.8	56.4	96.1	11.5	10	0	0	0
GHG Emission (kg_{CO2eq}/MWh)	812.3	518.4	518.4	9.6	10	33.7	13	14.5
Land Occupation (m^2/MWh)	18	0.2	0.2	0.6	0.5	5.8	1.8	0.4
Water Consumption (m^3/MWh)	2.1	0.8	0.8	2.7	0.8	0.4	0	0
Material Use (kg/MWh)	1.1	0.5	0.4	0.9	1	2.6	6.3	5.8
Human health impact (µDALY/MWh)	130	250	250	56	56	33	16	22

The reference data are taken from OECD, IAEA, CEA documents (they are debatable because of the variability linked to the geographical position, the evolution of the markets, etc.)