MERCURY – Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy

Future prospects of renewables, CCS, and nuclear in the EU and beyond

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The MERCURY project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 706330.

The project

From the proposal abstract:

"The reduction of greenhouse gas emissions is a vital target for the coming decades.

From a technology perspective, power generation is the largest responsible for CO_2 emissions, therefore great mitigation efforts will be required in this area.

From a policy perspective, it is common opinion that the European Union is and will remain leader in implementing clean policies.

*Basing on these considerations, the **power sector** and the **European Union** will be the two key actors of this project.*

*The main tool adopted in this work will be **WITCH**, the integrated assessment model developed at Fondazione Eni Enrico Mattei (FEEM)."*

Project outline

- WP 1 – Power sector modeling improvements (UC Berkeley → *interactions/integration with SWITCH*)
  - Task 1.1 – Training on the SWITCH model (months 1-2)
  - Task 1.2 – System integration of Variable Renewable Energies (VRE) (months 3-4)
  - Task 1.3 – Electricity storage (months 5-6)
  - Task 1.4 – Electrical grid (months 7-8)
  - Task 1.5 – ~~Electricity trade (months 9-12)~~ → Interactions/integration with SWITCH
- WP 2 – Technology prospects: EU policy scenario (FEEM)
  - Task 2.1 – Study of the state of the art of renewables, nuclear and CCS in the European Union (month 13)
  - Task 2.2 – Scenario definition (month 14)
  - Task 2.3 – Scenario run and analysis (months 15-18)

Today's presentation

- WP 3 – Technology prospects: global climate policies (FEEM)
  - Task 3.1 – Study of the state of the art of current EU and global climate policies (month 19)
  - Task 3.2 – Scenario definition (month 20)
  - Task 3.3 – Scenario run and analysis (months 21-24)

Today's presentation

1. Exploring pathways of **solar PV** learning-by-doing in Integrated Assessment Models
2. The techno-economic effects of the delayed deployment of **CCS** technologies on climate change mitigation
3. Reactor ageing and phase-out policies: global and European prospects for **nuclear** power generation

WITCH: Introduction

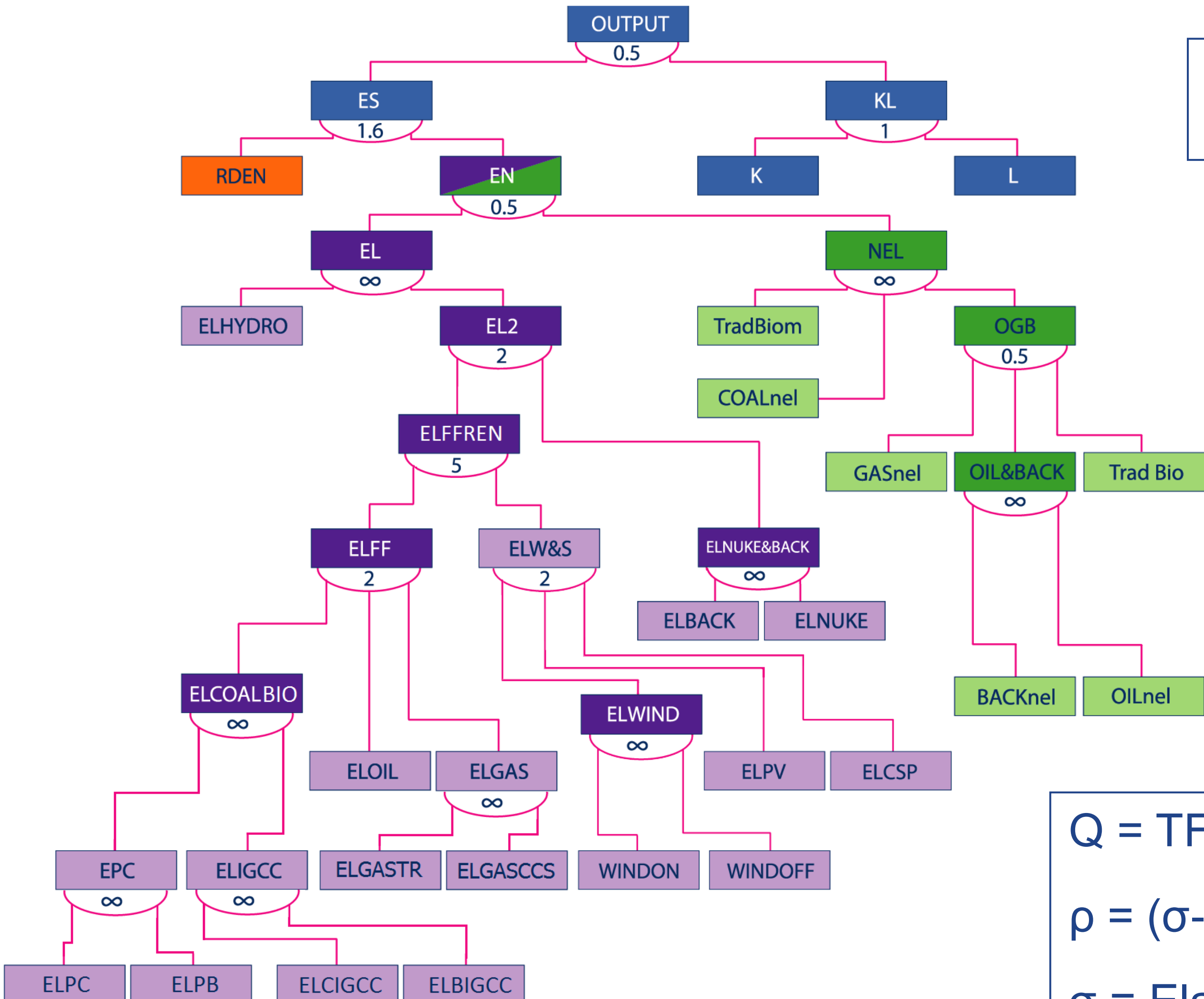
WITCH – World Induced Technical Change Hybrid

- Climate-energy-economic IAM (Integrated Assessment Model) → Socio-economic impacts of climate change
- Hybrid: aggregated, top-down, inter-temporal optimal-growth model + disaggregated description of the energy sector

CAJAZ
(Canada, Japan,
New Zealand)

KOSAU
(R. of Korea, South Africa,
Australia)

WITCH: The CES structure



CES = Constant Elasticity of Substitution

$$Q = TFP \cdot (a \cdot K^{\rho} + (1-a) \cdot L^{\rho})^{(1/\rho)}$$

$$\rho = (\sigma-1) / \sigma$$

σ = Elasticity of Substitution

MERCURY – Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy

Exploring pathways of solar PV learning-by-doing in Integrated Assessment Models

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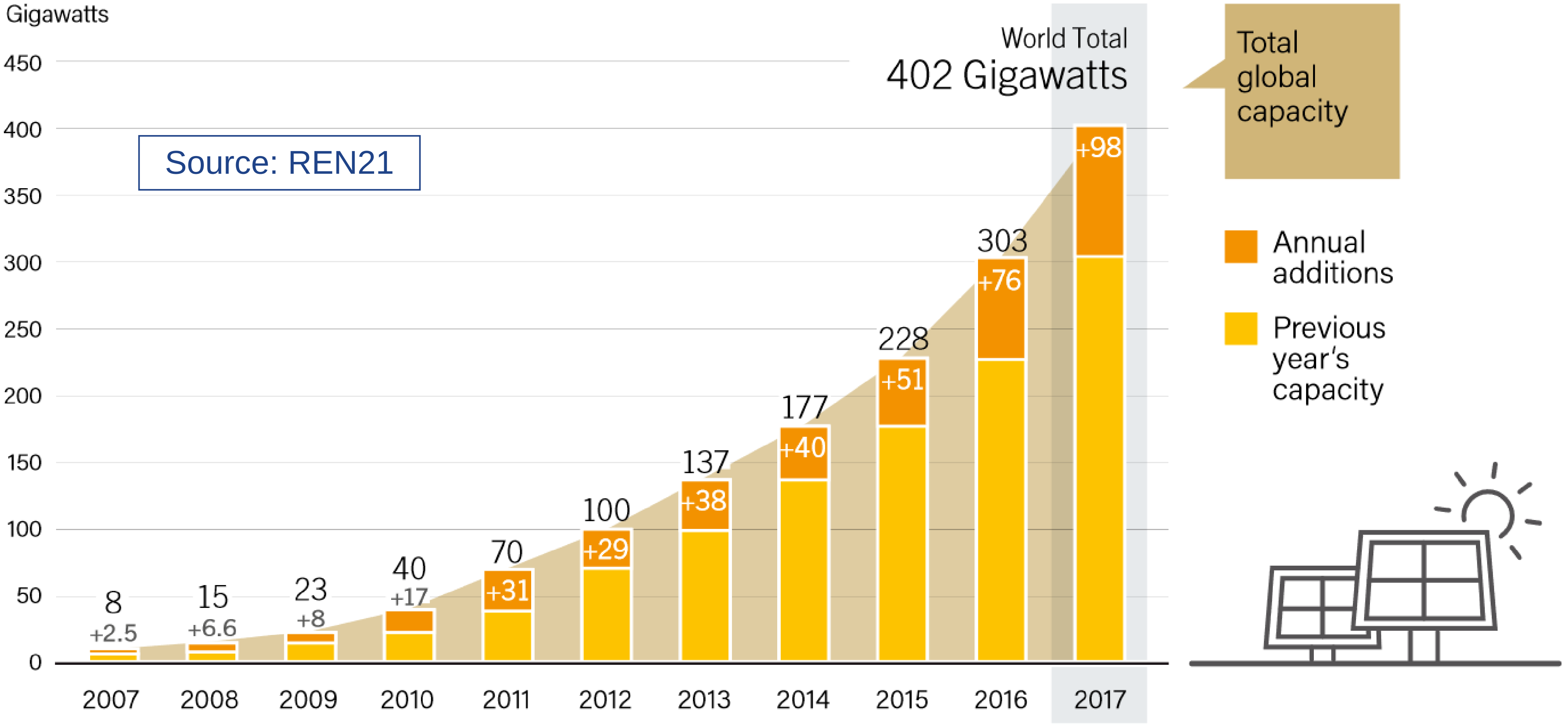
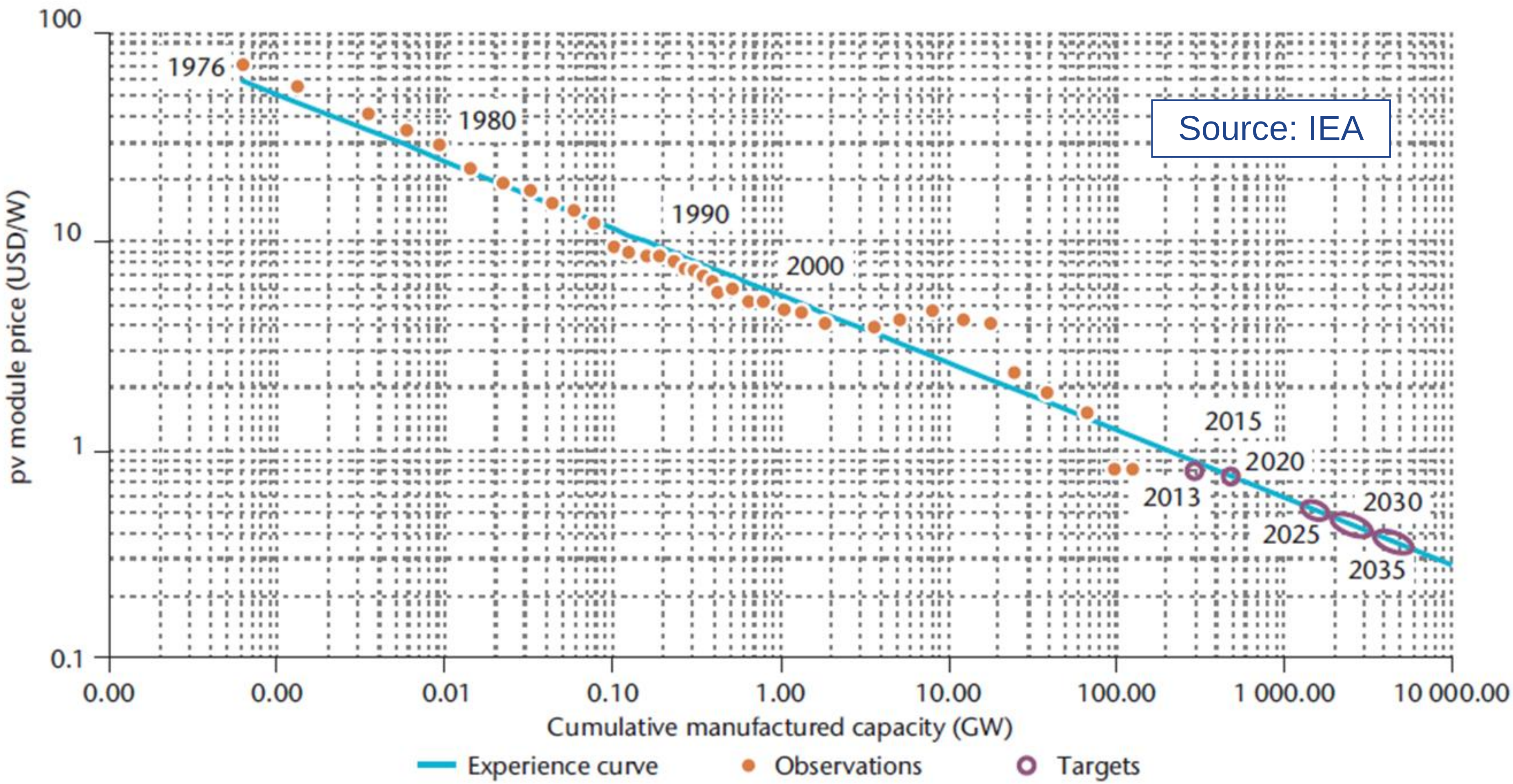
Motivation and Scope I – PV global capacity



Source: REN21

Motivation and Scope II – PV module price



Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

Motivation and Scope III – Objectives and models

Objectives

- From a policy-relevance perspective, explore different scenarios related to the possible future cost patterns of the solar PV technology
- From a modeling perspective, assess the responsiveness of models to changes in the cost data input

Participating models (→ Follow-up of the ADVANCE project on system integration modeling)

- IMAGE
- POLES

} Recursive dynamic partial equilibrium models

- REMIND
- WITCH

} Intertemporal optimal-growth general equilibrium models

Learning-by-Doing and Floor Cost

Investment cost (Learning-by-Doing):

$$CC_t = CC_1 \left(\frac{K_t}{K_1}\right)^{-b}$$

Floor cost: hard bound

$$CC_t = max\left(FC, CC_1 \left(\frac{K_t}{K_1}\right)^{-b}\right)$$

Floor cost: soft bound (asymptotic)

$$CC_t = FC + (CC_1 - FC) \cdot \left(\frac{K_t}{K_1}\right)^{-b}$$

- CC_t = capital cost at time t
- CC_1 = initial capital cost
- K_t = global cumulative capacity at time t
- K_1 = global initial capacity
- b = a measure of the strength of the learning effect
  → LR = Learning Rate = cost decrease deriving from doubling the installed capacity = $-1 + 2^b$
- FC = floor cost

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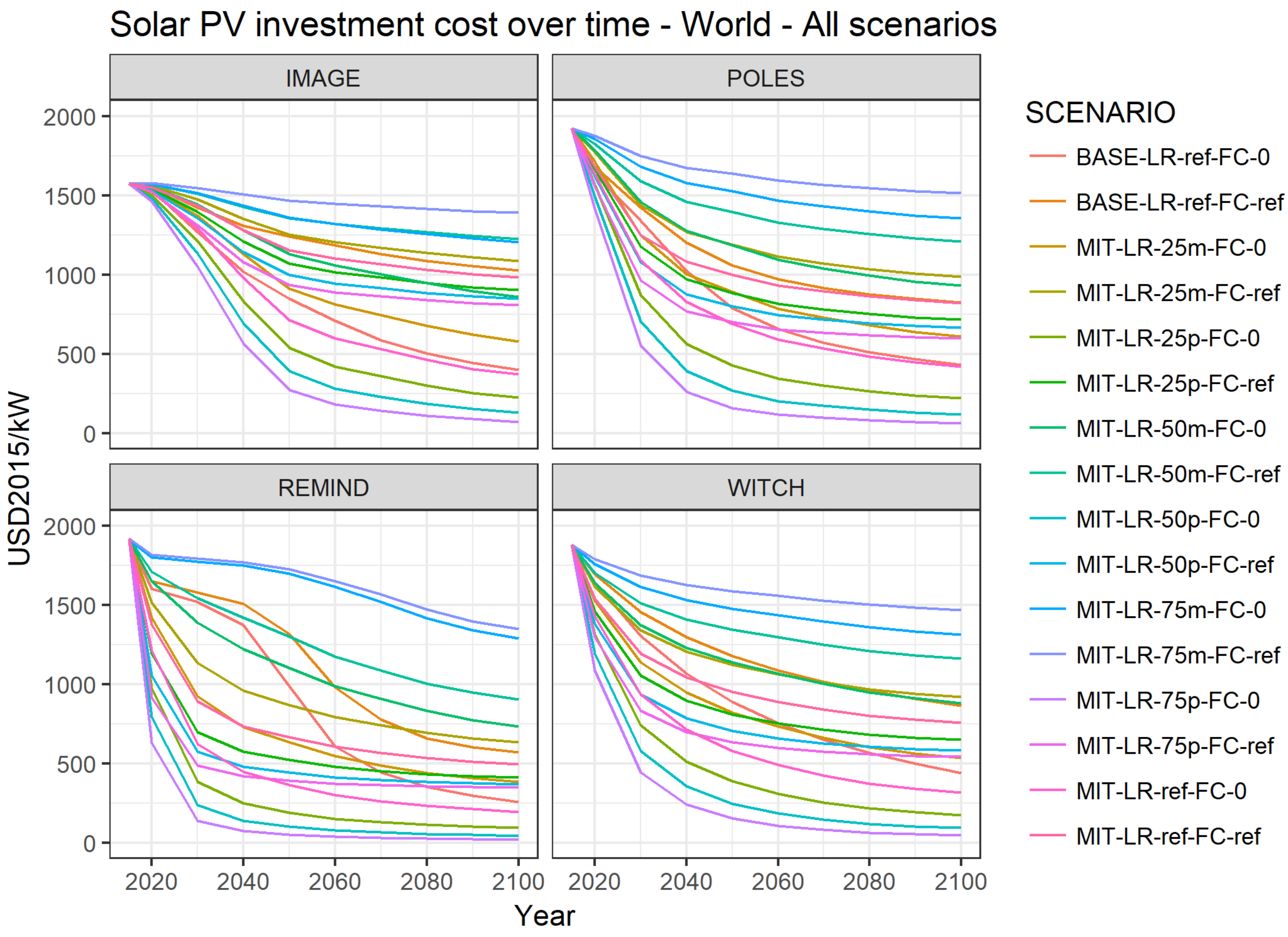
Scenario protocol

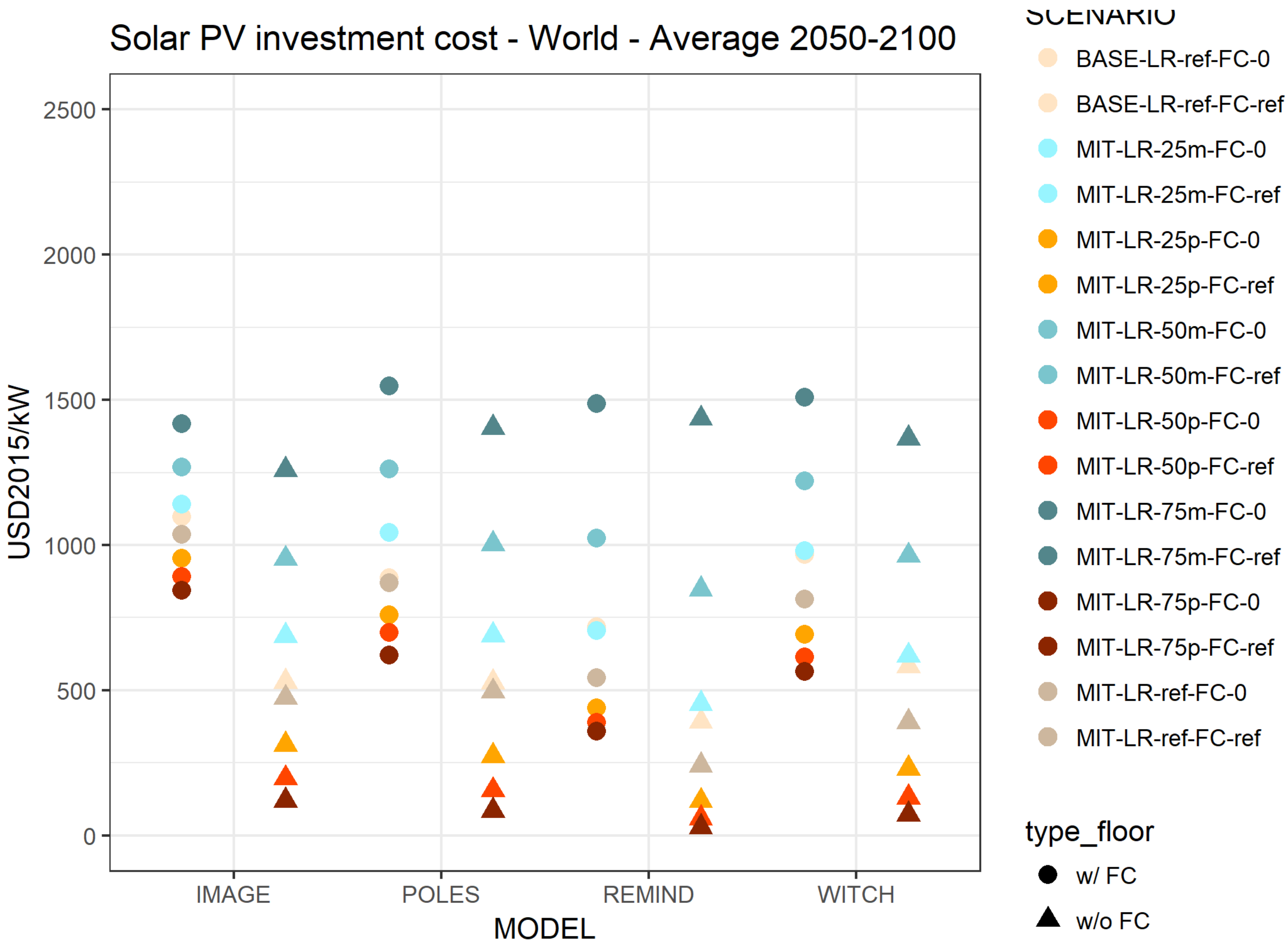
	Scenario Name	Policy	Learning Rate	Floor Cost
1	ADV4-PV-BASE-LR-ref-FC-ref	Baseline	Ref	Ref
2	ADV4-PV-BASE-LR-ref-FC-0	Baseline	Ref	0
3	ADV4-PV-MIT-LR-ref-FC-ref	Mitigation	Ref	Ref
4	ADV4-PV-MIT-LR-75p-FC-ref	Mitigation	+75%	Ref
5	ADV4-PV-MIT-LR-50p-FC-ref	Mitigation	+50%	Ref
6	ADV4-PV-MIT-LR-25p-FC-ref	Mitigation	+25%	Ref
7	ADV4-PV-MIT-LR-25m-FC-ref	Mitigation	-25%	Ref
8	ADV4-PV-MIT-LR-50m-FC-ref	Mitigation	-50%	Ref
9	ADV4-PV-MIT-LR-75m-FC-ref	Mitigation	-75%	Ref
10	ADV4-PV-MIT-LR-ref-FC-0	Mitigation	Ref	0
11	ADV4-PV-MIT-LR-75p-FC-0	Mitigation	+75%	0
12	ADV4-PV-MIT-LR-50p-FC-0	Mitigation	+50%	0
13	ADV4-PV-MIT-LR-25p-FC-0	Mitigation	+25%	0
14	ADV4-PV-MIT-LR-25m-FC-0	Mitigation	-25%	0
15	ADV4-PV-MIT-LR-50m-FC-0	Mitigation	-50%	0
16	ADV4-PV-MIT-LR-75m-FC-0	Mitigation	-75%	0

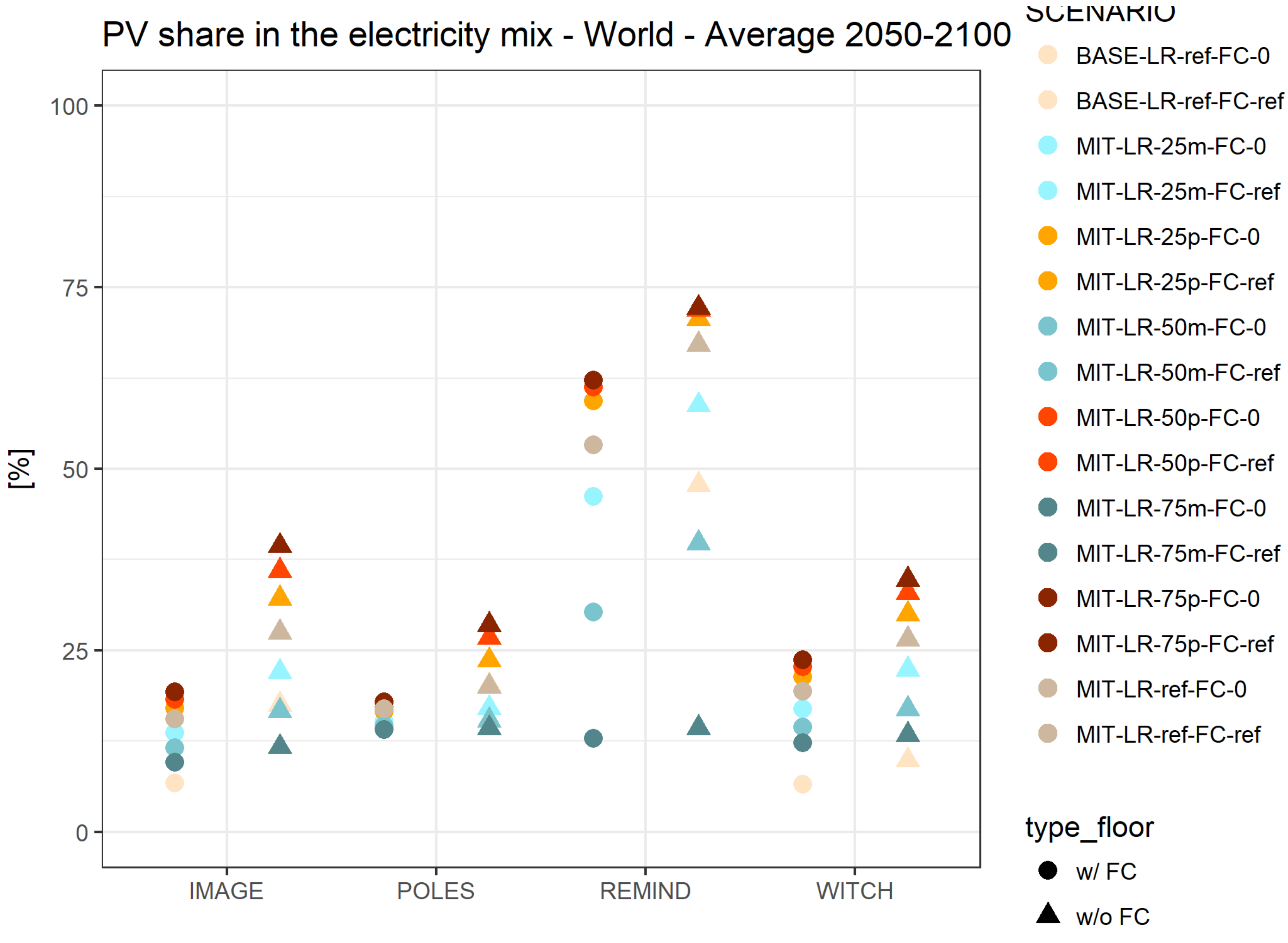
Mitigation → ctax | cumulative 1000 $GtCO_2$ in 2011-2100 in the Ref-Ref scenario → +2°C in 2100

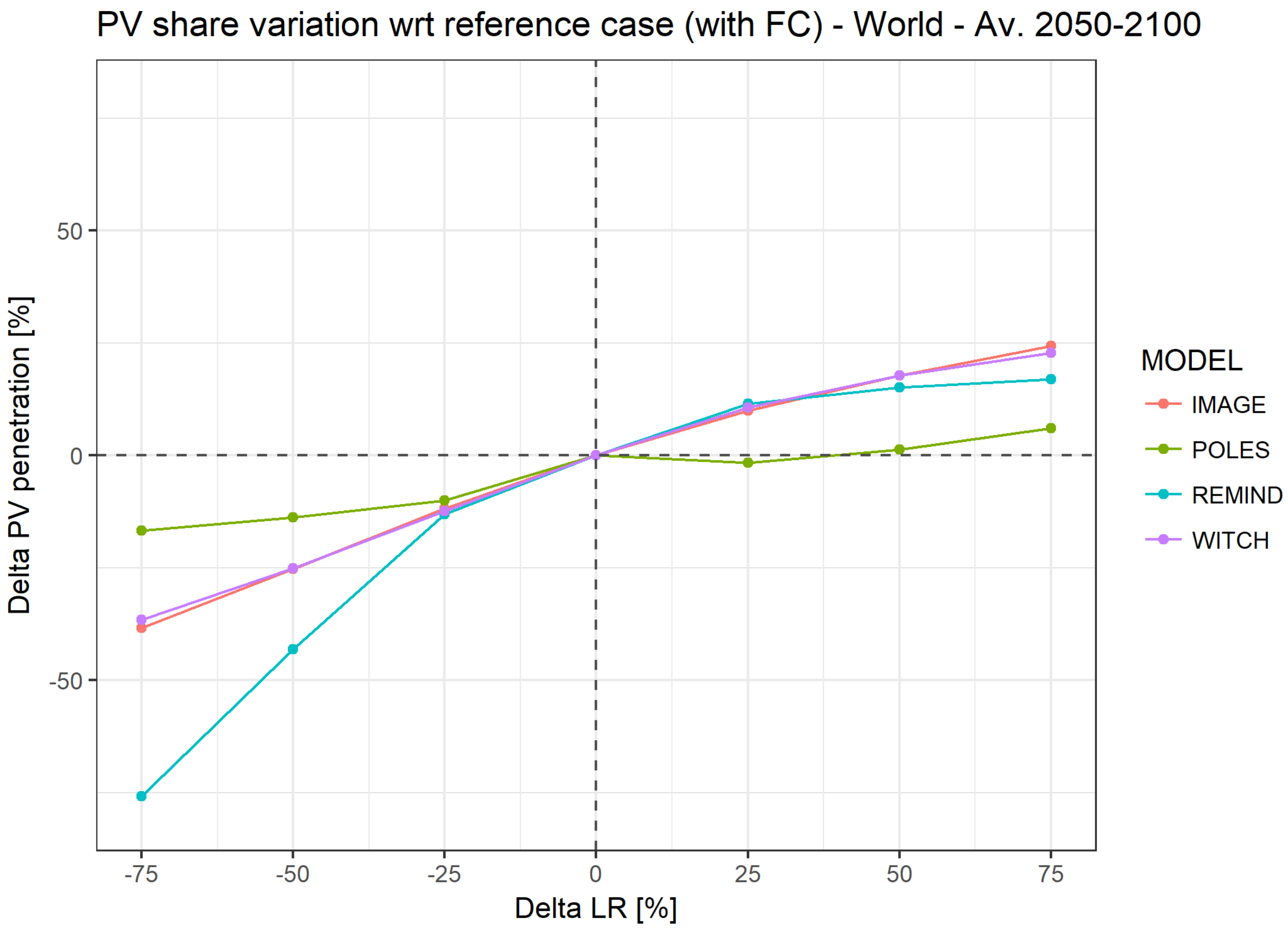
Modeling assumptions (stocktaking)

	IMAGE	POLES	REMIND	WITCH
Cost calculation	Endogenous			
Type of endogenous modeling	One-factor learning curve (LbD)			
Regional differentiation	Yes, with (limited) spillover effects	No, only one global cost		
Type of floor cost	Soft bound (asymptotic)			
Plant depreciation	Linear	Linear	Concave	Exponential
Depreciation rate	0.1	0.04	-	0.044
Lifetime [years]	25	25	30	25
2015 investment cost [USD2015/kW]	1576	1924	1916	1879
Learning rate	20%	15%	20%	20%
Floor cost [USD2015/kW]	433	619	458	495

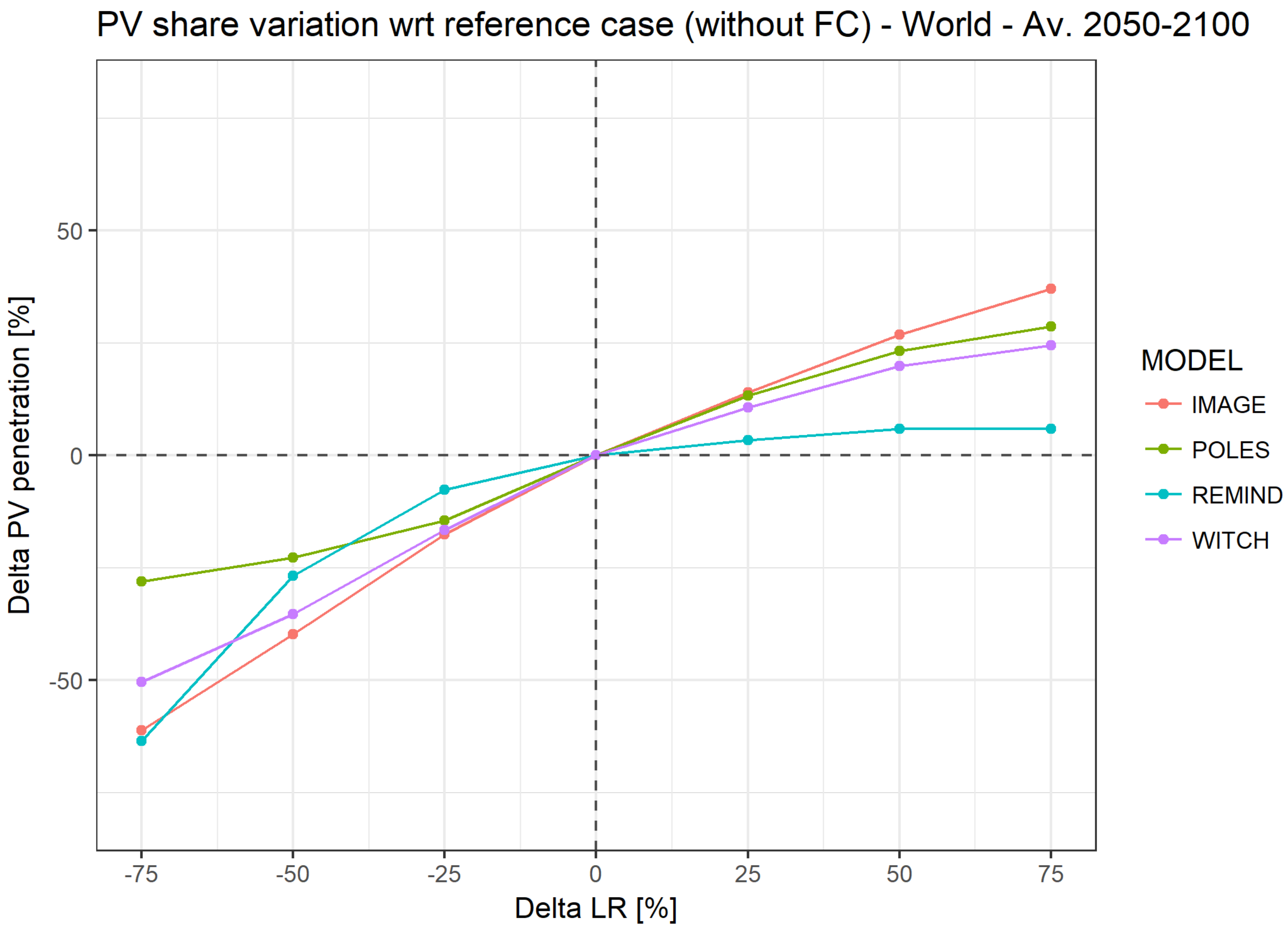

Solar PV investment cost over time - World - All scenarios
IMAGE
POLES
REMIND
WITCH
USD2015/kW
Year
2000
1500
1000
500
0
2020
2040
2060
2080
2100
SCENARIO
BASE-LR-ref-FC-0
BASE-LR-ref-FC-ref
MIT-LR-25m-FC-0
MIT-LR-25m-FC-ref
MIT-LR-25p-FC-0
MIT-LR-25p-FC-ref
MIT-LR-50m-FC-0
MIT-LR-50m-FC-ref
MIT-LR-50p-FC-0
MIT-LR-50p-FC-ref
MIT-LR-75m-FC-0
MIT-LR-75m-FC-ref
MIT-LR-75p-FC-0
MIT-LR-75p-FC-ref
MIT-LR-ref-FC-0
MIT-LR-ref-FC-ref

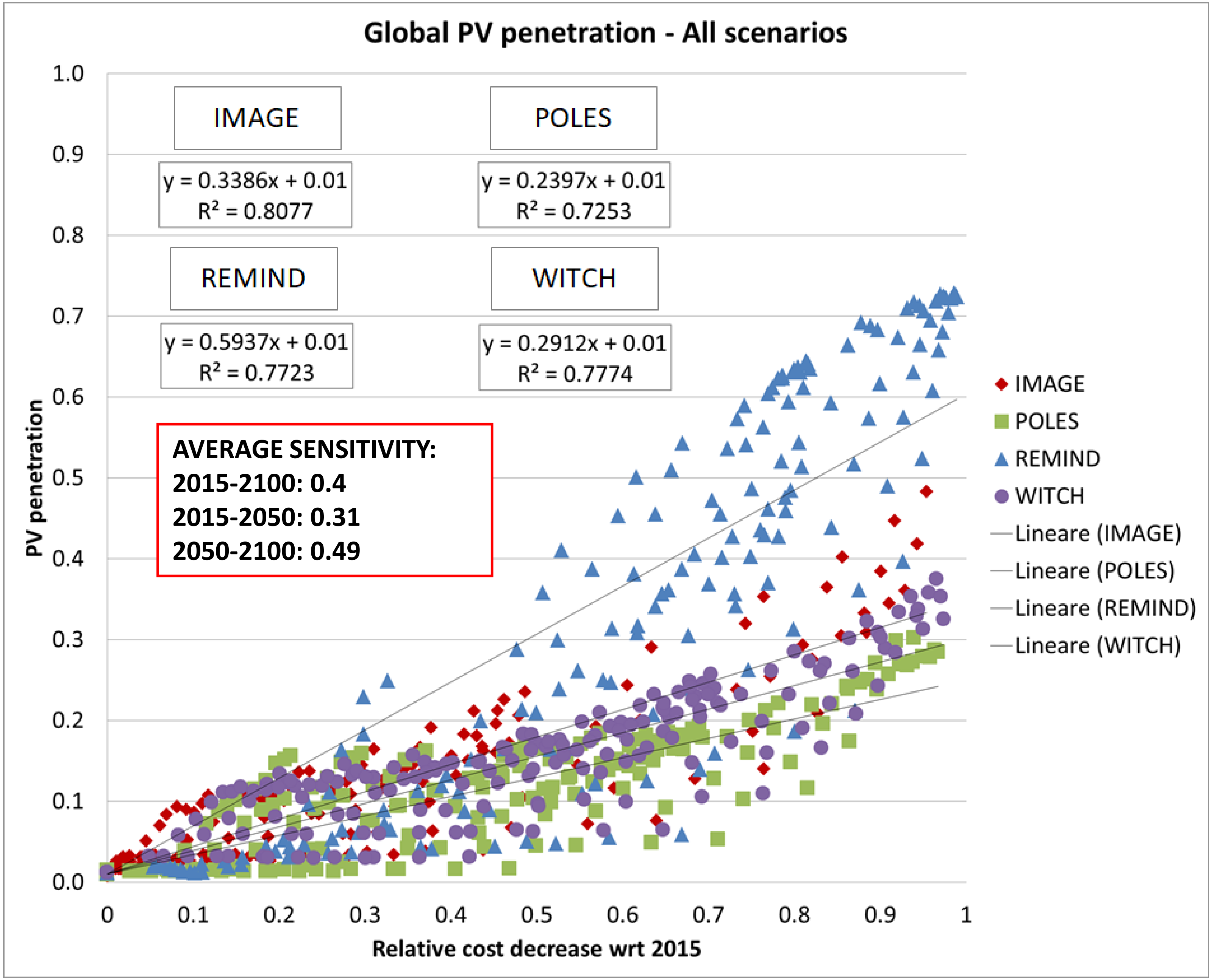

Solar PV investment cost - World - Average 2050-2100
USD2015/kW
2500
2000
1500
1000
500
0
IMAGE
POLES
REMIND
WITCH
MODEL
SCENARIO
BASE-LR-ref-FC-0
BASE-LR-ref-FC-ref
MIT-LR-25m-FC-0
MIT-LR-25m-FC-ref
MIT-LR-25p-FC-0
MIT-LR-25p-FC-ref
MIT-LR-50m-FC-0
MIT-LR-50m-FC-ref
MIT-LR-50p-FC-0
MIT-LR-50p-FC-ref
MIT-LR-75m-FC-0
MIT-LR-75m-FC-ref
MIT-LR-75p-FC-0
MIT-LR-75p-FC-ref
MIT-LR-ref-FC-0
MIT-LR-ref-FC-ref
type_floor
w/ FC
w/o FC


PV share in the electricity mix - World - Average 2050-2100
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
SCENARIO
BASE-LR-ref-FC-0
BASE-LR-ref-FC-ref
MIT-LR-25m-FC-0
MIT-LR-25m-FC-ref
MIT-LR-25p-FC-0
MIT-LR-25p-FC-ref
MIT-LR-50m-FC-0
MIT-LR-50m-FC-ref
MIT-LR-50p-FC-0
MIT-LR-50p-FC-ref
MIT-LR-75m-FC-0
MIT-LR-75m-FC-ref
MIT-LR-75p-FC-0
MIT-LR-75p-FC-ref
MIT-LR-ref-FC-0
MIT-LR-ref-FC-ref
type_floor
w/ FC
w/o FC

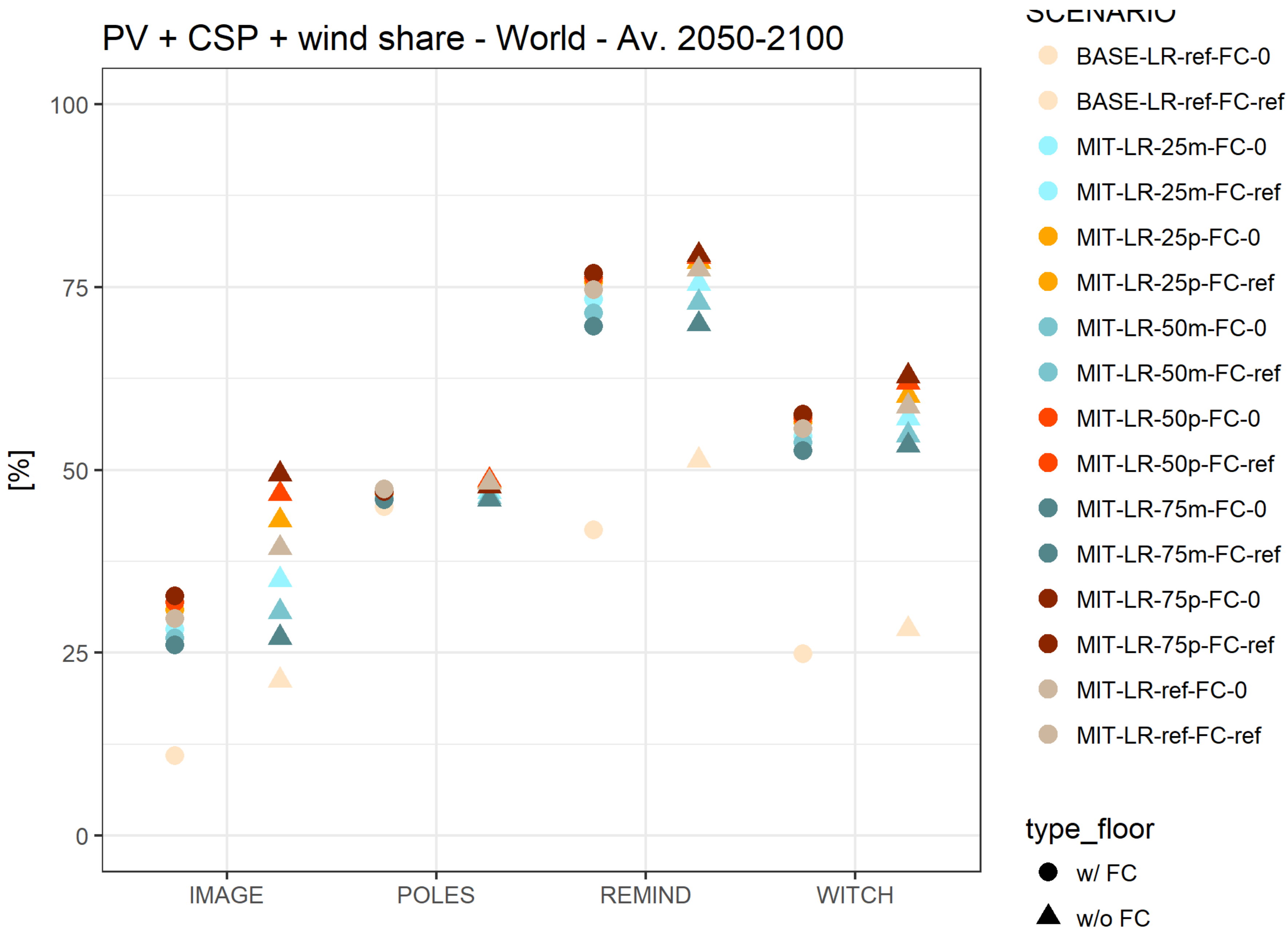


PV share variation wrt reference case (with FC) - World - Av. 2050-2100
Delta PV penetration [%]
50
0
-50
-75
-50
-25
0
25
50
75
Delta LR [%]
MODEL
IMAGE
POLES
REMIND
WITCH


PV share variation wrt reference case (without FC) - World - Av. 2050-2100
Delta PV penetration [%]
50
0
-50
-75
-50
-25
0
25
50
75
Delta LR [%]
MODEL
IMAGE
POLES
REMIND
WITCH


Global PV penetration - All scenarios
IMAGE
POLES
y = 0.3386x + 0.01
R² = 0.8077
y = 0.2397x + 0.01
R² = 0.7253
REMIND
WITCH
y = 0.5937x + 0.01
R² = 0.7723
y = 0.2912x + 0.01
R² = 0.7774
AVERAGE SENSITIVITY:
2015-2100: 0.4
2015-2050: 0.31
2050-2100: 0.49
PV penetration
Relative cost decrease wrt 2015
IMAGE
POLES
REMIND
WITCH
Lineare (IMAGE)
Lineare (POLES)
Lineare (REMIND)
Lineare (WITCH)

MERCURY


PV + CSP + wind share - World - Av. 2050-2100
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
SCENARIO
BASE-LR-ref-FC-0
BASE-LR-ref-FC-ref
MIT-LR-25m-FC-0
MIT-LR-25m-FC-ref
MIT-LR-25p-FC-0
MIT-LR-25p-FC-ref
MIT-LR-50m-FC-0
MIT-LR-50m-FC-ref
MIT-LR-50p-FC-0
MIT-LR-50p-FC-ref
MIT-LR-75m-FC-0
MIT-LR-75m-FC-ref
MIT-LR-75p-FC-0
MIT-LR-75p-FC-ref
MIT-LR-ref-FC-0
MIT-LR-ref-FC-ref
type_floor
w/ FC
w/o FC

Conclusions

- In the long run (2050-2100), global PV penetration spans a range of 10-72%, with a marked growth with respect to the current 1% in all scenarios and models.
- Models tend to show a limited sensitivity to PV penetration in their specific results. Sensitivity of PV penetration to capital cost reduction is averagely 0.4 across scenarios.
- Sensitivity to learning rates is not symmetric, being markedly higher for decreasing learning rates than for increasing learning rates.
- Models show a sort of "threshold" on which PV penetration tends to progressively collapse in the most favorable scenarios. This highlights the role of non-capital cost factors, especially system integration.
- Sensitivity to PV capital cost even diminishes when all Variable Renewable Energies (VREs, i.e. wind and solar CSP in addition to PV) are focused. This means that the higher/lower PV penetration related to its lower/higher capital cost mainly occurs to the detriment/benefit of wind and CSP.

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The techno-economic effects of the delayed deployment of CCS technologies on climate change mitigation

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Introduction

- Carbon Capture & Storage (CCS) has widely been recognized as one of the main technological solutions to decarbonize the energy sector and virtually all research studies project a considerable role in future mitigation pathways, especially if the target is to stay below 2°C (→ importance of negative emissions)
- Main advantage → (theoretically) zero or negative CO_2 emissions (→ BECCS, i.e. biomass CCS) without changing the fossil-based generation paradigm (→ plant dispatchability)
- However, large-scale CCS deployment is yet to come
  → globally, 30 $MtCO_2$/yr storage capacity vs. 37 $GtCO_2$/yr emissions
- Main obstacles to CCS diffusion:

  - safety concerning the stability of storage sites
  - public acceptance
  - high technology costs
  - incomplete or unclear regulatory framework
  - absence of business models

Objective and scenario design

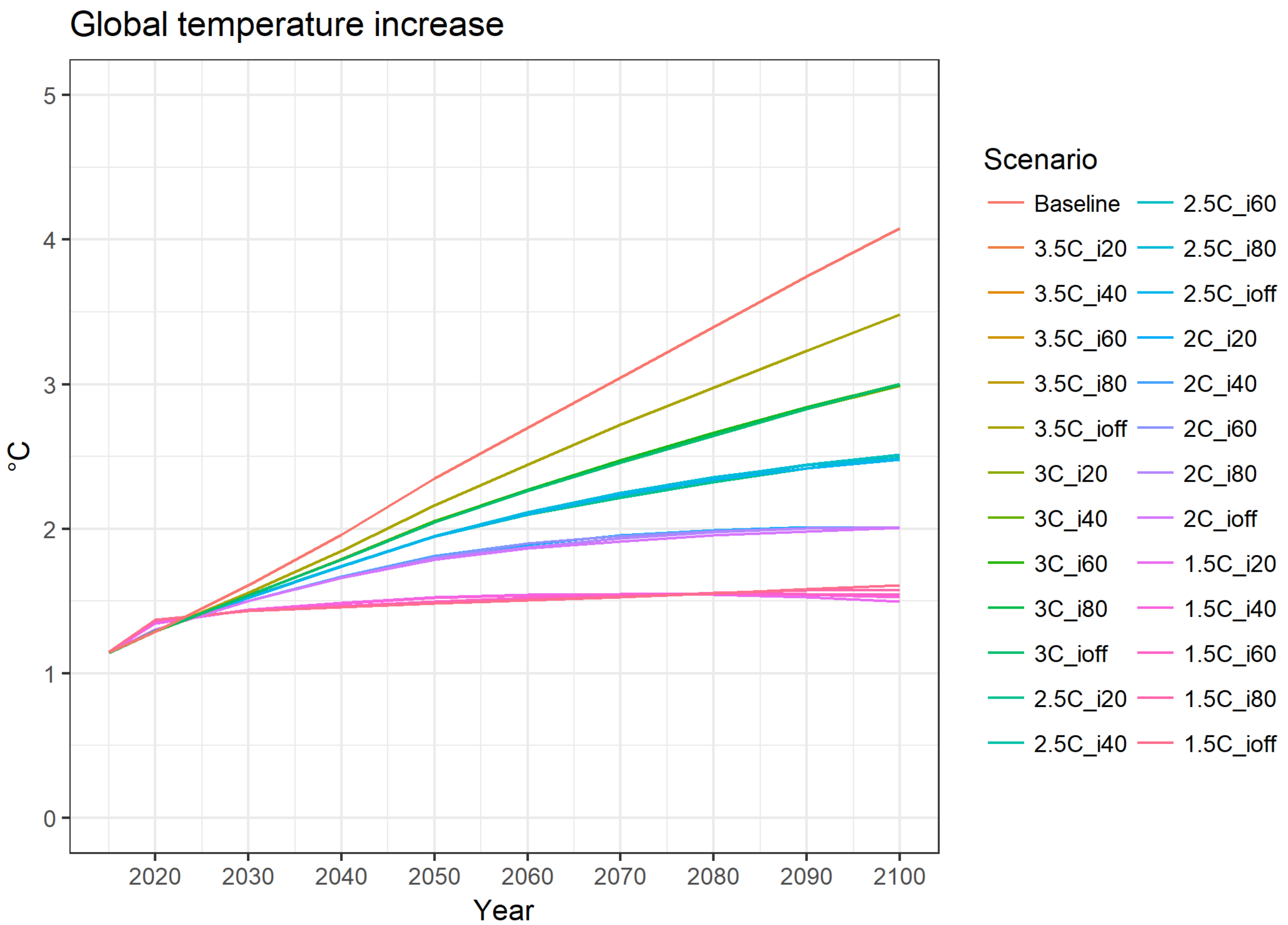
Objective

- Assess the impacts that a progressively delayed CCS deployment can have both in terms of re-arrangement of the energy mix (technical dimension) and in terms of policy costs (economic dimension).

  → Alternatively, how urgent is the installation of CCS plants for the techno-economic feasibility of more and more stringent climate targets?

Scenario design

- 26 scenarios: BAU + 5 climate targets x 5 “starting years” when CCS deployment is allowed
- BAU → 4°C
- [3.5°C, 3°C, 2.5°C, 2°C, 1.5°C] x [2020 (i20), 2040 (i40), 2060 (i60), 2080 (i80), no CCS (ioff)]


Global temperature increase
°C
Year
Scenario
Baseline
3.5C_i20
3.5C_i40
3.5C_i60
3.5C_i80
3.5C_ioff
3C_i20
3C_i40
3C_i60
3C_i80
3C_ioff
2.5C_i20
2.5C_i40
2.5C_i60
2.5C_i80
2.5C_ioff
2C_i20
2C_i40
2C_i60
2C_i80
2C_ioff
1.5C_i20
1.5C_i40
1.5C_i60
1.5C_i80
1.5C_ioff
0
1
2
3
4
5
2020
2030
2040
2050
2060
2070
2080
2090
2100

CCS modeling in WITCH

- CO_2 sequestration, transport, and storage are modeled via regional supply cost curves, which depend on site availability.
- The unit cost curve C_{CCS} has a convex shape:

$$C_{CCS}(t,n) = a_{CCS}(n) \cdot \exp(\alpha_{CCS}(n) \cdot M_{CCS}(t,n)^{\beta_{CCS}(n)})$$

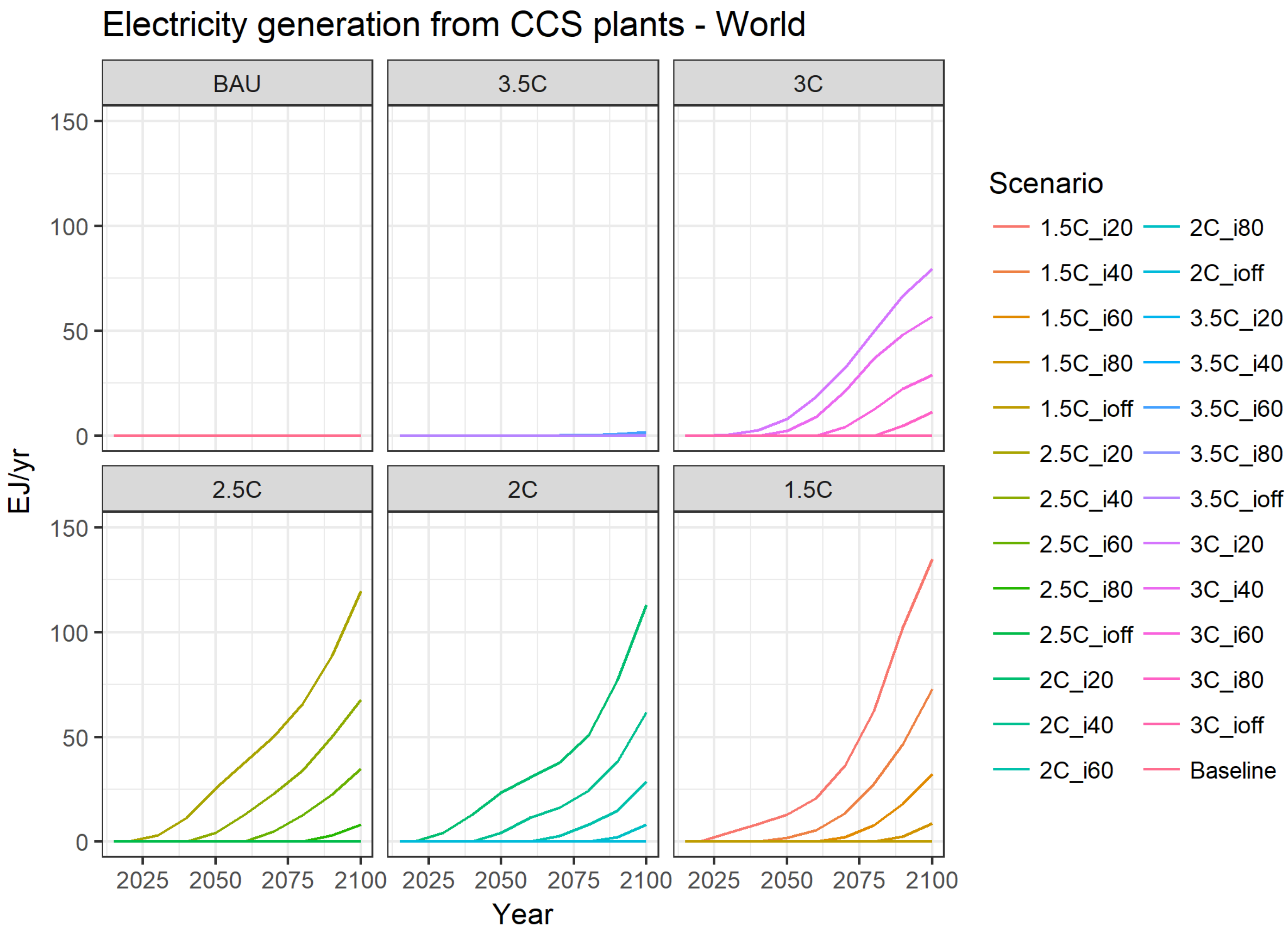
- t: time step

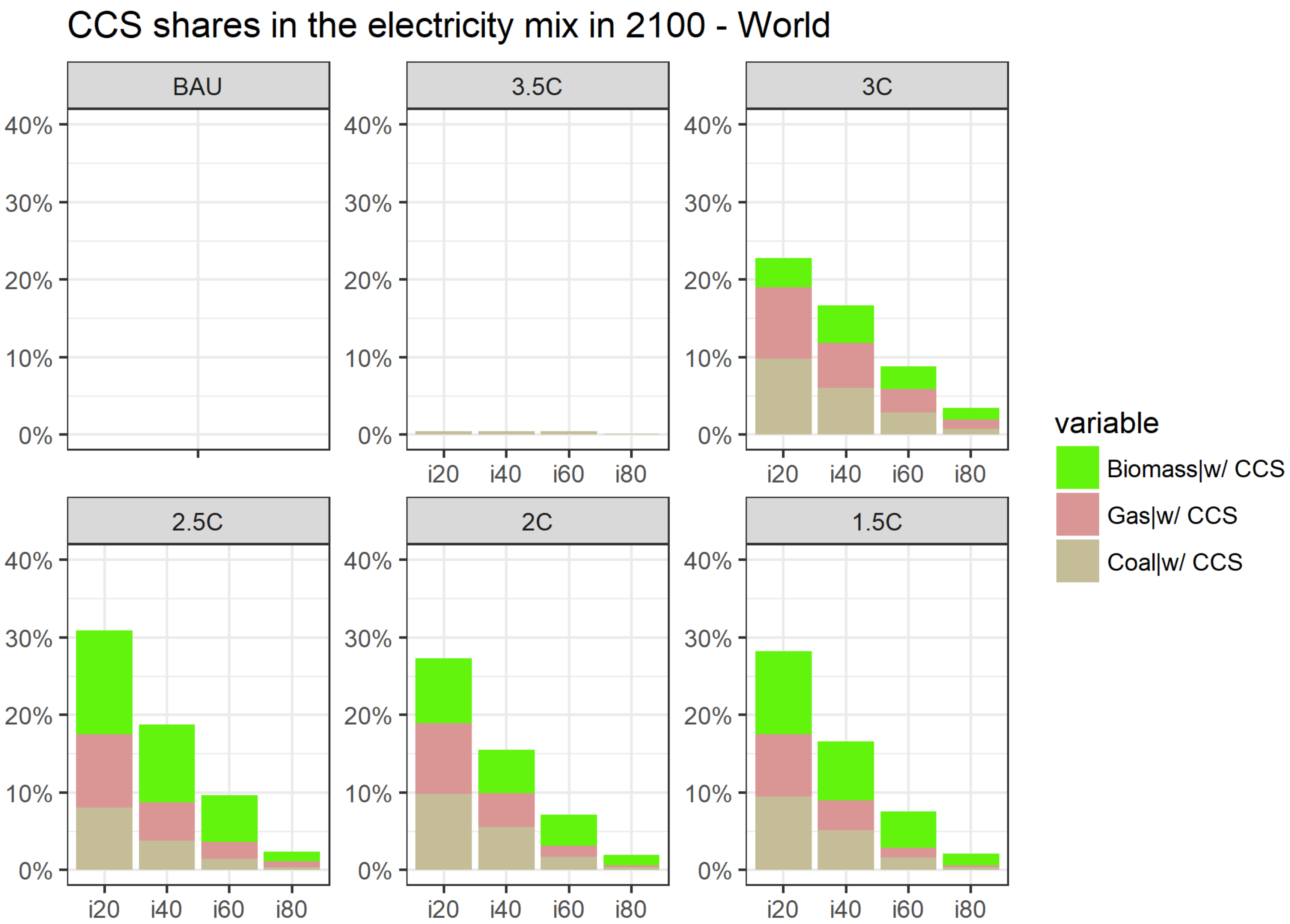
- n: region

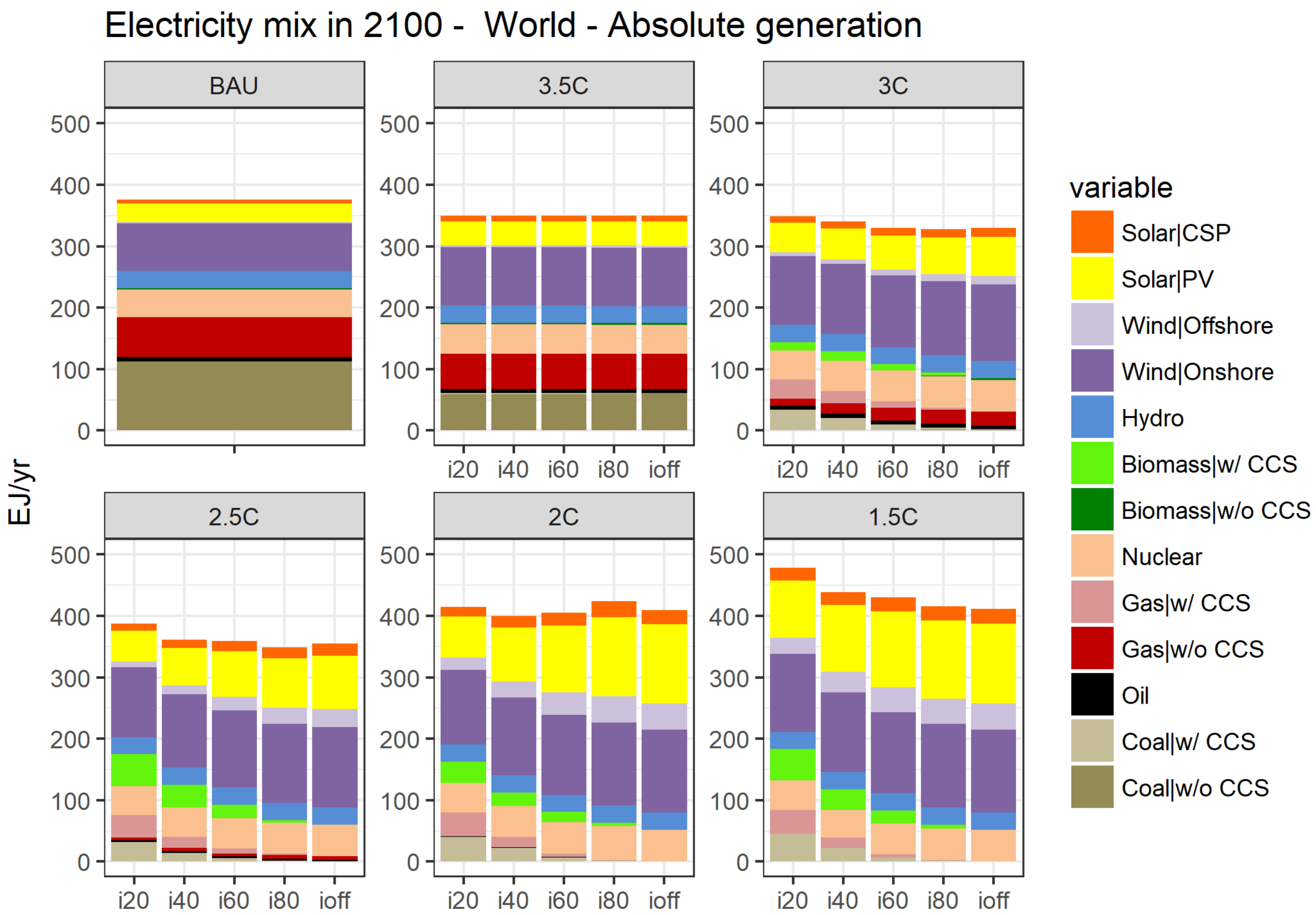
- $M_{CCS}(t,n)$: cumulated amount of CO_2 captured over the years

- a, α, β: parameters calibrated on the storage capacities in the different regions (→ global estimated capacity: 1678-11100 $GtCO_2$ according to the IPCC)

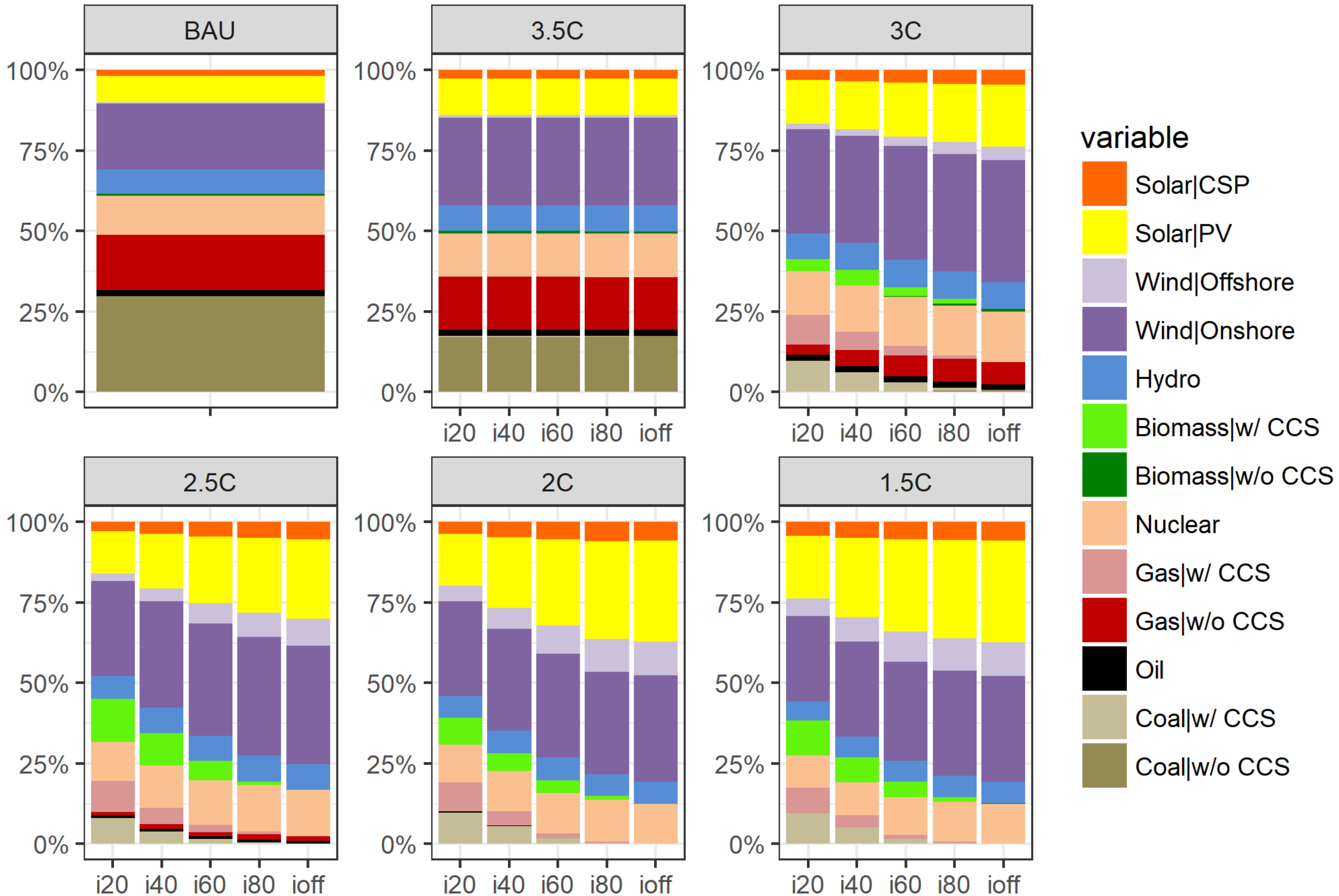
- The total CCS cost is finally computed by multiplying the unit cost C_{CCS} by the amount of fuel burnt in the relevant power plants.


Electricity generation from CCS plants - World
BAU
3.5C
3C
2.5C
2C
1.5C
150
100
50
0
EJ/yr
2025
2050
2075
2100
Year
Scenario
1.5C_i20
1.5C_i40
1.5C_i60
1.5C_i80
1.5C_ioff
2.5C_i20
2.5C_i40
2.5C_i60
2.5C_i80
2.5C_ioff
2C_i20
2C_i40
2C_i60
2C_i80
2C_ioff
3.5C_i20
3.5C_i40
3.5C_i60
3.5C_i80
3.5C_ioff
3C_i20
3C_i40
3C_i60
3C_i80
3C_ioff
Baseline

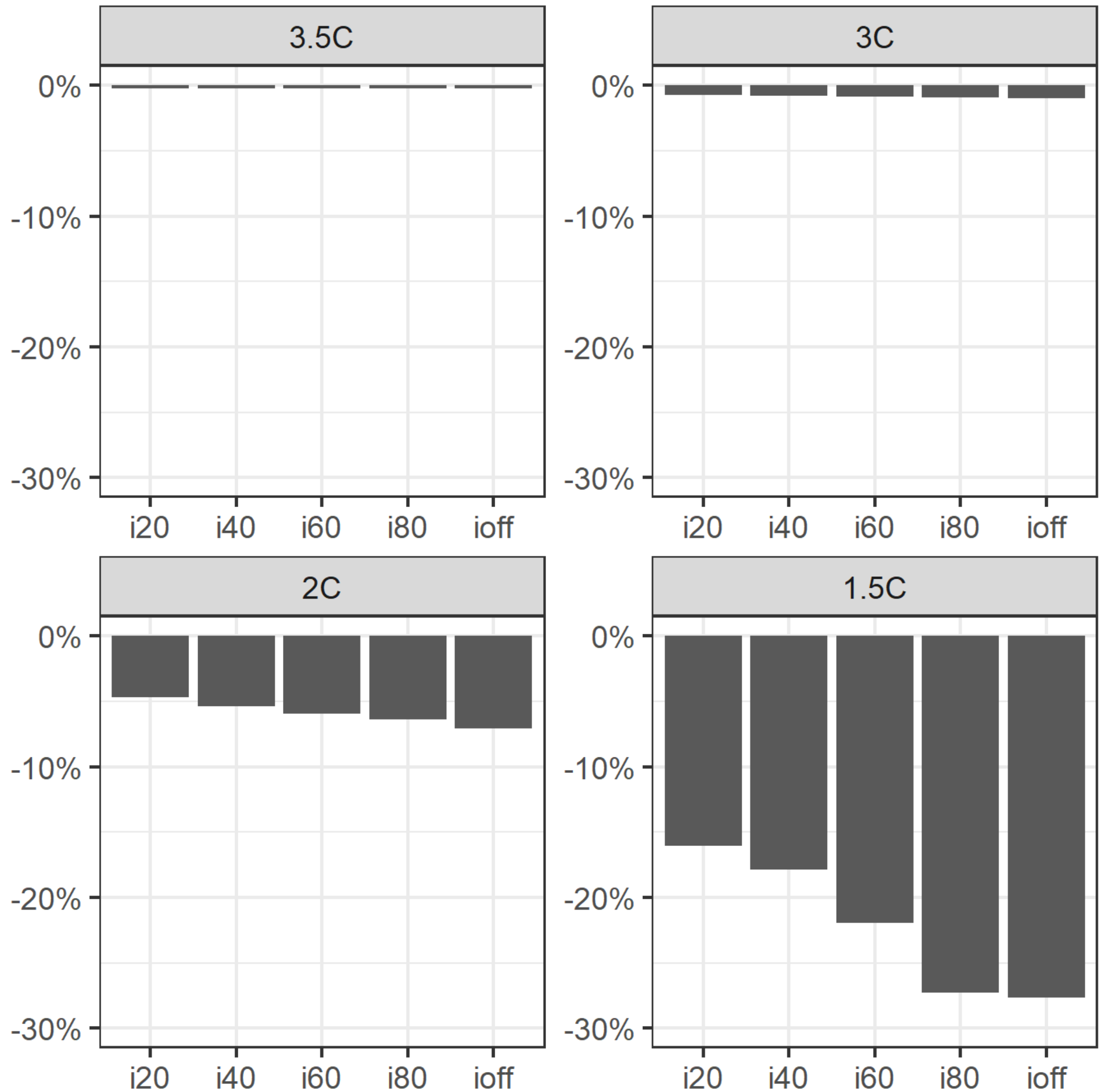

CCS shares in the electricity mix in 2100 - World
BAU
3.5C
3C
2.5C
2C
1.5C
40%
30%
20%
10%
0%
i20
i40
i60
i80
variable
Biomass|w/ CCS
Gas|w/ CCS
Coal|w/ CCS


Electricity mix in 2100 - World - Absolute generation
BAU
3.5C
3C
2.5C
2C
1.5C
EJ/yr
0
100
200
300
400
500
i20
i40
i60
i80
ioff
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

Electricity mix in 2100 - World - Relative shares

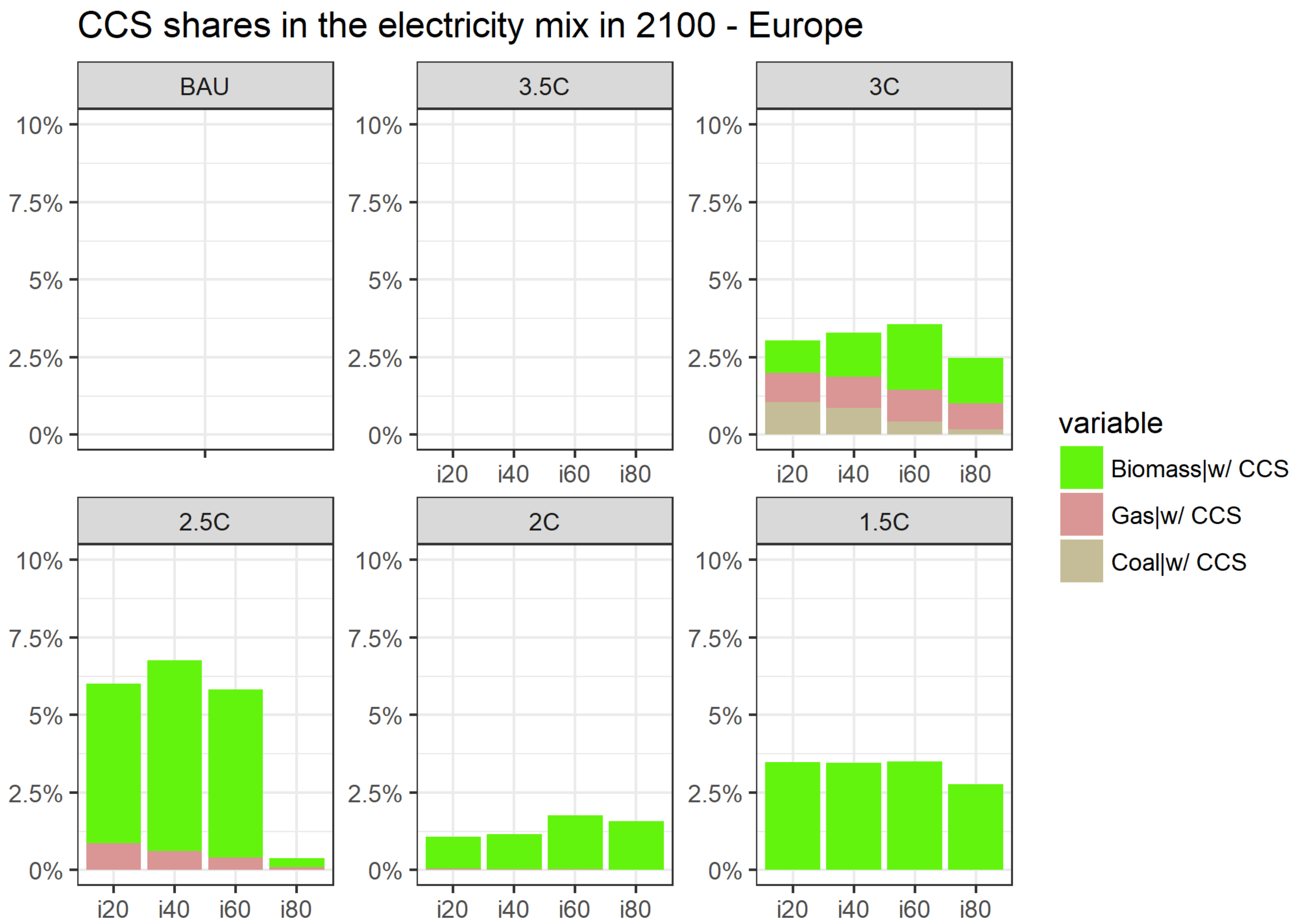


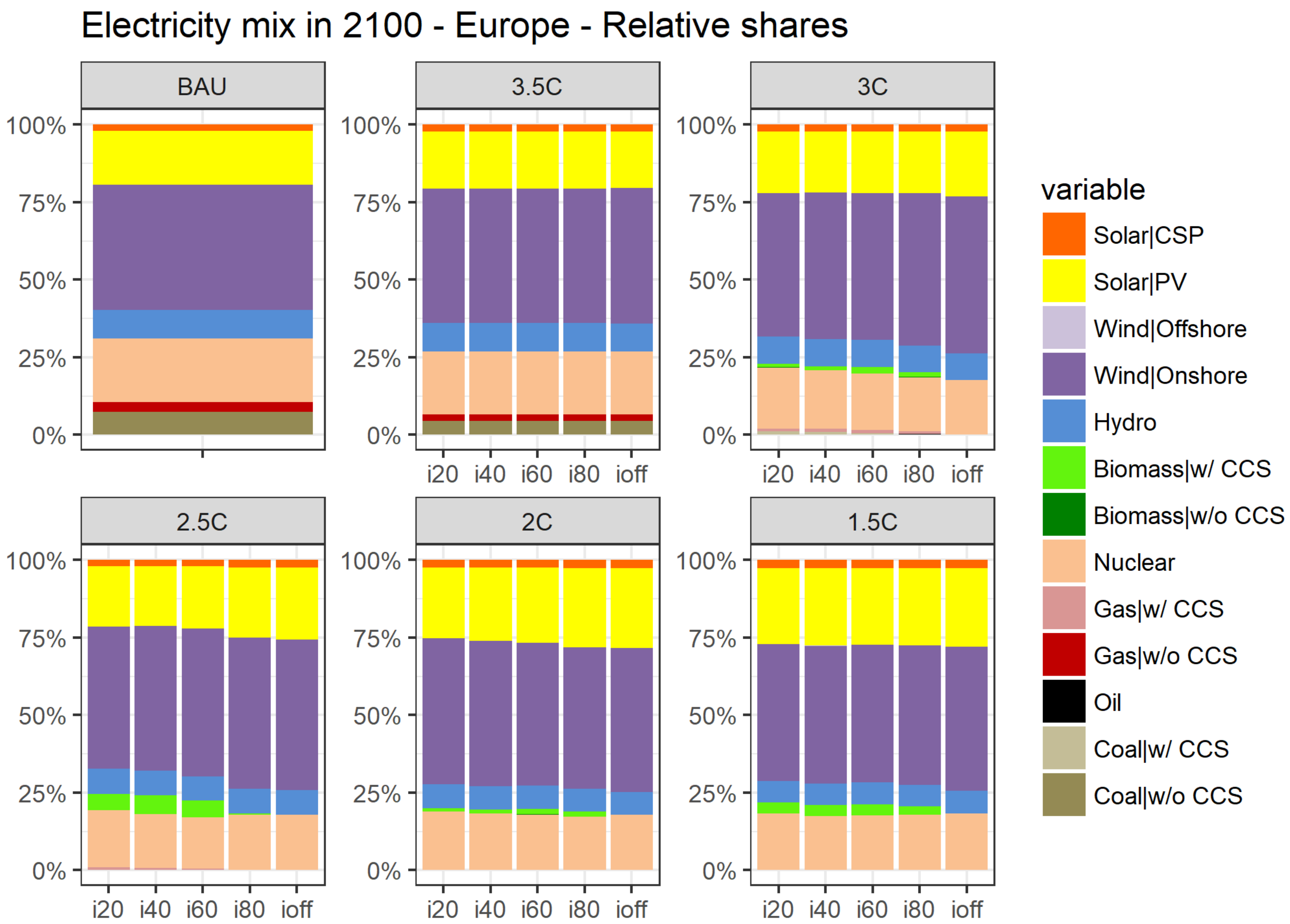
Policy cost 2p5



Policy cost = cumulative discounted GDP loss with respect to BAU in 2015-2100 (discount rate = 2.5%)

$$\frac{\text{P. Cost ioff}}{\text{P. Cost i20}} \approx 1.5$$


CCS shares in the electricity mix in 2100 - Europe
BAU
3.5C
3C
2.5C
2C
1.5C
10%
7.5%
5%
2.5%
0%
i20
i40
i60
i80
variable
Biomass|w/ CCS
Gas|w/ CCS
Coal|w/ CCS



Electricity mix in 2100 - Europe - Relative shares
BAU
3.5C
3C
2.5C
2C
1.5C
100%
75%
50%
25%
0%
i20
i40
i60
i80
ioff
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

Conclusions

- CCS is likely to play a major role in the decarbonization of the electricity sector at a global level, as it is installed in all scenarios with a policy target equal to 3°C or less.
- As soon as the investment in CCS is allowed, this option is immediately activated by the optimization model. Due to expansion constraints, the delayed installation prevents CCS from reaching the optimal level which would be achieved in the unconstrained scenarios.
- This implies a progressively lower penetration in the electricity mix as the deployment is delayed: global CCS penetration achieves around 25-30% in 2100 in all scenarios from 1.5°C to 3°C, gradually decreasing to zero as the deployment is delayed or not allowed.
- The lower or no CCS generation is mostly compensated by renewables (notably wind and solar), also with a slight increase in nuclear.
- The overall electricity demand slightly diminishes with the progressively delayed CCS deployment (more markedly in the 1.5°C scenarios).
- Delaying or removing CCS from the optimal electricity mix has negative effects on the overall economic performance: the no CCS scenario is characterized by a cumulative GDP loss which is averagely 50% higher than the corresponding unconstrained CCS scenario.
- Europe is characterized by low availability of storage sites and by high renewable potential and technology maturity → low CCS penetration in all scenarios → little sensitivity to the CCS starting year.

MERCURY – Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy

Reactor ageing and phase-out policies: global and European prospects for nuclear power generation

The MERCURY project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 706330.

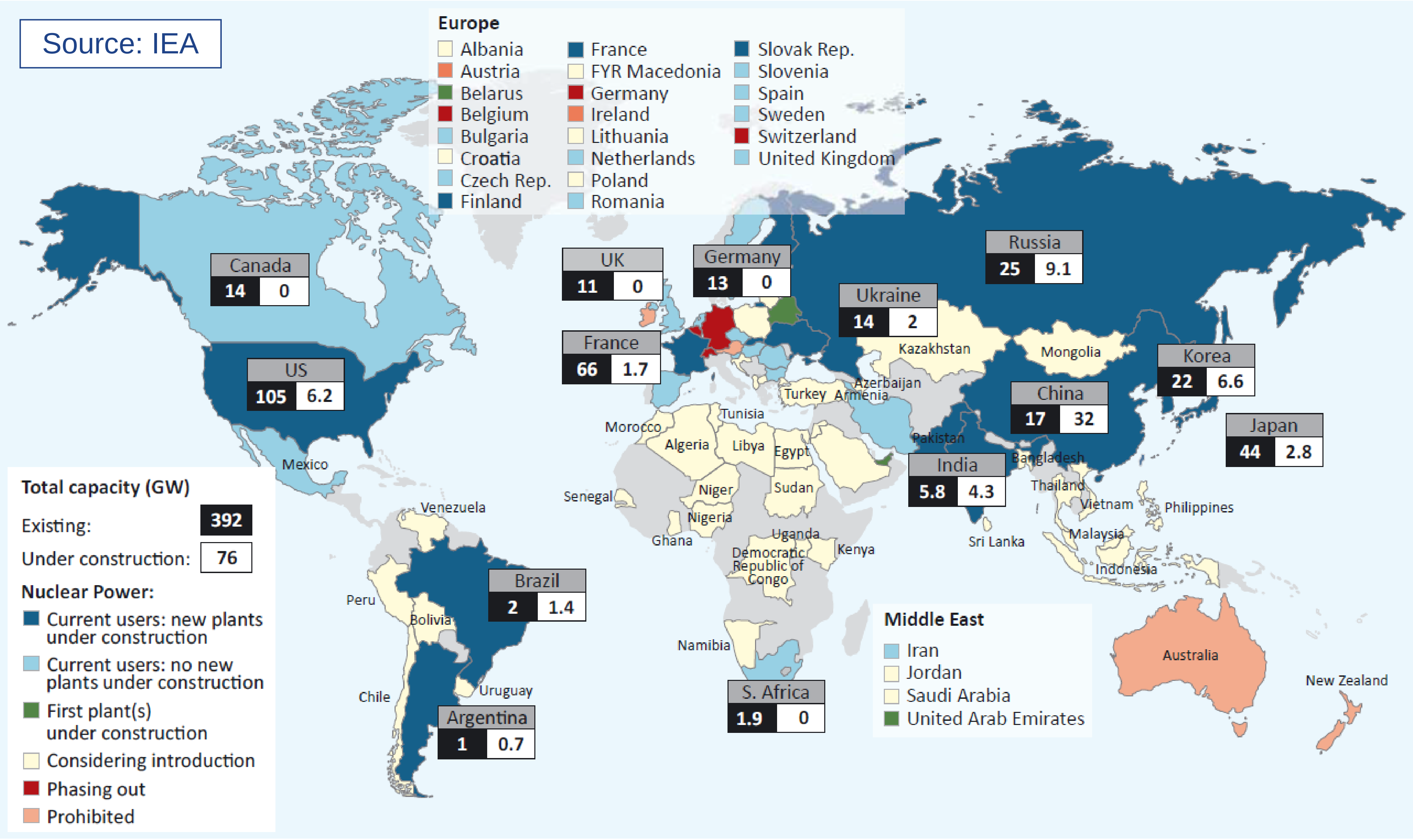
Introduction

- Nuclear has widely been recognized as one of the main technological solutions to decarbonize the energy sector and virtually all research studies project a considerable role in future mitigation pathways (*… same as CCS!*).
- Main advantage → zero CO_2 emissions with a consolidated and dispatchable power generation technology.
- Very different prospects in different areas of the world:

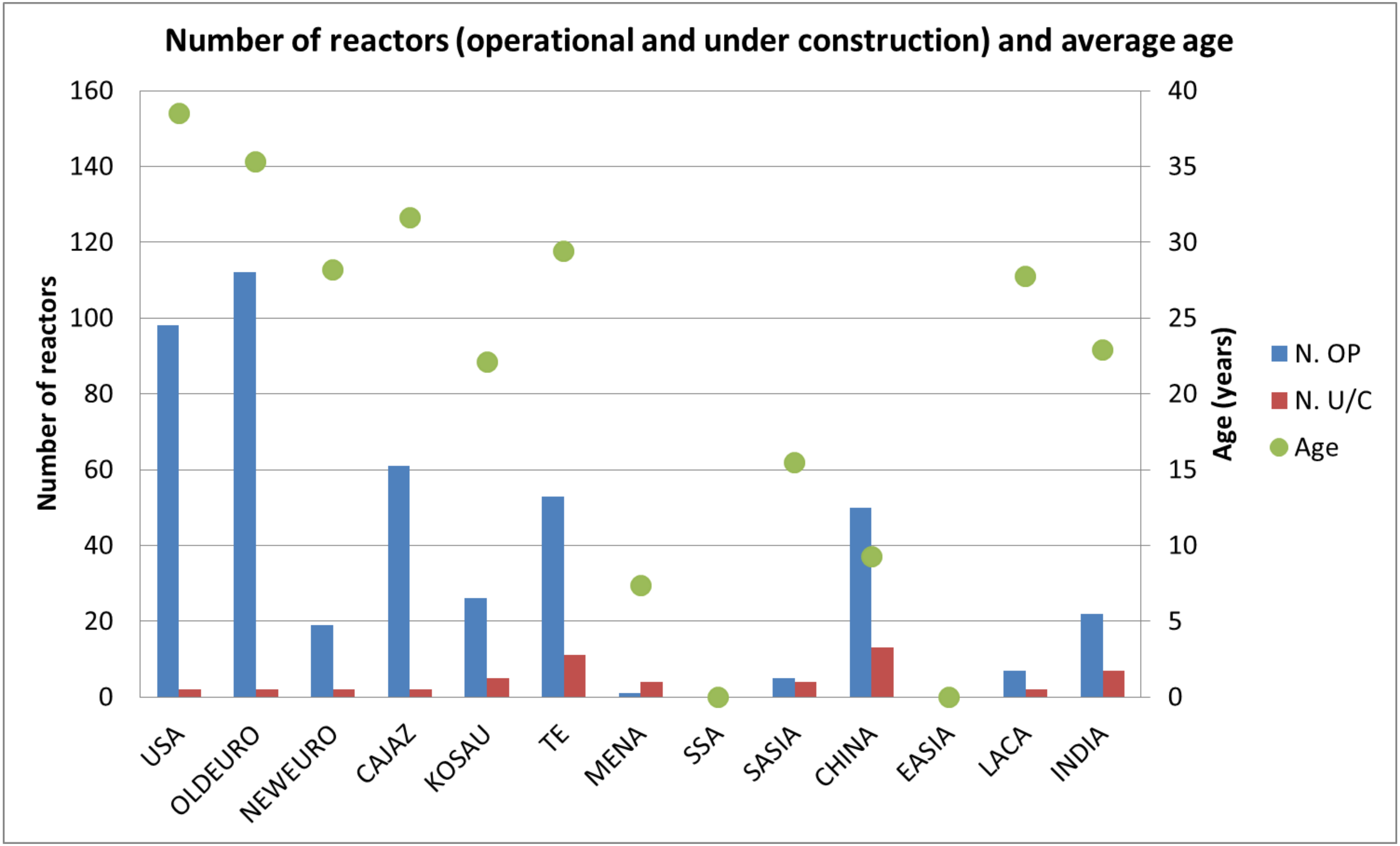
  - non-OECD countries (especially China, India, Russia) + Republic of Korea: nuclear characterized by high momentum

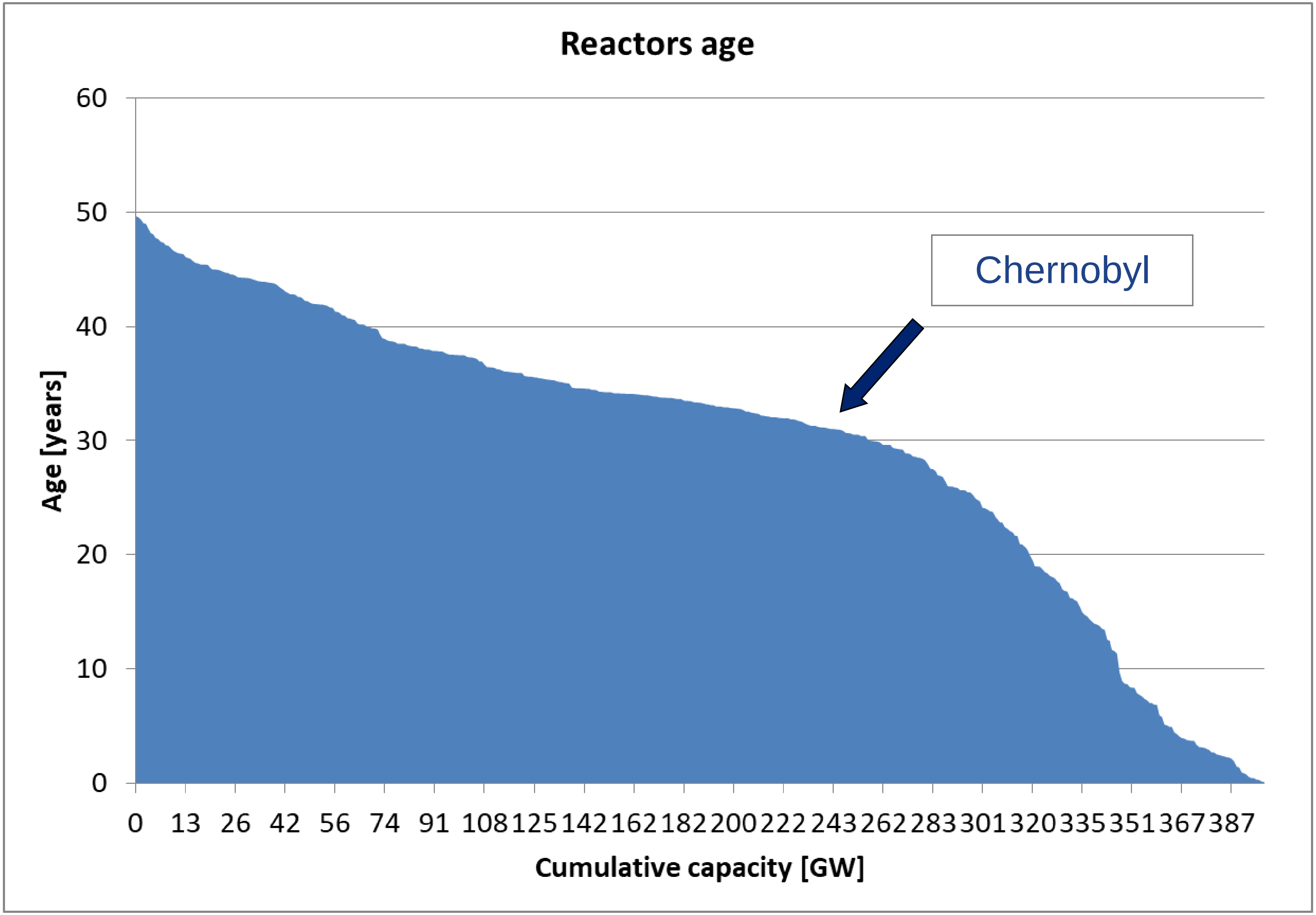
  - OECD countries:
  i) nuclear reactors, mostly built between the 70s and the 80s, are approaching the end of their operational life
  ii) political, social, and economic constraints hinder the construction of new plants
  → even in presence of massive investments to extend the operational lifetime (from about 40 to about 60 years) the actual prospects in these countries are controversial

Figure 10.4 ▷ **Status of nuclear power programmes, end-2013**



MERCURY


Number of reactors (operational and under construction) and average age
Number of reactors
Age (years)
0
20
40
60
80
100
120
140
160
0
5
10
15
20
25
30
35
40
USA
OLDEURO
NEWEURO
CAJAZ
KOSAU
TE
MENA
SSA
SASIA
CHINA
EASIA
LACA
INDIA
N. OP
N. U/C
Age


Reactors age
Chernobyl
Age [years]
60
50
40
30
20
10
0
0 13 26 42 56 74 91 108 125 142 162 182 200 222 243 262 283 301 320 335 351 367 387
Cumulative capacity [GW]

Objective and scenario design

Objective

- Most scenario exercises consider either a full nuclear scenario (no constraints) or a complete, global nuclear phase-out.

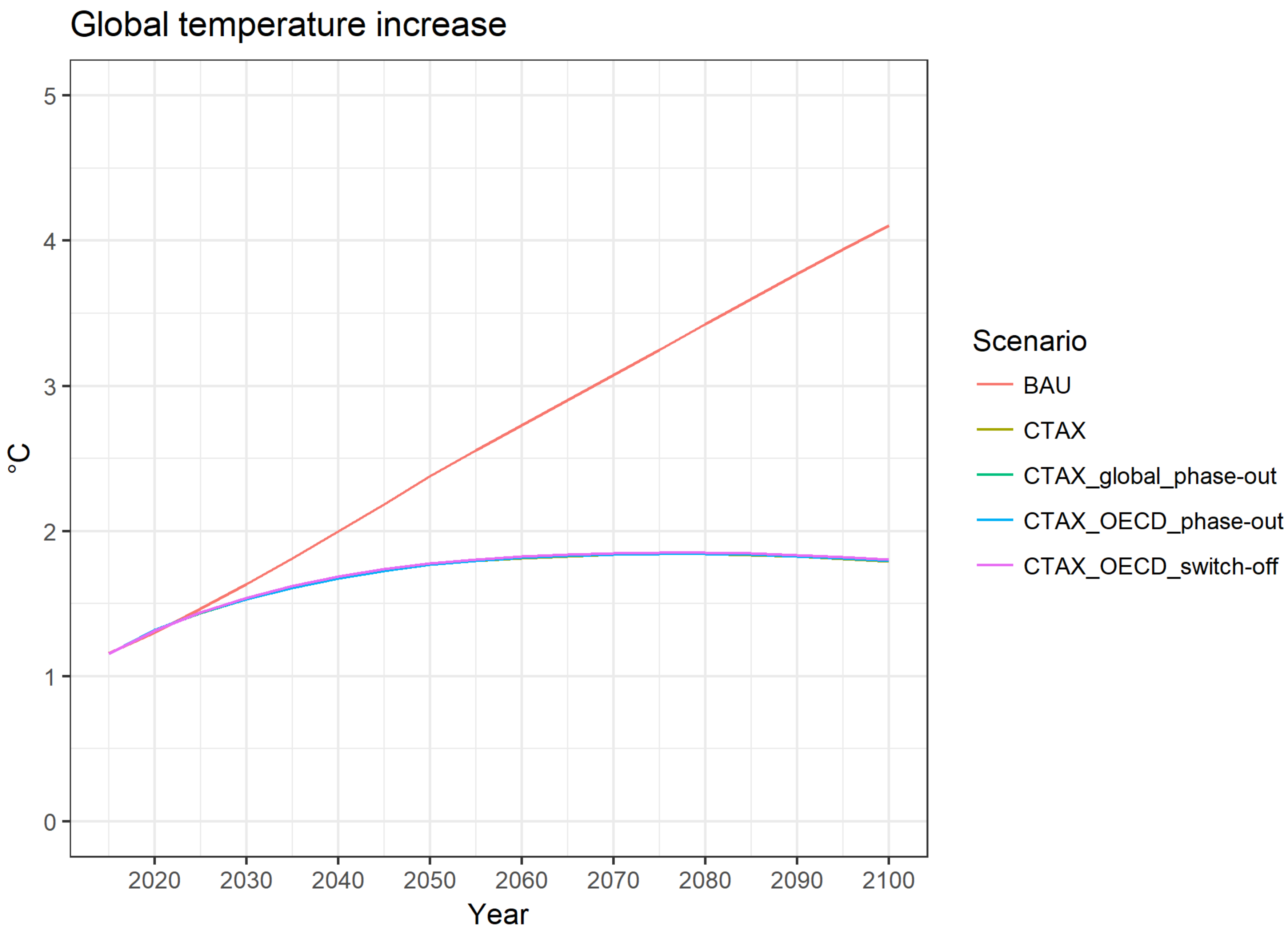
→ The objective is to investigate more calibrated and realistic scenarios.

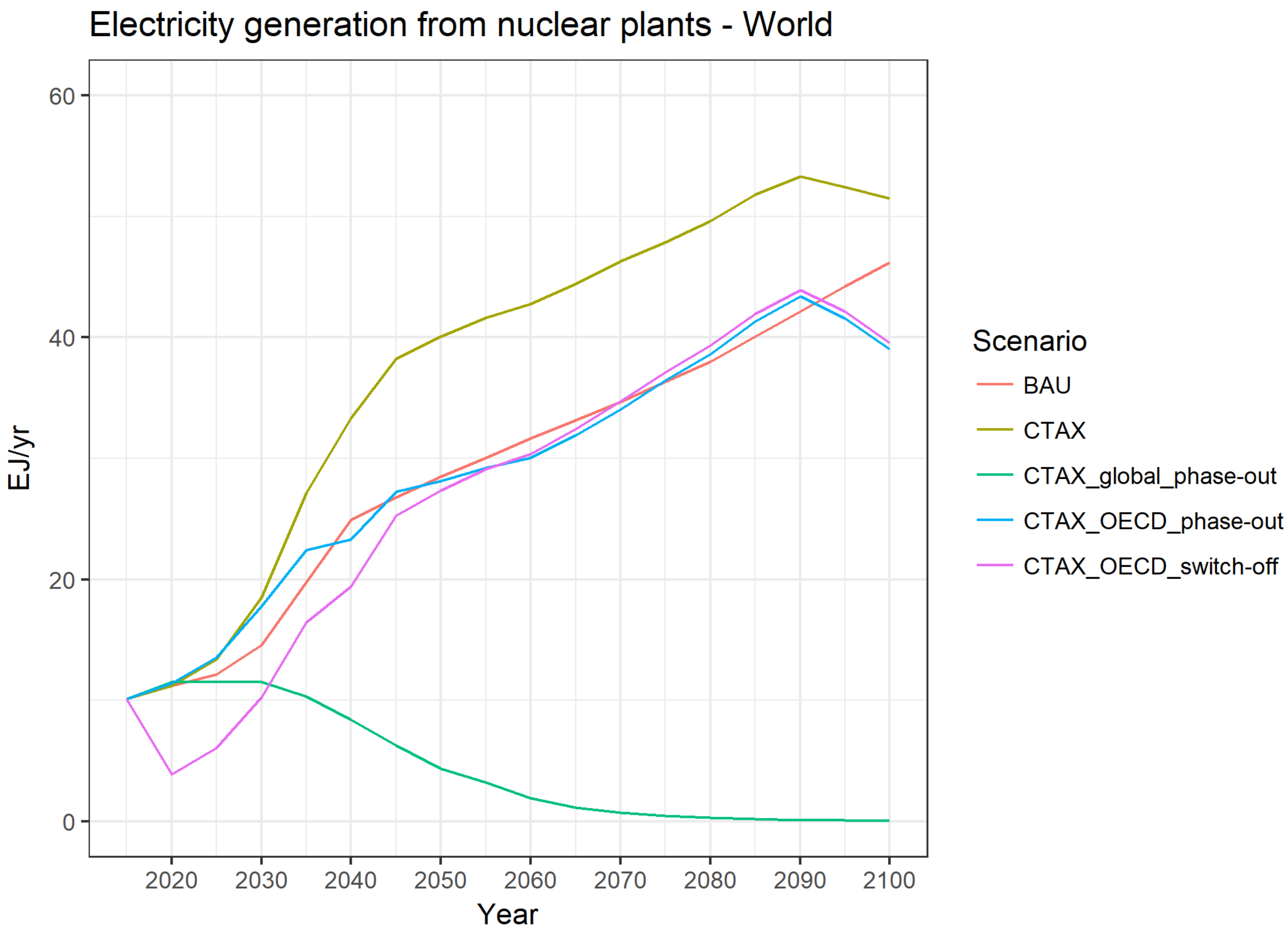
Scenario design

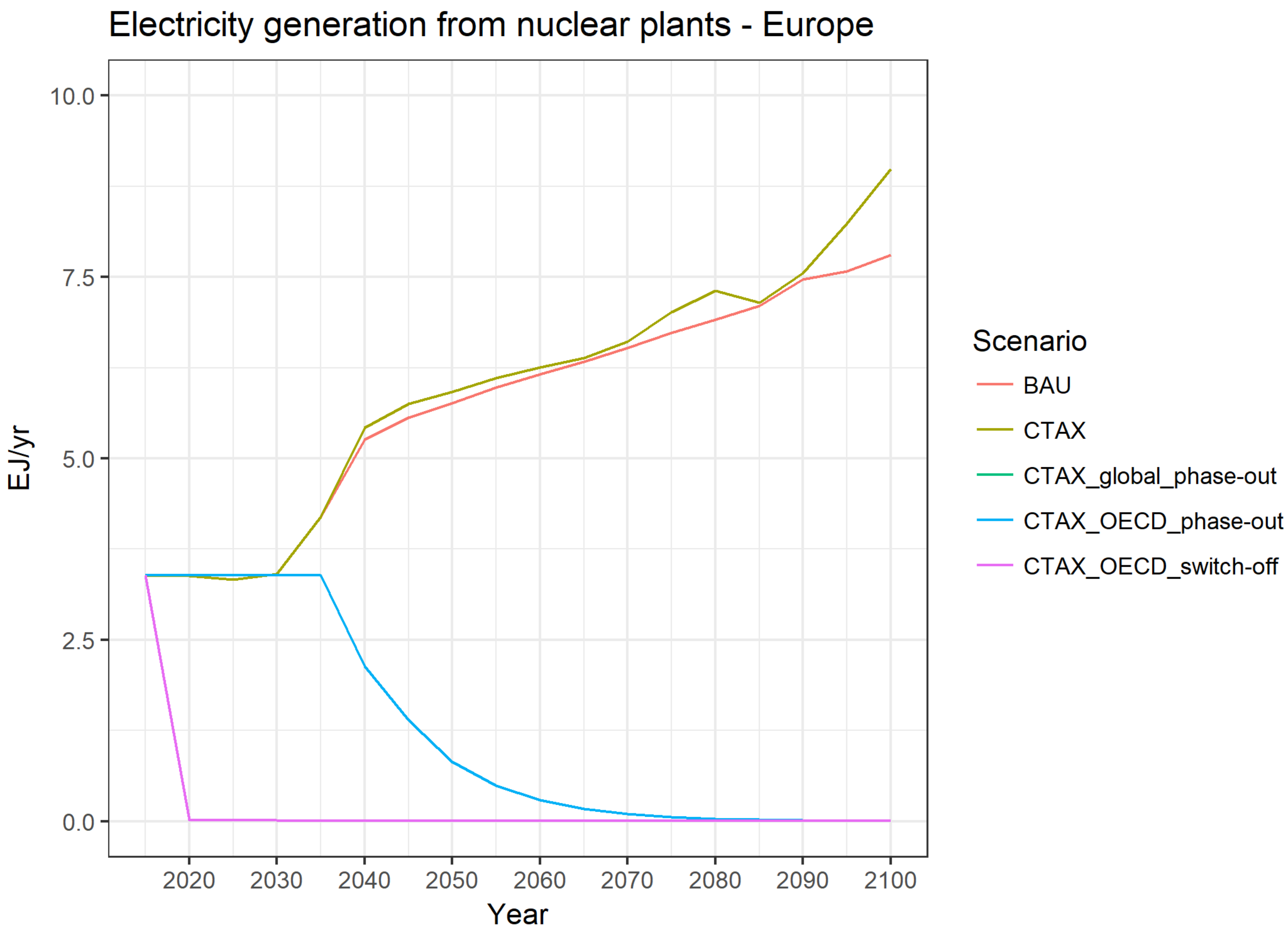
- BAU
- CTAX
- CTAX_global_phase-out
- CTAX_OECD_phase-out
- CTAX_OECD_switch-off

OECD = OECD w/o R. of Korea (i.e. KOSAU)

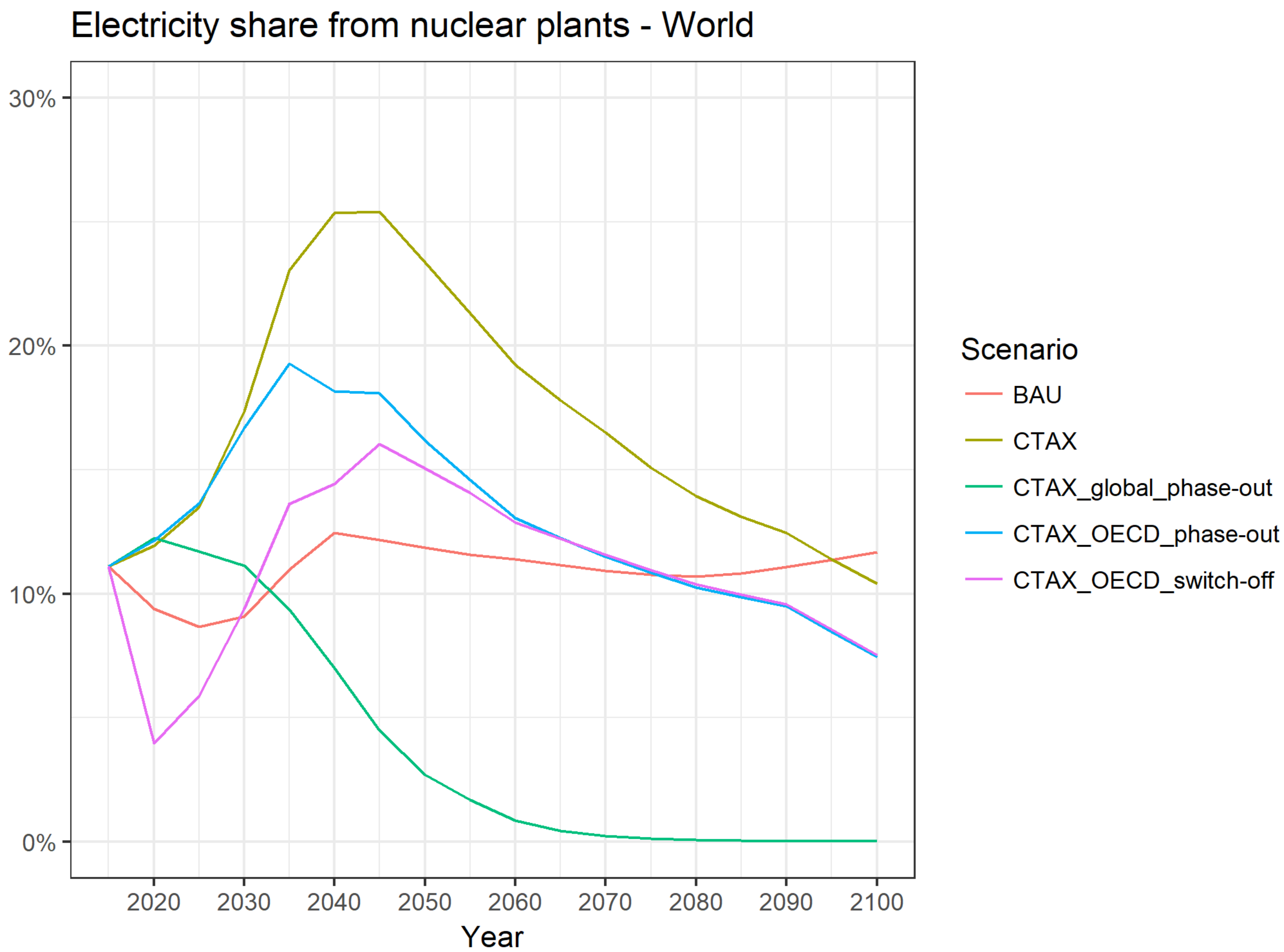
→ CTAX | cumulative 1000 $GtCO_2$ in 2011-2100 → +2°C in 2100

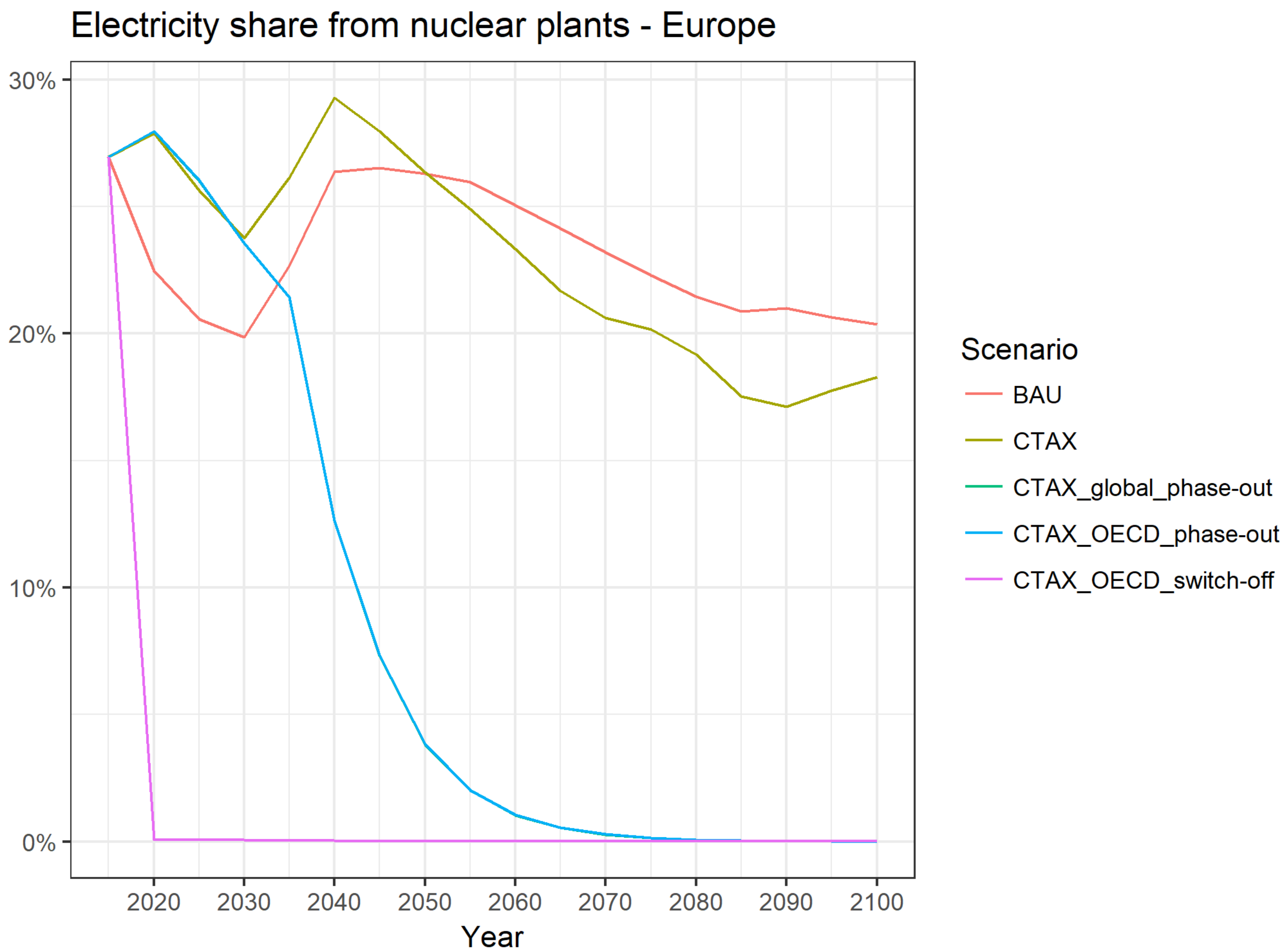

Global temperature increase
5
4
3
2
1
0
°C
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Scenario
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off


Electricity generation from nuclear plants - World
60
40
20
0
EJ/yr
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Scenario
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off

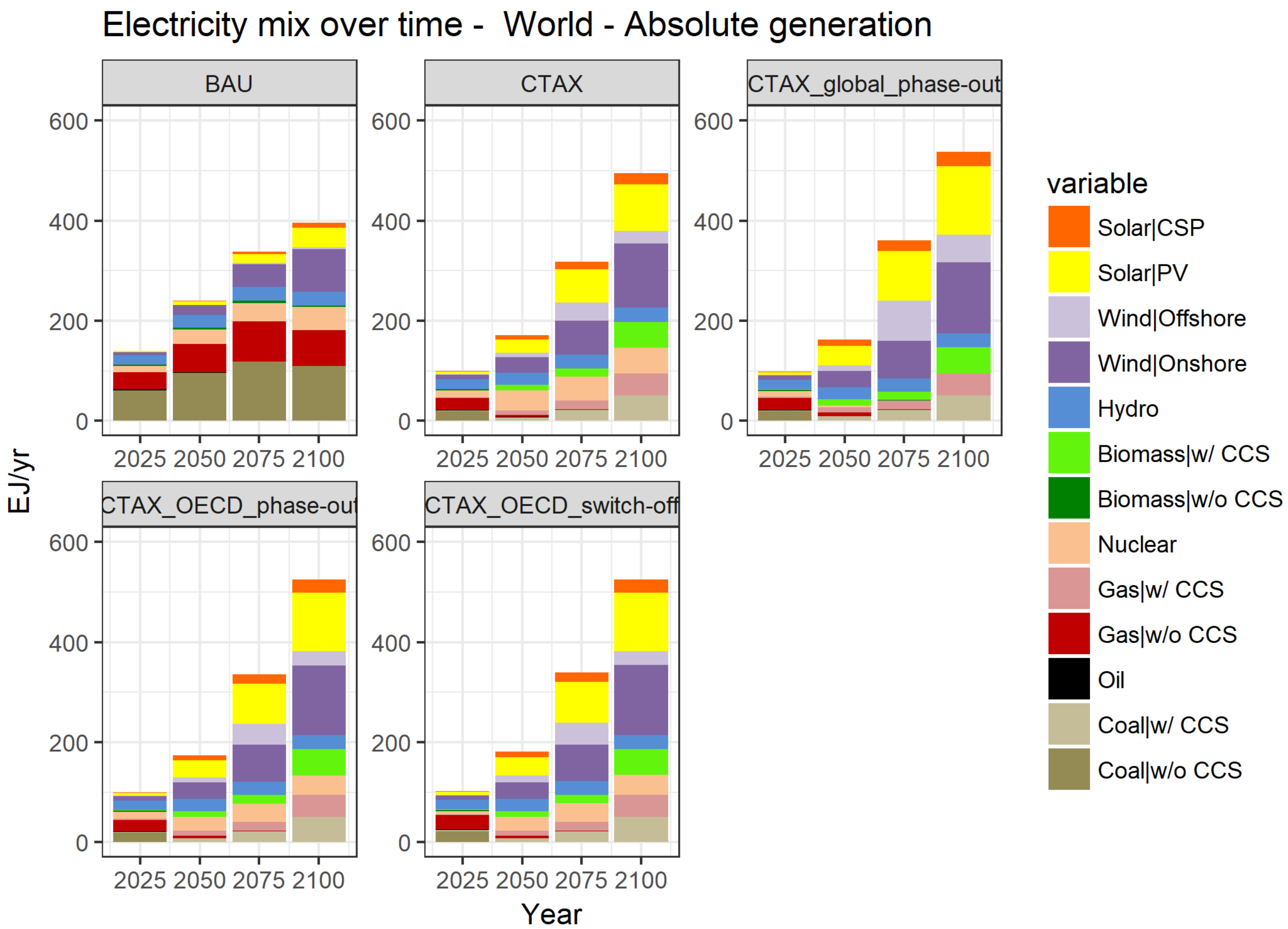

Electricity generation from nuclear plants - Europe
10.0
7.5
5.0
2.5
0.0
EJ/yr
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Scenario
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off

MERCURY

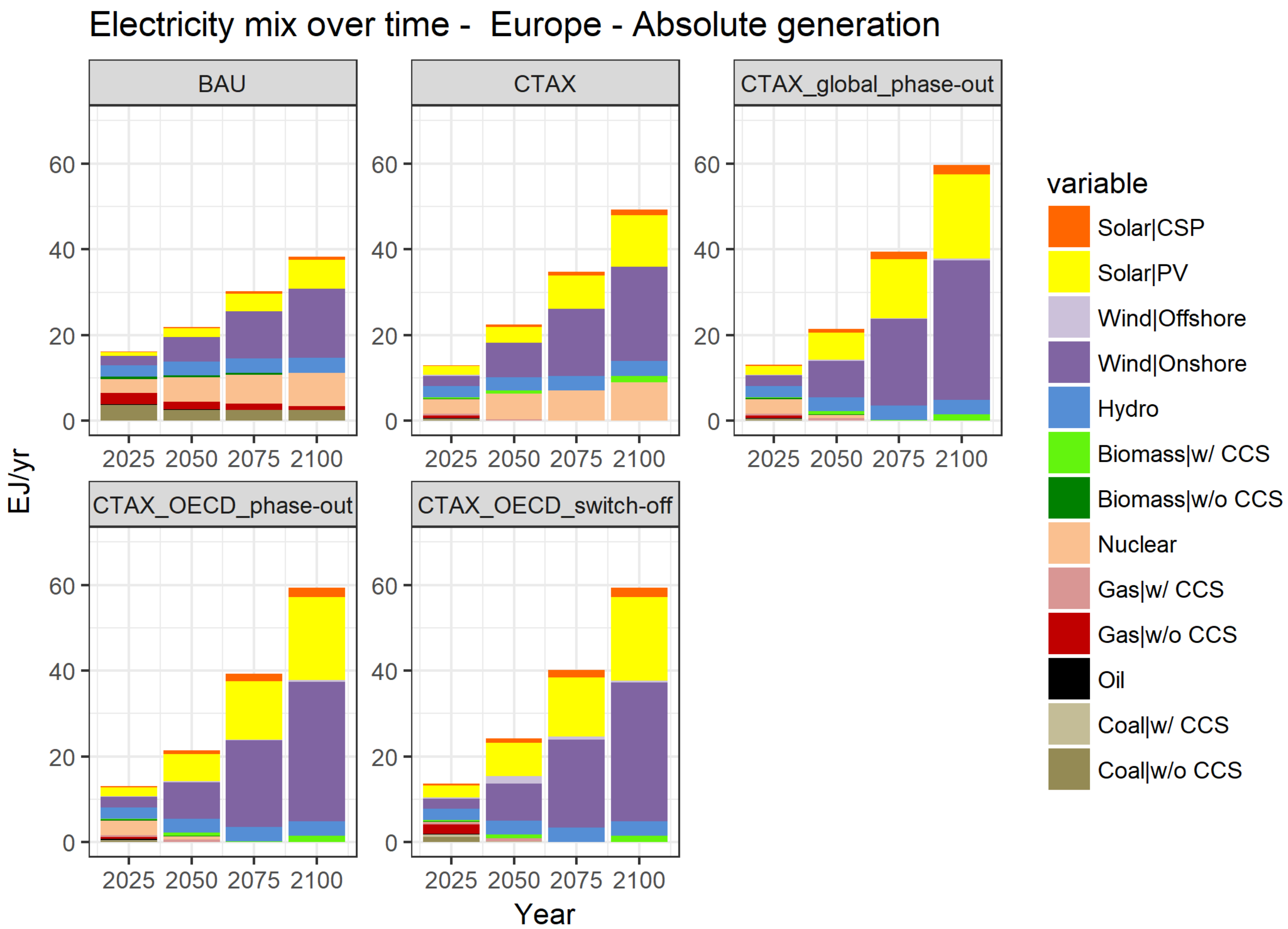

Electricity share from nuclear plants - World
30%
20%
10%
0%
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Scenario
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off

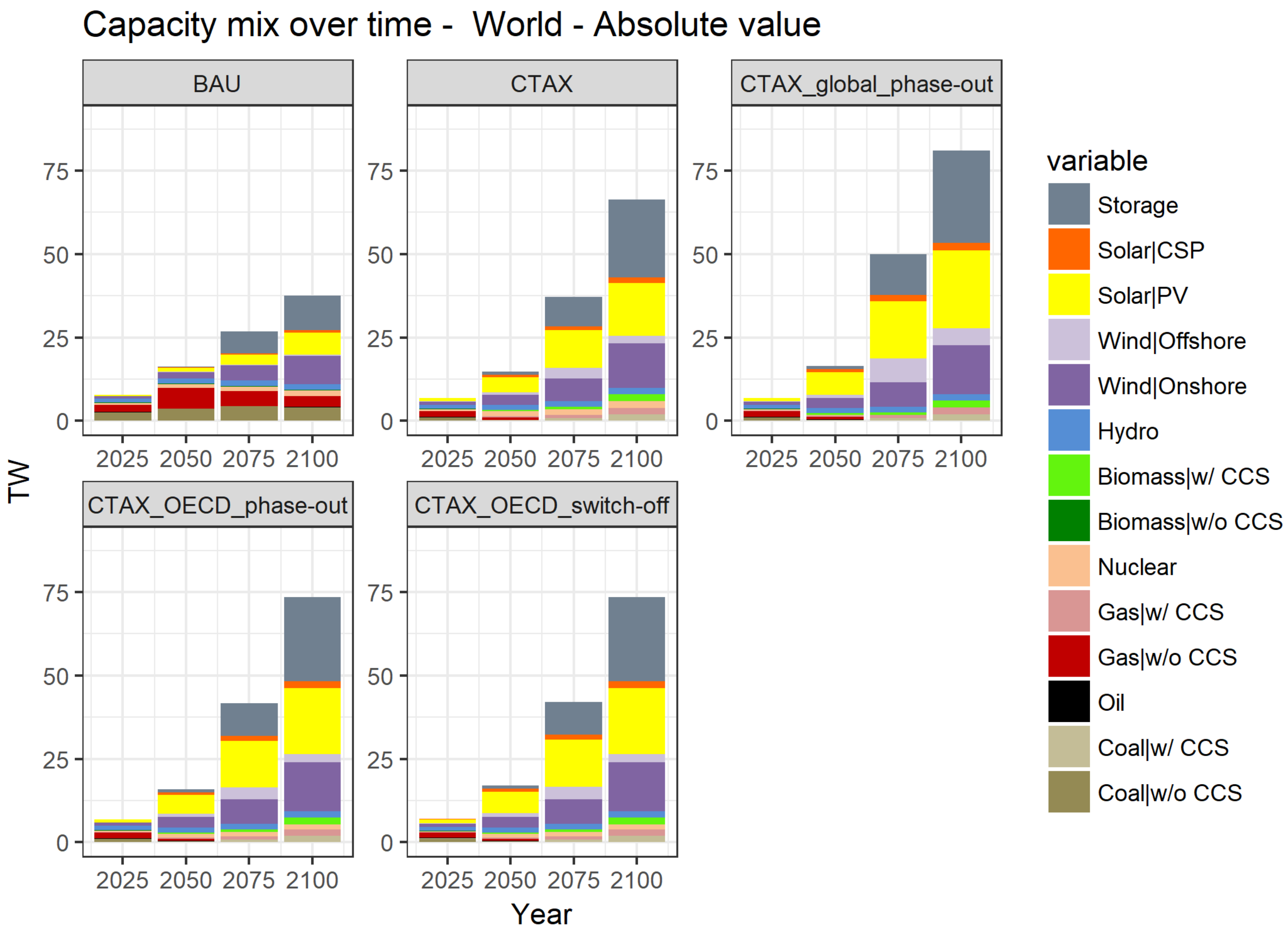


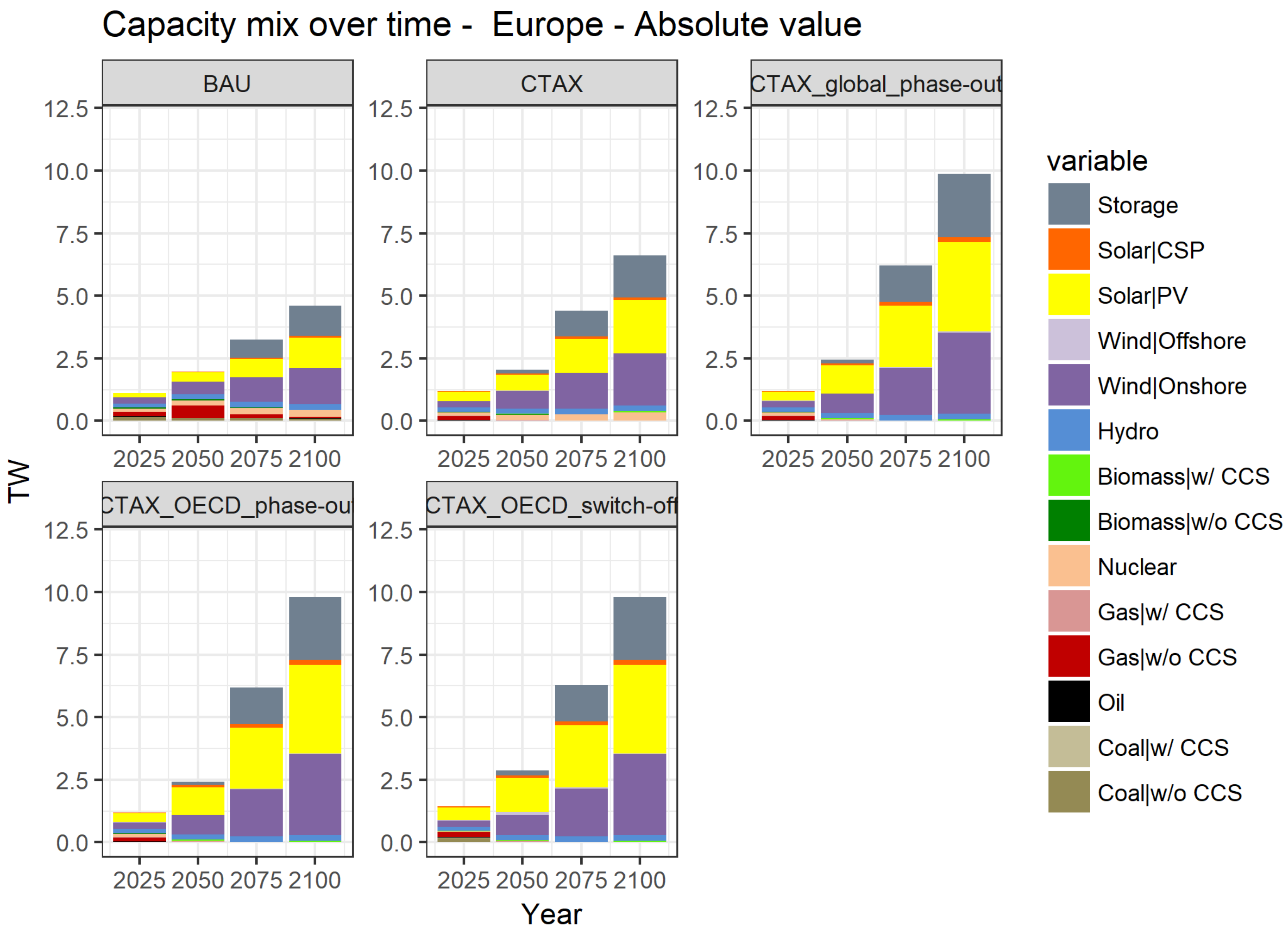
Electricity share from nuclear plants - Europe
30%
20%
10%
0%
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Scenario
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off

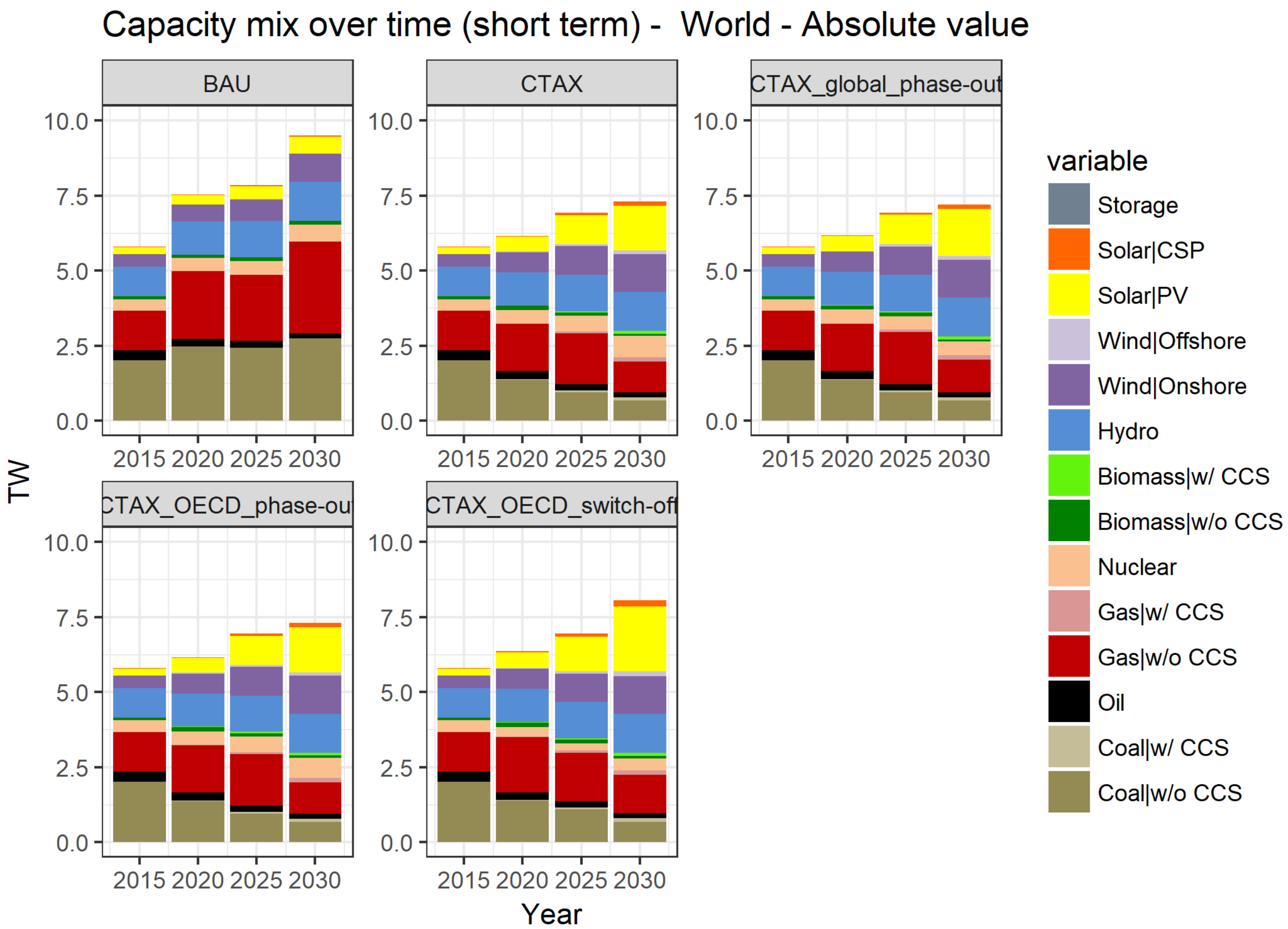


Electricity mix over time - World - Absolute generation
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
600
400
200
0
2025 2050 2075 2100
EJ/yr
Year
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS


Electricity mix over time - Europe - Absolute generation
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
EJ/yr
0
20
40
60
2025
2050
2075
2100
Year
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS


Capacity mix over time - World - Absolute value
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
TW
Year
0
25
50
75
2025
2050
2075
2100
variable
Storage
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS


Capacity mix over time - Europe - Absolute value
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
TW
Year
12.5
10.0
7.5
5.0
2.5
0.0
2025 2050 2075 2100
variable
Storage
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS


Capacity mix over time (short term) - World - Absolute value
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
TW
Year
10.0
7.5
5.0
2.5
0.0
2015 2020 2025 2030
variable
Storage
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

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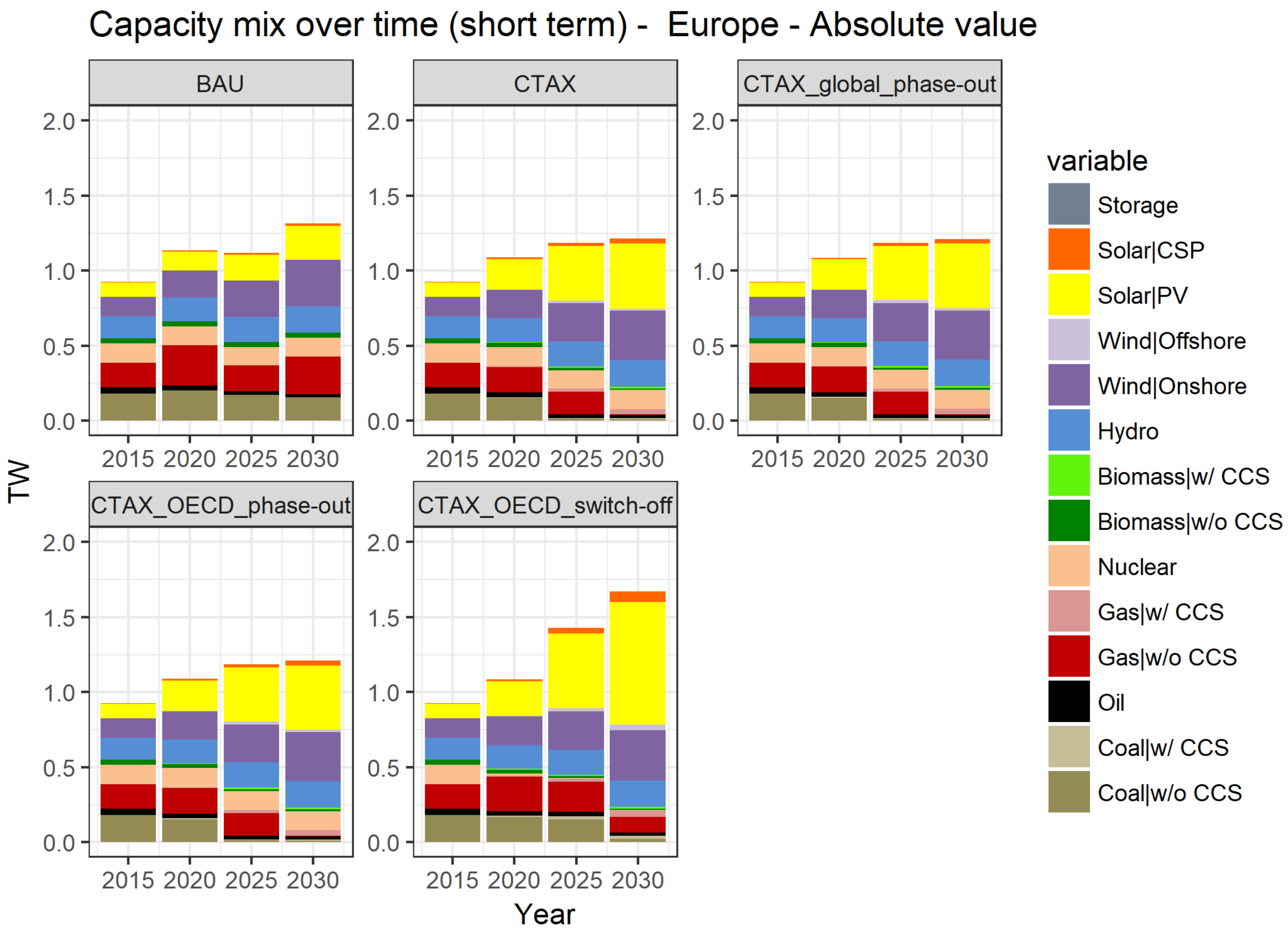
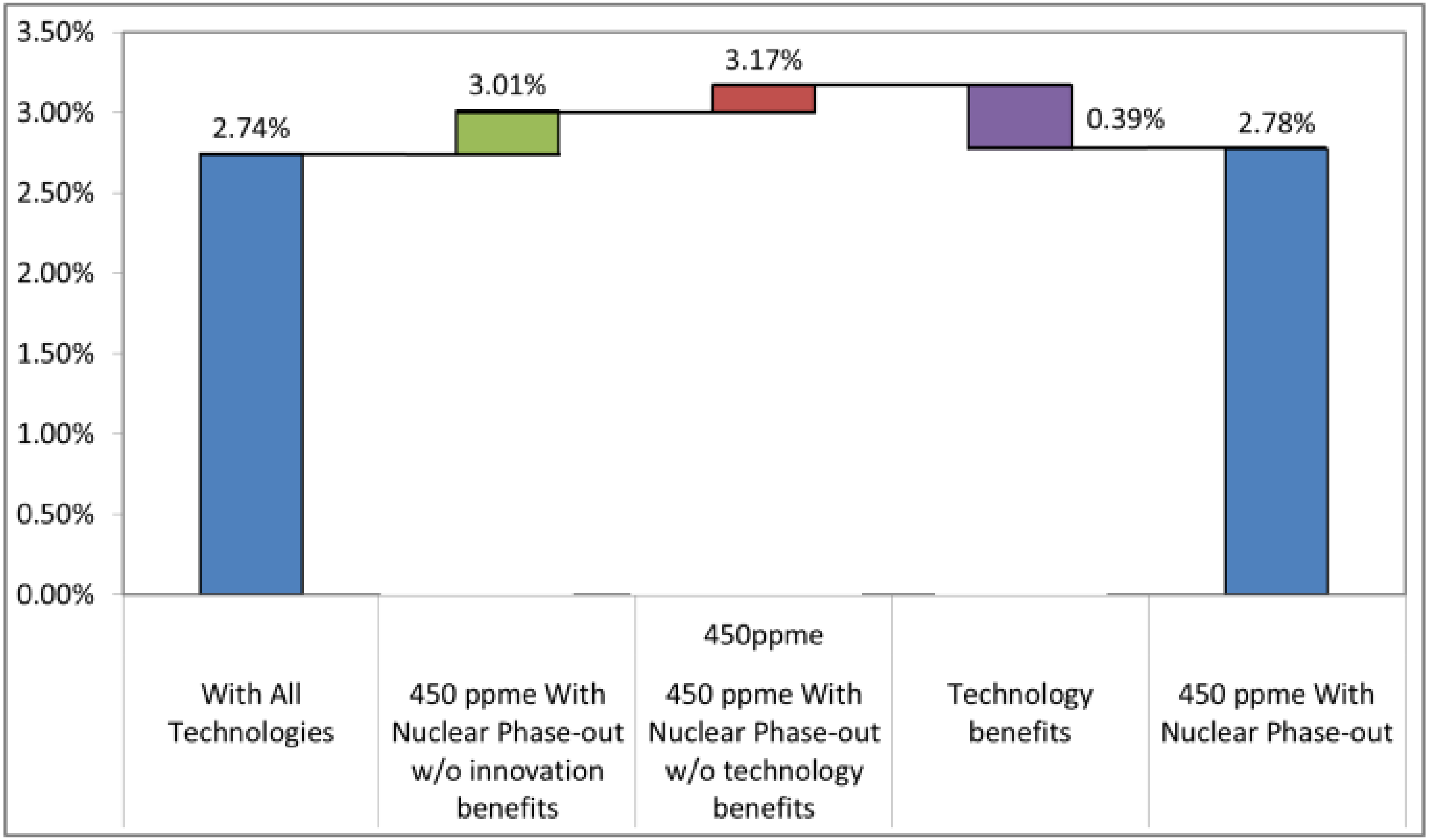
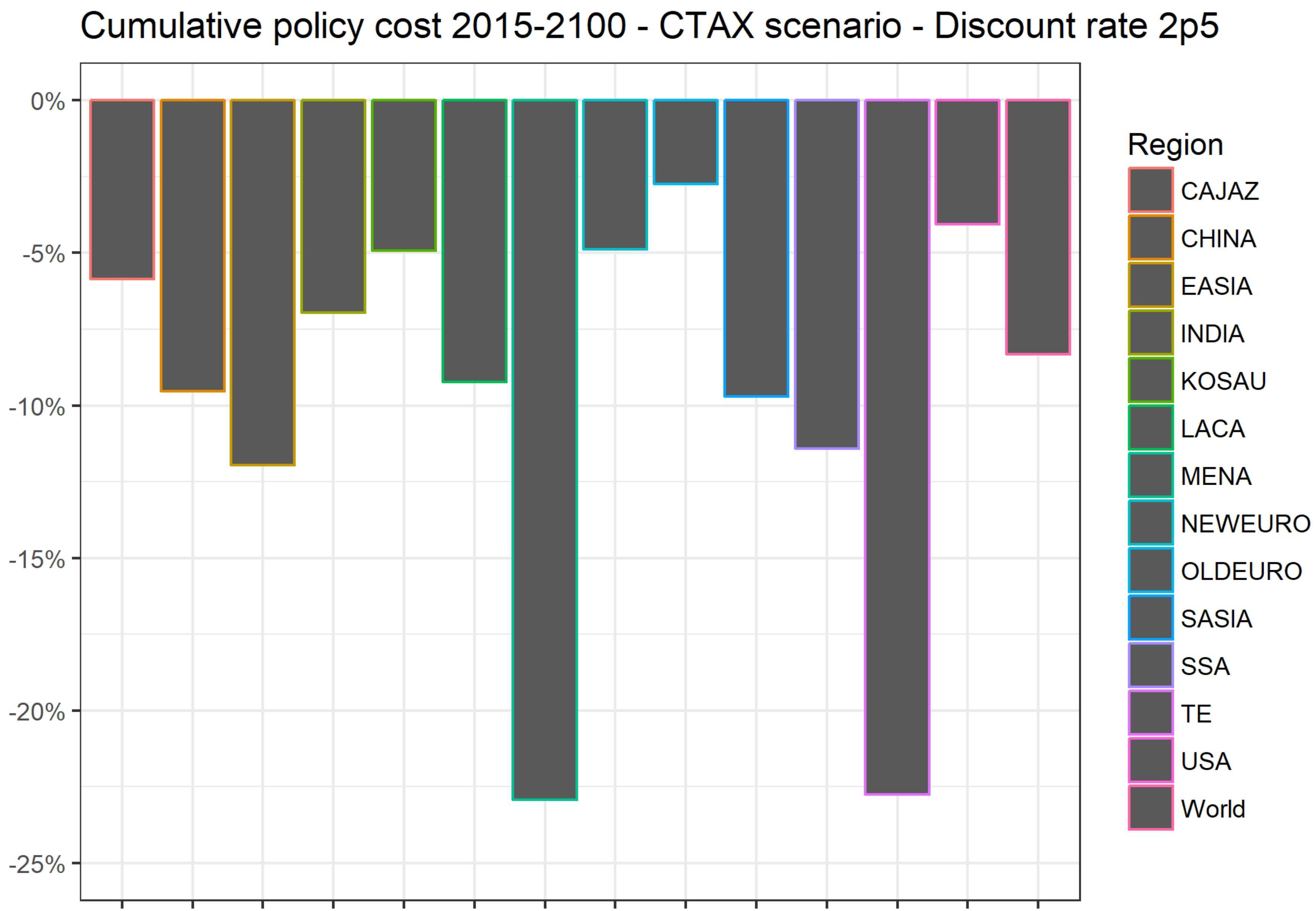
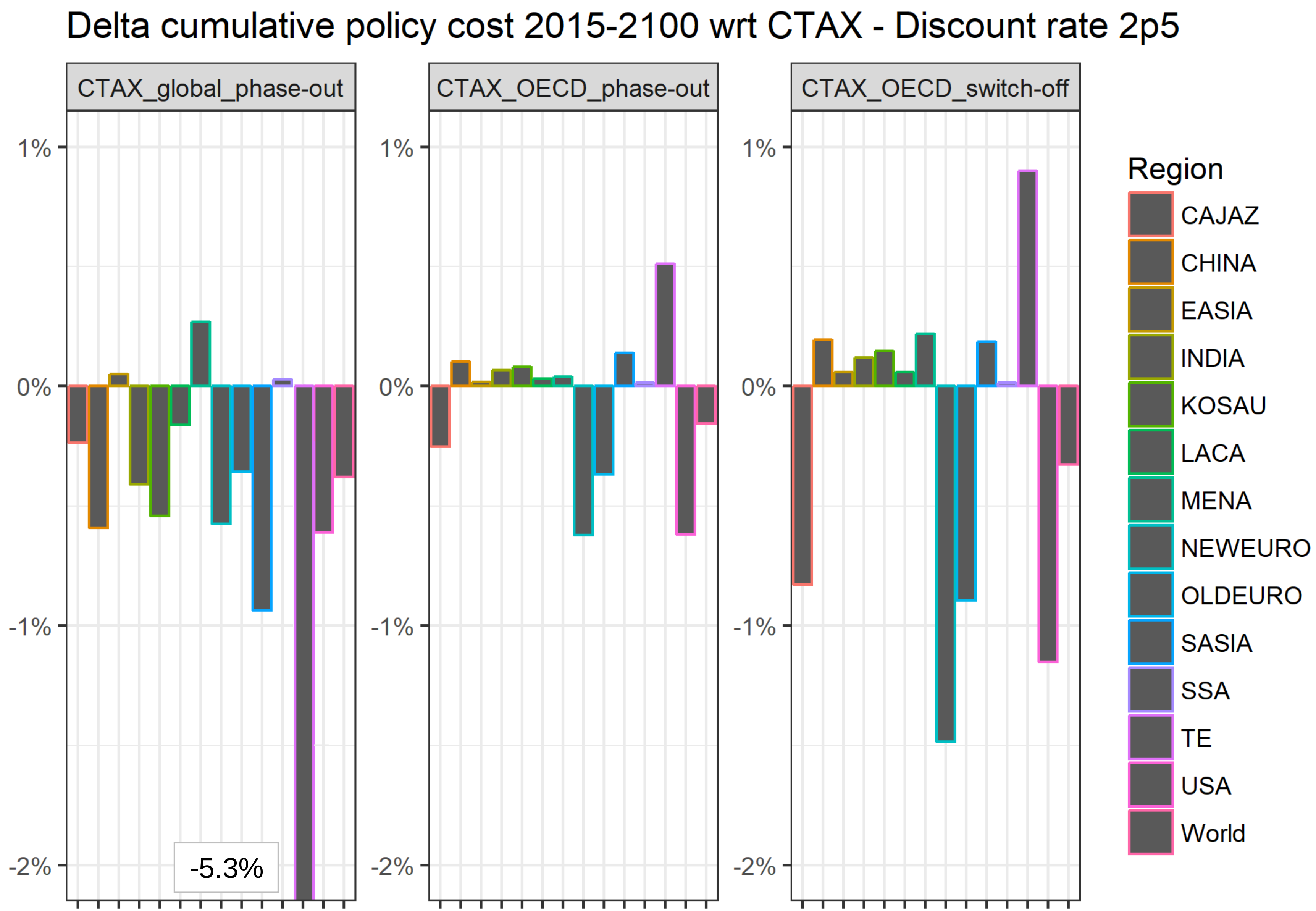

Capacity mix over time (short term) - Europe - Absolute value
BAU
CTAX
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
TW
Year
2.0
1.5
1.0
0.5
0.0
2015 2020 2025 2030
variable
Storage
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

Innovation benefits from nuclear phase-out



E. De Cian, S. Carrara, M. Tavoni (2014). Innovation benefits from nuclear phase-out: Can they compensate the costs?, Climatic Change, Vol. 123, N. 3-4, pp. 637-650


Cumulative policy cost 2015-2100 - CTAX scenario - Discount rate 2p5
0%
-5%
-10%
-15%
-20%
-25%
Region
CAJAZ
CHINA
EASIA
INDIA
KOSAU
LACA
MENA
NEWEURO
OLDEURO
SASIA
SSA
TE
USA
World


Delta cumulative policy cost 2015-2100 wrt CTAX - Discount rate 2p5
CTAX_global_phase-out
CTAX_OECD_phase-out
CTAX_OECD_switch-off
1%
0%
-1%
-2%
-5.3%
Region
CAJAZ
CHINA
EASIA
INDIA
KOSAU
LACA
MENA
NEWEURO
OLDEURO
SASIA
SSA
TE
USA
World

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Conclusions

- Nuclear power generation is expected to grow both in the baseline and in the policy scenarios (apart from the global phase-out scenario, naturally), even if to an extent which is in line with the overall demand growth, so that the nuclear share does not significantly change over time, both at a global and at a European level (apart from a temporary increase in the first part of the century at a global level in the CTAX scenario).
- Over time, and especially in the phase-out or switch-off scenarios, the nuclear contribution is compensated by renewables (wind and solar PV) and, to a lower extent, by CCS (only marginally in the EU).
- The huge increase in the generation from variable renewable energies entails the need for a massive deployment of storage capacity, especially in the EU (given the low deployment of dispatchable CCS plants) and especially in the second part of the century (when the generation other than from variable renewables is marginal).
- The policy costs related to the nuclear phase-out are not particularly high (0.4% additional global GDP loss wrt the unconstrained CTAX scenario), as they are almost compensated by the lower costs of renewables, deriving from higher investments in the non-nuclear low-carbon technologies, and by overall energy efficiency improvements (→ *comparison with CCS* ◀)
- Phase-out policies applied to the OECD regions only do not entail any additional policy costs, while the non-OECD regions marginally benefit from lower uranium prices. The OECD switch-off scenario results in a doubling of these losses and gains.

THANK YOU
FOR YOUR ATTENTION

www.mercury-energy.eu

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