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

Introduction to the project: Objectives and methods (first year)
Achievements of the first quarter

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WITCH modeling meeting – Milan, June 20, 2017

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 <u>technology perspective</u>, power generation is the largest responsible for CO_2 emissions, therefore great mitigation efforts will be required in this area.

From a <u>policy perspective</u>, 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 → *interaction/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)
- WP 2 – Technology prospects: EU policy scenario (FEEM – *partly anticipated to the first year*)
  - 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)
- 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)

WP1: Objectives

From the proposal:

"[SWITCH] will represent a solid reference which will allow firstly aligning WITCH to the state-of-the-art modeling of system integration, and secondly integrating an unprecedented and highly detailed description of the power system (storage, grid and trade) in an IAM, which represents the innovative aspect of the first part of the project."

More explicitly, after the literature review (system integration modeling in IAMs and SWITCH papers):

- Improvement of WITCH (based on SWITCH, but mostly on the IAM literature)
- Interactions and joint applications between WITCH and SWITCH

➡ Ideally: Soft-linkage of WITCH and SWITCH for the European Union

(but: probably infeasible due to time constraints → future research work?)

WP2: Objectives

From the proposal:

*"In the second half of the project, developed at FEEM and divided into two sub-parts, attention will be focused on the **mitigation pathways in Europe**, analysing in particular three low-carbon technologies which are predicted to play a major role in carbon mitigation: **renewables, CCS (Carbon Capture and Storage), and nuclear**. […]*

*In the first part (WP2), the actual **prospects of these three technologies** will be investigated, focusing not so much on technological aspects, but rather on **broadly intended policy issues**. […]*

*Concerning **renewables**, […] what are the impacts of differently calibrated incentives? Are they still necessary? Additionally, how will system integration influence their diffusion? Are there strong implications on the power infrastructure side?"*

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Today's presentation

- WP1: System integration in WITCH
- WP1: Interactions and joint applications between WITCH and SWITCH

  → Dynamics of decarbonization
- WP2: Learning in solar PV

  → Incorporation of an activity started within the ADVANCE project

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

WP1: System integration in WITCH

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WITCH: VRE integration – Summary

The limitation to VRE penetration into the electrical grid is modeled in WITCH through the following constraints:

- The **CES structure**
- A constraint on the **flexibility** of the power generation fleet
- A constraint on the installed **capacity** of the power generation fleet

Sullivan et al., 2013

Sullivan, P., Krey, V., and Riahi, K. (2013). Impacts of considering electric sector variability and reliability in the MESSAGE model, Energy Strategy Reviews, Vol. 1, pp. 157-163

WITCH: VRE integration – Weaknesses

- The flexibility and the capacity constraints are quite aggregated tools to model VRE system integration. In particular:

  - the coefficients are poorly parameterized and documented
  - they have been calibrated on the US power system (regional variability)
  - also the flexibility coefficients might change with VRE penetration

- WITCH does not feature power technologies which might lead to different electricity mixes (combustion turbines, etc.).
- No curtailment of VRE electricity generation is considered.
- The costs associated with operating plants flexibly (like efficiency, load factor, and O&M penalties) should also be taken into account.
- The flexibility parameters of CCS plants have been assumed equal to the corresponding non-CCS ones, while a higher inflexibility might be envisioned.
- Storage and grid are modeled quite rudimentarily.
- Electricity trade is not considered.

VRE integration in IAMs: The ADVANCE project

Discuss/evaluate the main VRE modeling approaches →

Qualitative approach:

- Identify key features of power sector dynamics
- Evaluate if and how an approach can cover this dynamic

Quantitative approach:

- Compare model results between scenarios for plausibility
- Compare model results with results from bottom-up model (REMIX)

Pietzcker, R.C., Ueckerdt, F., Carrara, S., de Boer, H.S., Després, J., Fujimori, S., Johnson, N., Kitous, A., Scholz, Y., Sullivan, P., Luderer, G. (2017). System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches, Energy Economics, Vol. 64, pp. 583-599

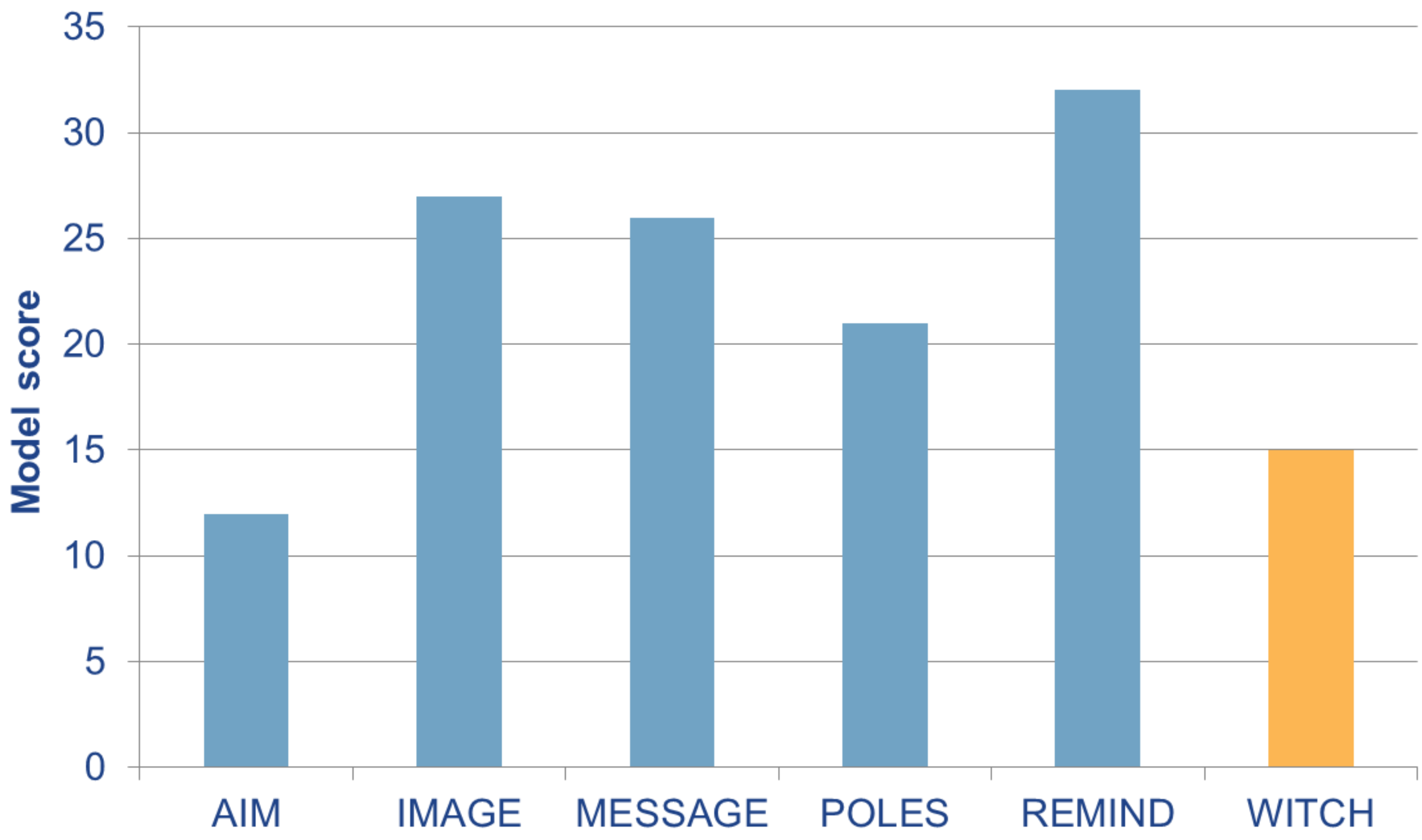
ADVANCE: Features of power sector dynamics

Investment dynamics	Investment into dispatchable technologies differentiated by load band
	Investment into VRE (incl. feedback on the system)
	Expansion dynamics
	Capital stock inertia and vintaging
	Structural shift of generation capacity mix
	Love of variety
Power system operation	Dispatch
	Flexibility and ramping
	Capacity adequacy
	Curtailment
Temporal matching of VRE and demand	Wind/solar complementarity
	Demand profile evolution
Storage	Short-term storage
	Seasonal storage
	Demand response (incl. electric vehicles & V2G)
Grid	General transmission and distribution grid
	Grid expansion linked to VRE
	Pooling effect from grid expansion

ADVANCE: Qualitative evaluation framework (examples)

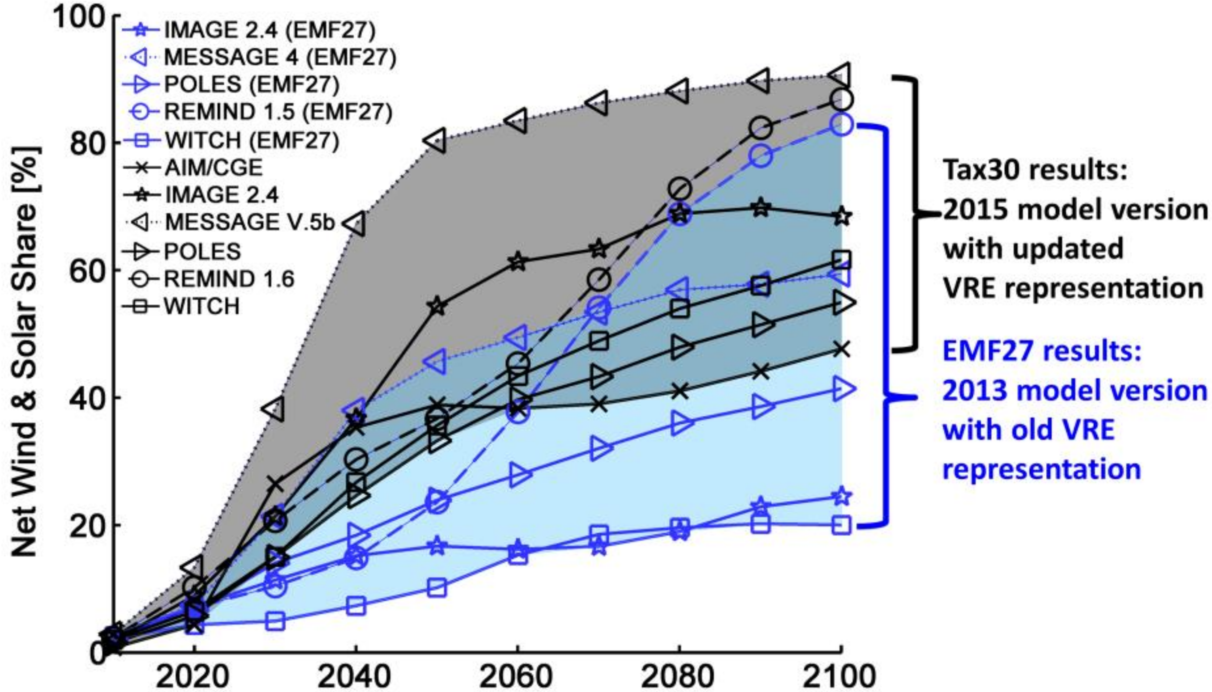
	Investment dynamics											
Model	Investment into dispatch. technol. differentiated by load band		Investment into VRE (incl. feedback on the system)		Expansion dynamics		Capital stock inertia & vintaging		Structural shift of generation capacity mix		Love of variety	
AIM/CGE	0	homogeneous good	+	Curtailment and storage increase LCOE	0	na	++	exponential vintaging (+); early retirement (+)	++	possible	++	logit
IMAGE	+++	region-specific RLDCs with 20 load bands	++	Curtailment and storage increase LCOE (+); backup cost markups partially emulate additional VRE interaction (+)	0	na	+++	non-exponential (+) vintaging (+) of capacities; early retirement (+)	++	possible	++	logit
MESSAGE	++	homogeneous good; share dependent flex&cap constraint partially reproduce RLDC shape (++)	++	Optimization provides feedback on effects of VRE on VRE-share-dependent (+) flex. & cap. equation (+)	++	constraints on expansion rate that can be weakened at additional cost	+++	non-exponential (+) vintaging (+) of capacities; early retirement (+)	++	possible	+	intertemporal optimization & expansion constraints ensure variety
POLES	+	RLDC load bands (+++); but combinatorial RLDC[1] (-) with region-mixed data[2] (-);	+	Curtailment increases investment LCOE	0	na	+++	non-exponential (+) vintaging (+) of capacities; early retirement (+)	+	possible, but limited by slow convergence of non-cost logit parameters [3]	++	logit
REMIND	+++	region-specific RLDCs with 4 load bands	+++	Optimization provides full feedback of VRE investment on RLDC	++	adjustment costs that increase non-linearly with fast expansion	+++	non-exponential (+) vintaging (+) of capacities; early retirement (+)	++	possible	+	intertemporal optimization & adjustment costs ensure variety
WITCH	+	homogeneous good; flex&cap constraints with fixed parameters creates demand for peak-load technologies (+)	+	Optimization accounts for feedback of VRE on flexibility constraint and capacity equation (+)	+	hard constraints on expansion rate	++	exponential vintaging (+); early retirement (+)	+	possible, but limited by CES[4] with elasticity 5	+	CES[4]

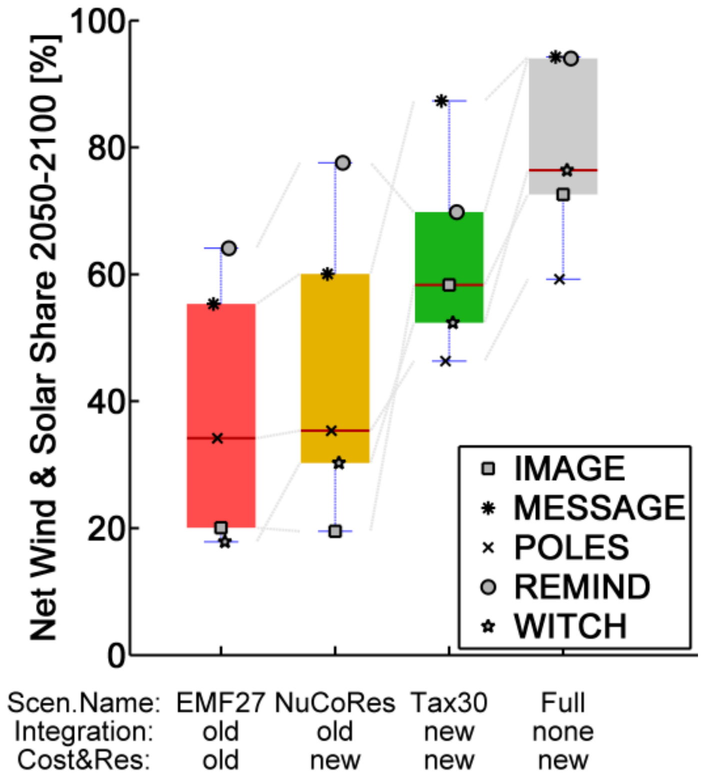
ADVANCE: IAMs qualitative score



Theoretical maximum: 54

ADVANCE: Model comparison





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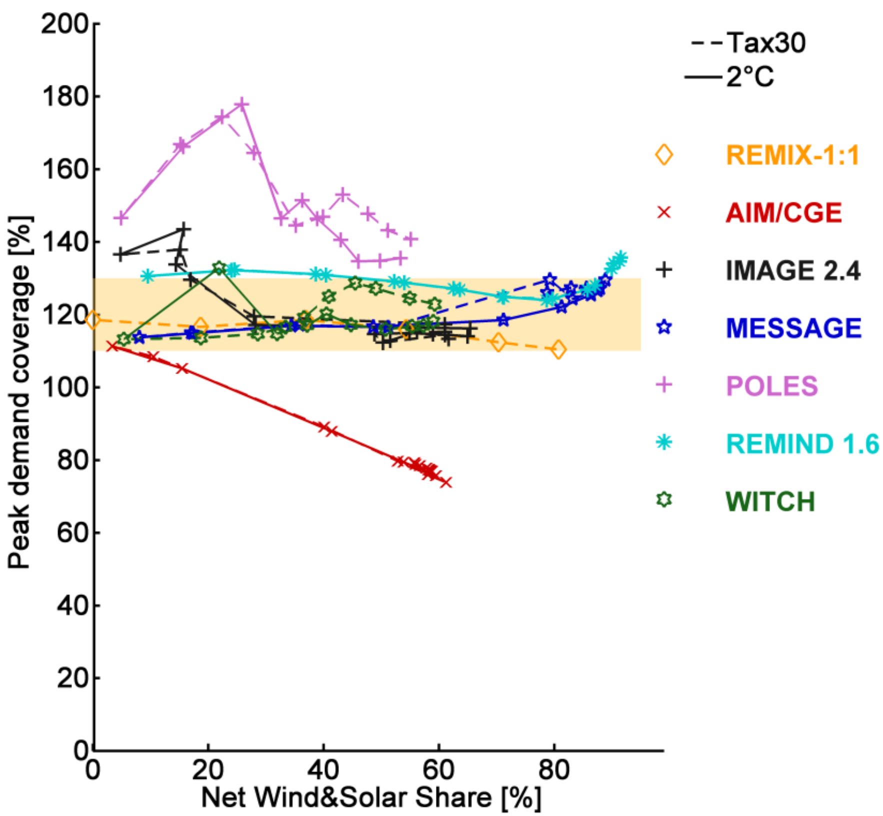
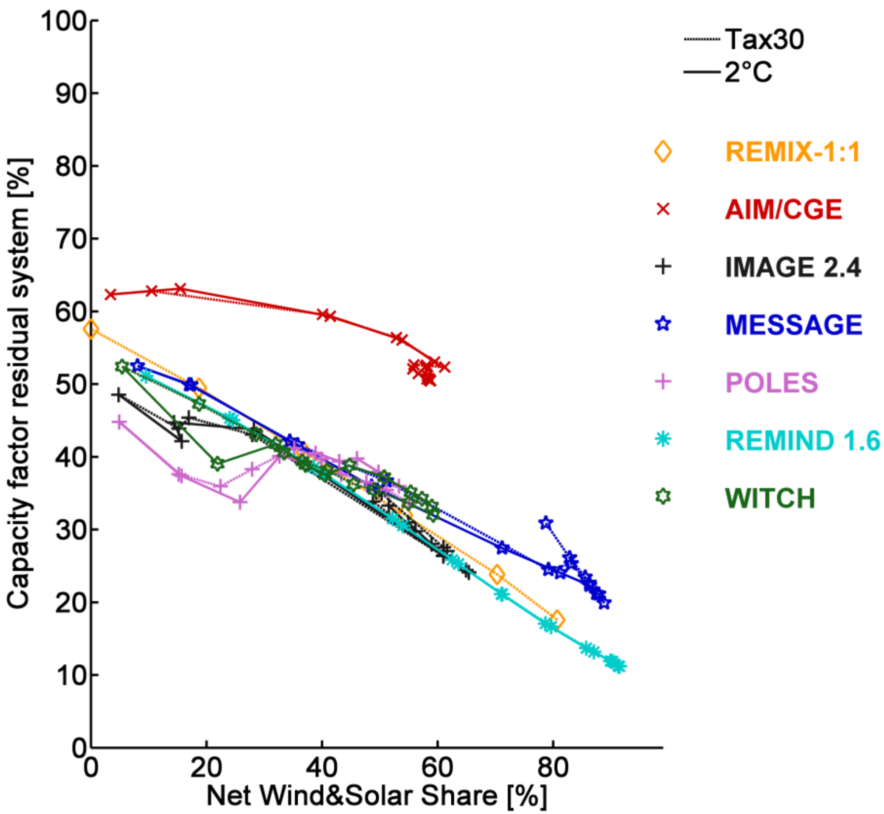
ADVANCE: Quantitative evaluation (examples)



Proxy for capacity adequacy: peak demand coverage



Capacity factor of the residual non-VRE system

WITCH: New VRE integration – Planned improvements

- Update the flexibility and capacity constraints → Region-specific Residual Load Duration Curves (RLDCs)
- Add curtailment
- Revise vintaging modeling
- Revise expansion constraint
- Improve storage modeling (interaction with curtailment, add technological detail, add seasonal storage, improve Vehicle-to-Grid modeling, etc.)
- Improve grid modeling (add technological detail, improve VRE/power infrastructure expansion relationship, etc.)
- Add electricity trade

➡ Estimated target qualitative score according to the ADVANCE framework: **28-30**

WITCH: New VRE integration – Reference

Johnson, N., Strubegger, M., McPherson, M., Parkinson, S.C., Krey, V., Sullivan, P. (2017). A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system, Energy Economics, Vol. 64, pp. 651-664

➡

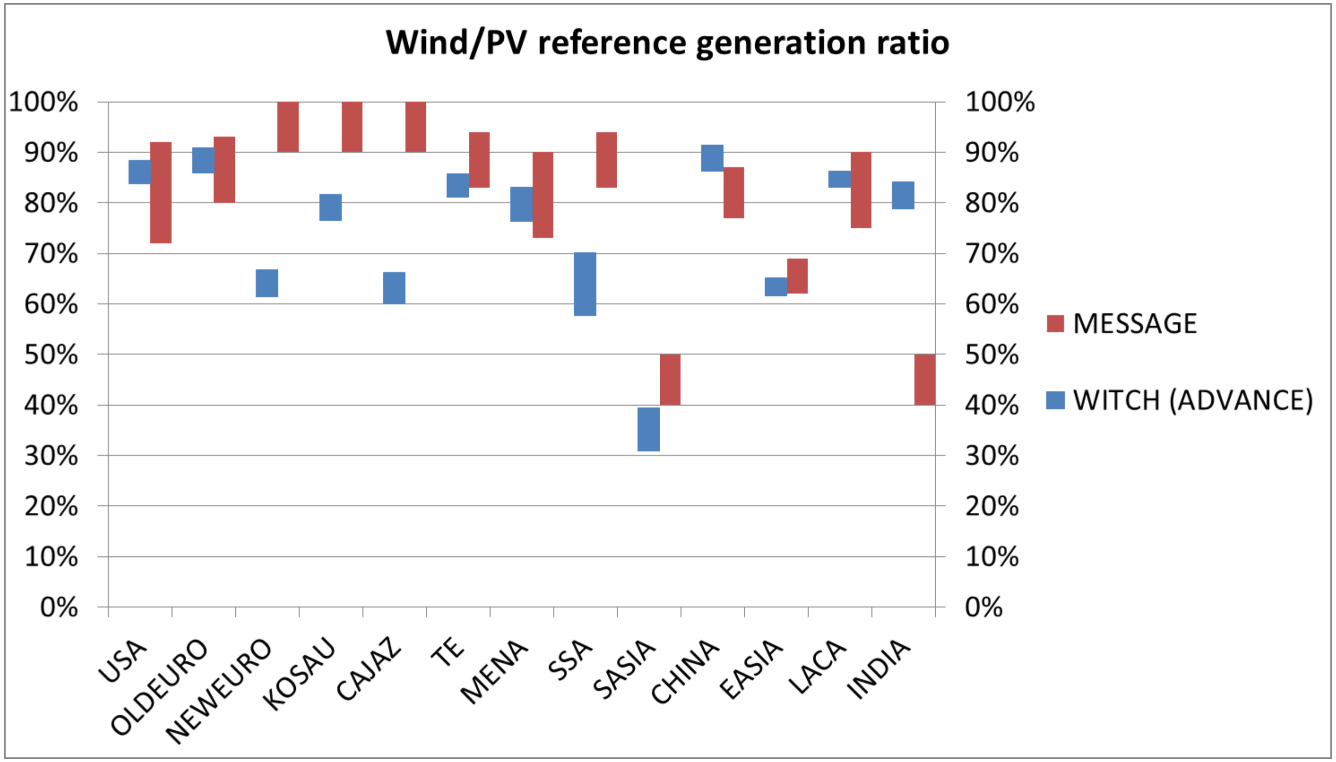
Indirect implementation of the RLDCs in the MESSAGE model, i.e. in a framework based on:

- Electricity treated as a homogeneous good
- Flexibility constraint
- Capacity constraint

MESSAGE – RLDCs

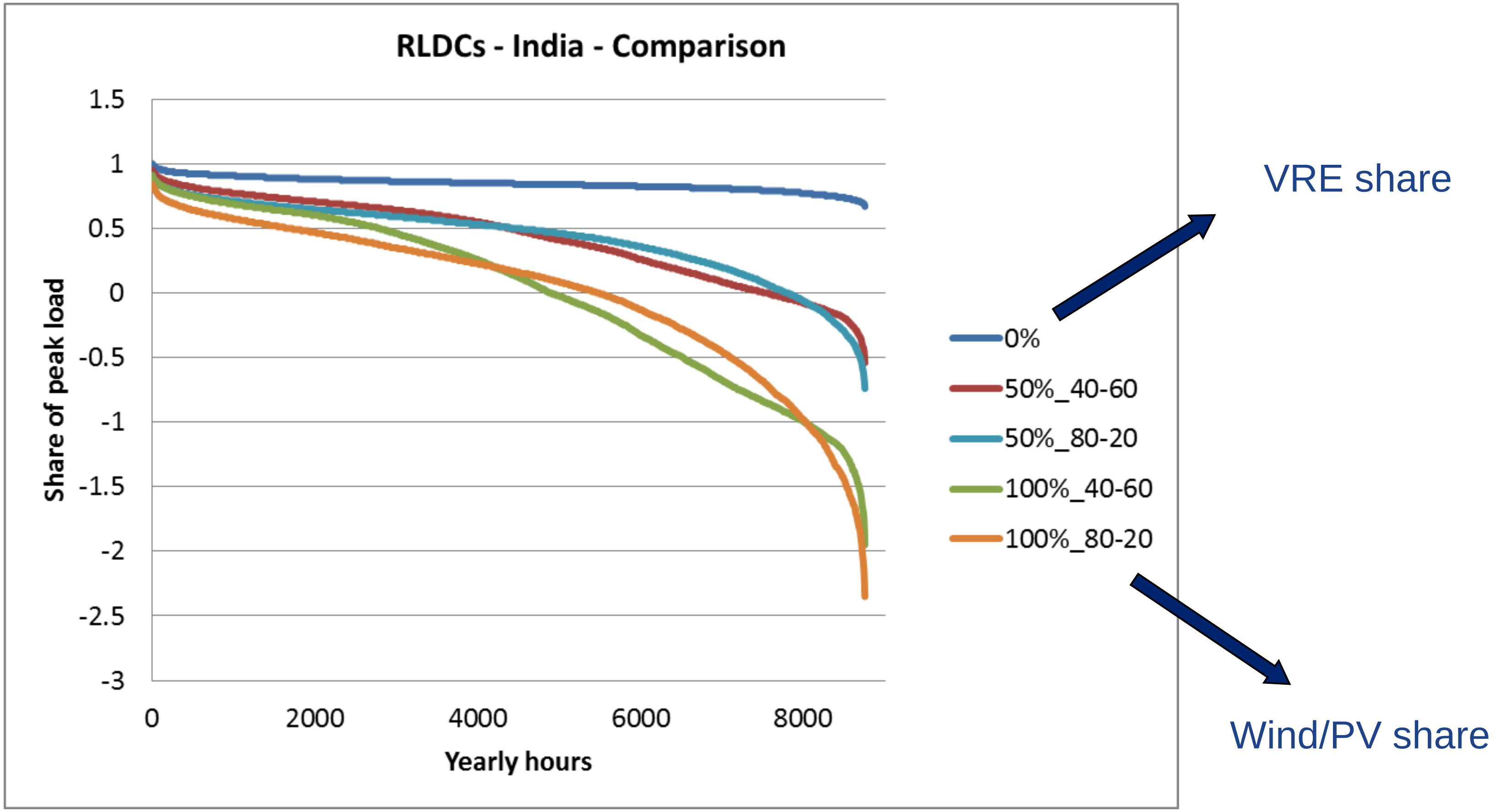
Limitation of the approach: the RLDCs are implemented considering a range of **fixed proportion between wind and PV generation** in the different regions.

→ But: 1) WITCH and MESSAGE show similar trends for most regions, with a clear predominance of wind (Note: the regional aggregation of the two models is comparable as well).



MESSAGE – RLDCs

2) In any case, RLDCs are not markedly different in the most “unlucky” cases either.



MESSAGE – Provided data

- Short-term and seasonal curtailment
- Firm capacity requirement
- Capacity values

Capacity constraint

- Load flexibility coefficients
- VRE flexibility coefficients
- Non-VRE flexibility coefficients and operation

Flexibility constraint (and more…)

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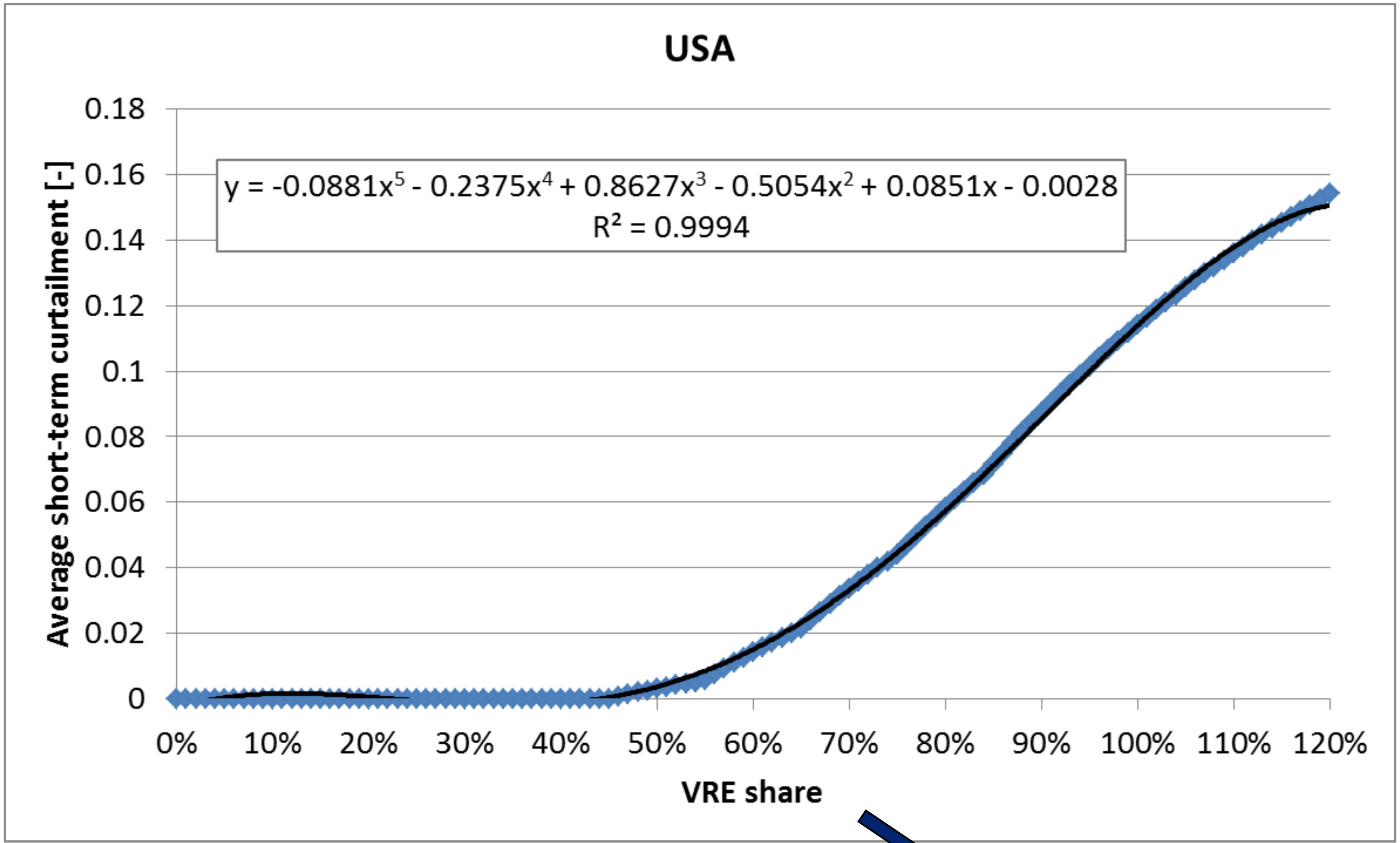
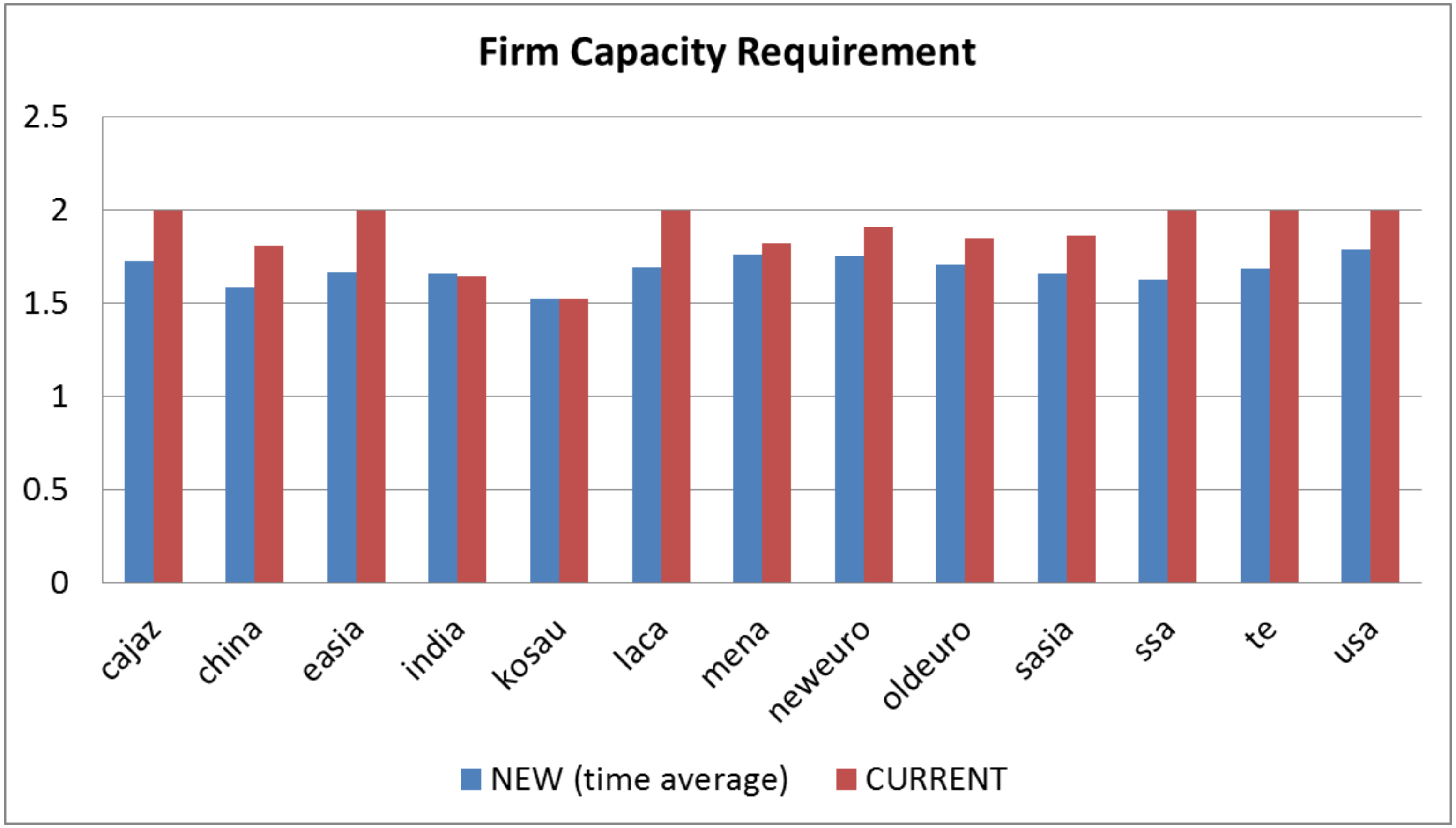
WITCH: New VRE integration – Curtailment



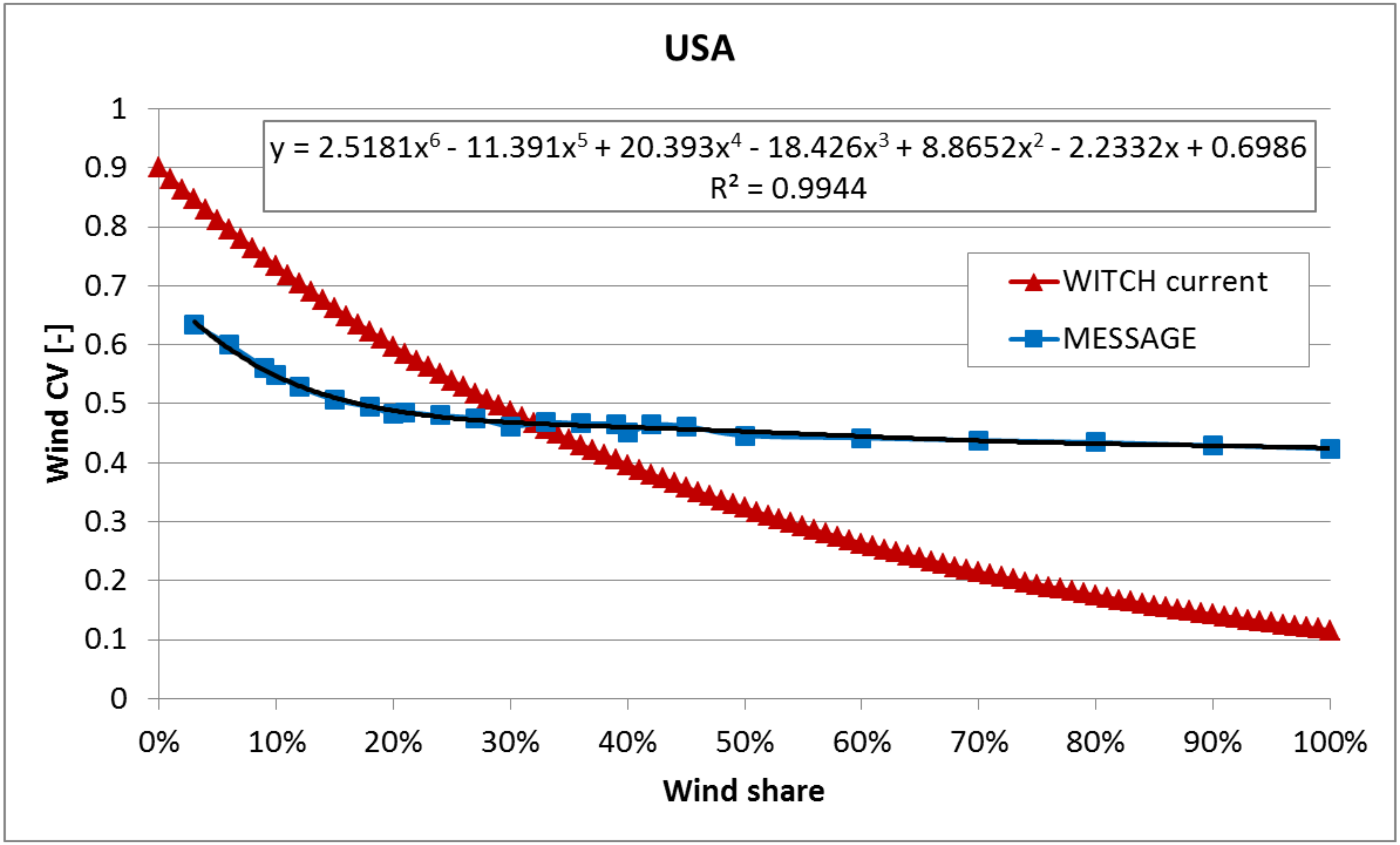
before curtailment

WITCH: New VRE integration – Firm capacity requirement

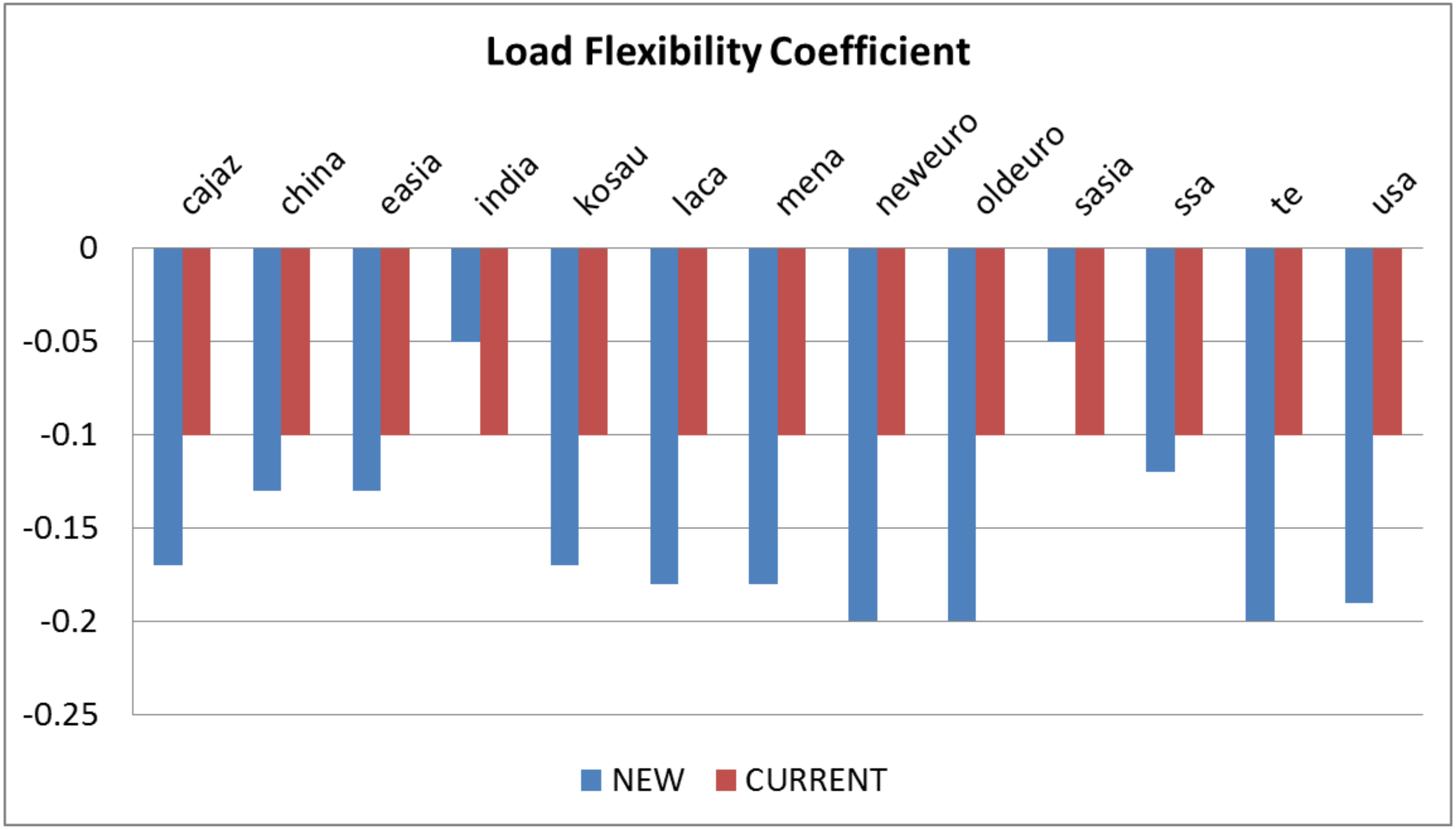
CURRENT: constant over time **NEW**: varying over time



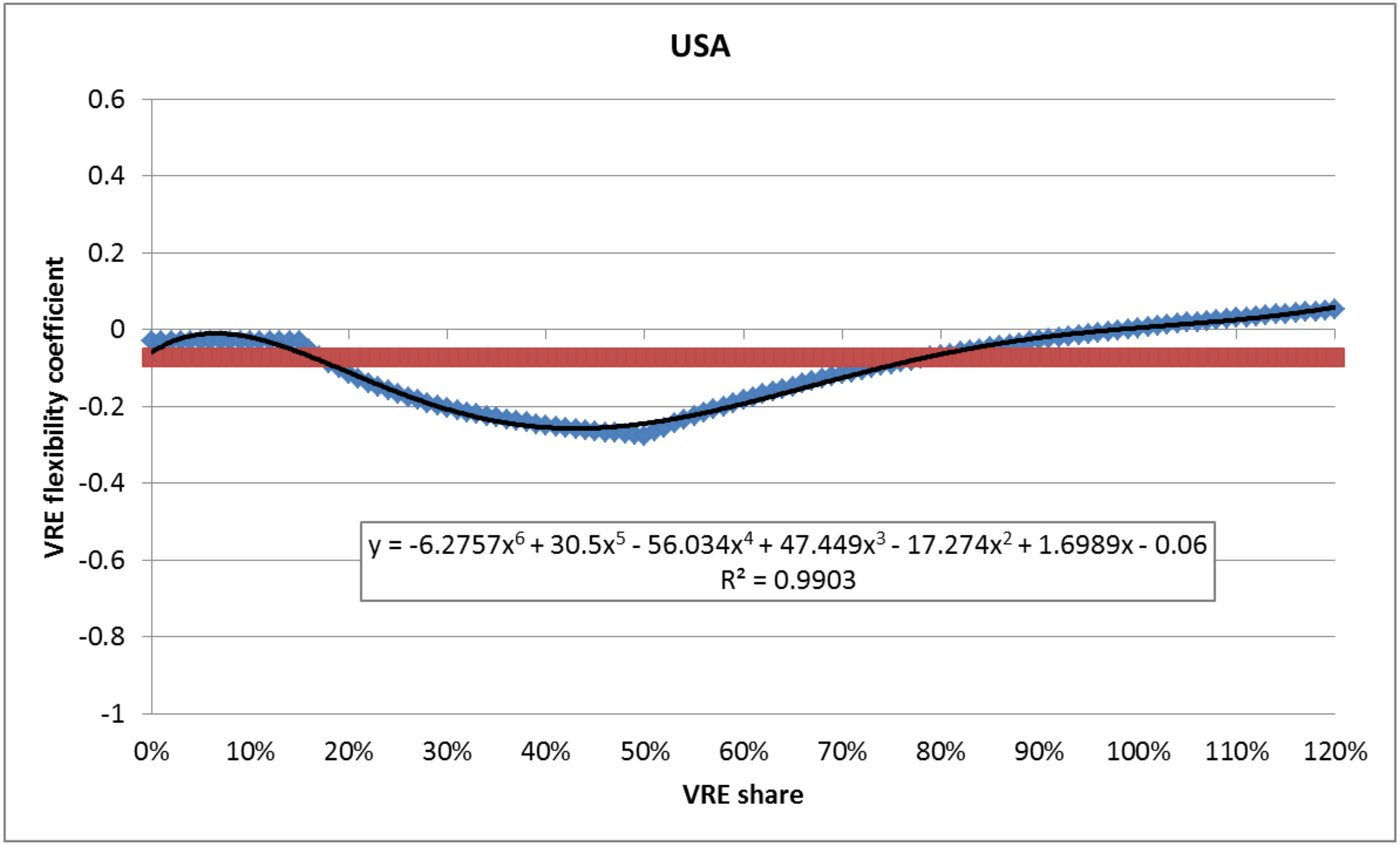
WITCH: New VRE integration – Capacity value



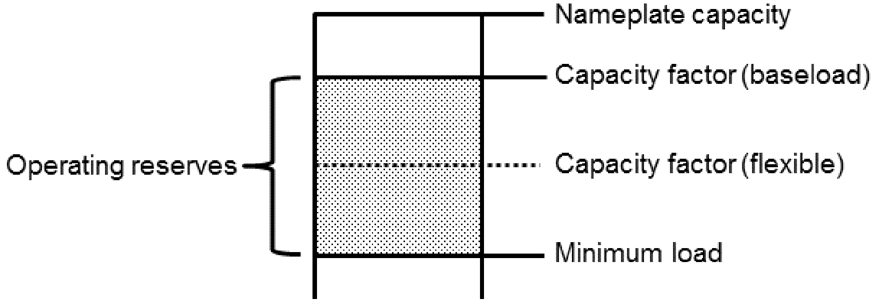
WITCH: New VRE integration – Load flexibility coefficient



WITCH: New VRE integration – VRE flexibility coefficients



MESSAGE – Non-VRE flexibility coefficients and operation



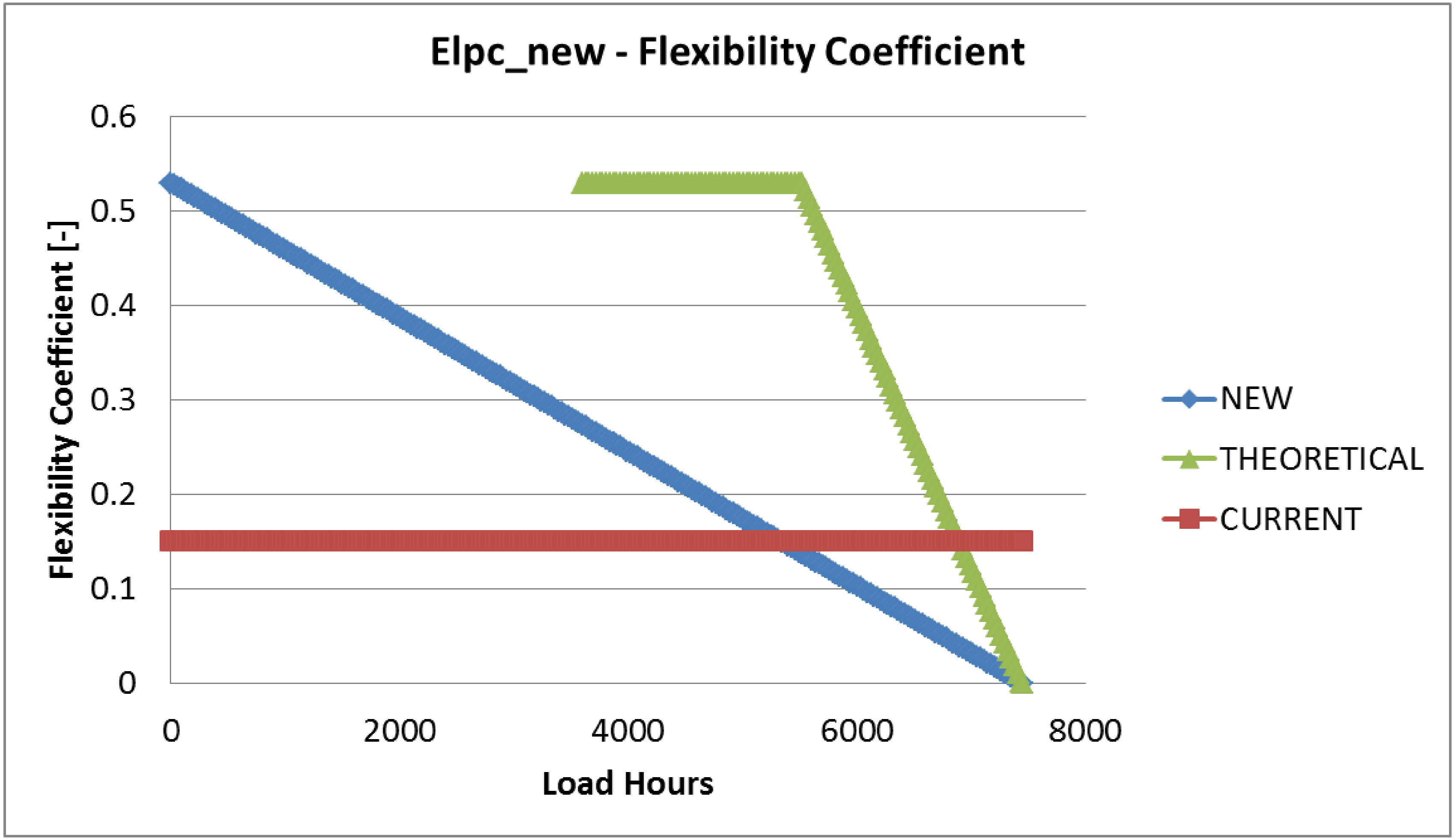
Two operation modes: baseload and flexible
→ VRE coefficient, capacity factor, O&M cost mark-up and efficiency penalty

Table 1
Operating reserve, capacity factor, O&M cost, and efficiency penalty assumptions for flexible operation of thermoelectric power plants.

Power plant type	Operating reserve coefficient (fraction of generation)	Capacity factor (fraction of installed capacity)	Cycling-related variable O&M cost ($/MWh)[a]	Efficiency penalty (% reduction)[b]
Coal/biomass combustion and gas combined-cycle	0.53	0.63	0.58–1.56	6%
Gas and oil combustion	0.86	0.49	9.24–9.36	8%
Gas/H_2 combustion turbine	1	0.43	12.47	N/A
CCS and nuclear	0.20	0.77	1.28–1.39	14%
Coal/biomass gasification	0	0.85	N/A	N/A
Hydropower	0.66	0.42	N/A	N/A
Geothermal	0.32	0.70	N/A	N/A
Flexible CSP	1	Resource-dependent	N/A	N/A
Baseload CSP	0.50	Resource-dependent	N/A	N/A
Utility-scale H_2 fuel cell	1	0.35	N/A	N/A
Electricity storage	1	0.25	N/A	N/A

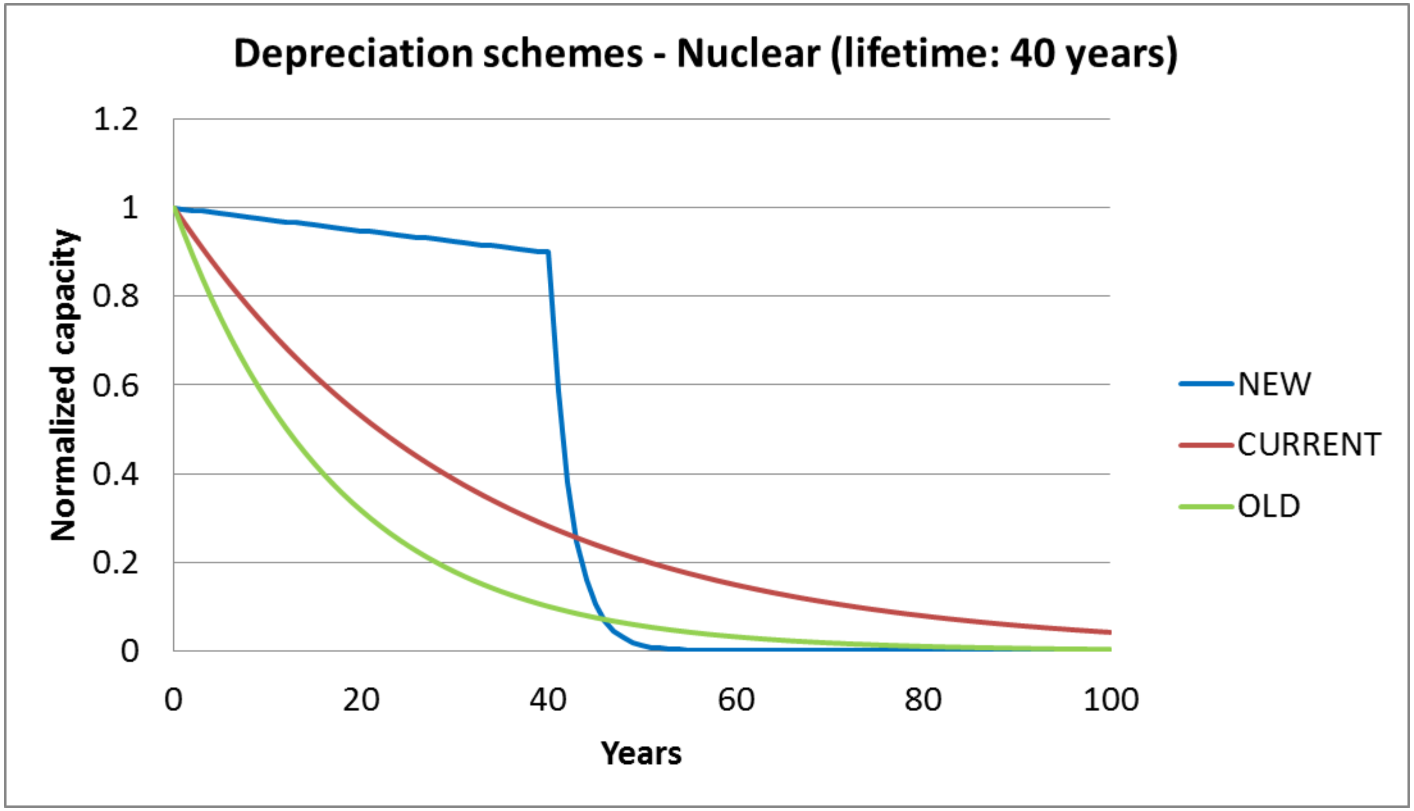
[a] Ranges are provided to represent variation among technologies in each category.
[b] For plant types that always provide flexibility, efficiency and O&M cost penalties associated with cycling are not added, but rather are implied in the standard efficiency and cost estimates.

WITCH: New VRE integration – Non-VRE flexibility coefficients and operation



WITCH – New depreciation (concept)

Distinction between depreciation **during** lifetime (leading to 90% of the initial capacity) and **after** lifetime (leading to about 10% of the initial capacity after 5 years and 1% after 10 years).



WITCH – New depreciation (concept)

Same formulation:

$$(1-\delta)^5 = \alpha \cdot \left(1-\delta_{life}\right)^5 + (1-\alpha)\cdot(1-\delta_{vint})^5$$

$$\delta = 1 - \sqrt[5]{\alpha \cdot \left(1-\delta_{life}\right)^5 + (1-\alpha)\cdot(1-\delta_{vint})^5}$$

α = share of capacity with an age lower than lifetime

(Implementation temporarily frozen due to computational issues and need for a deeper investigation of the modeling concept).

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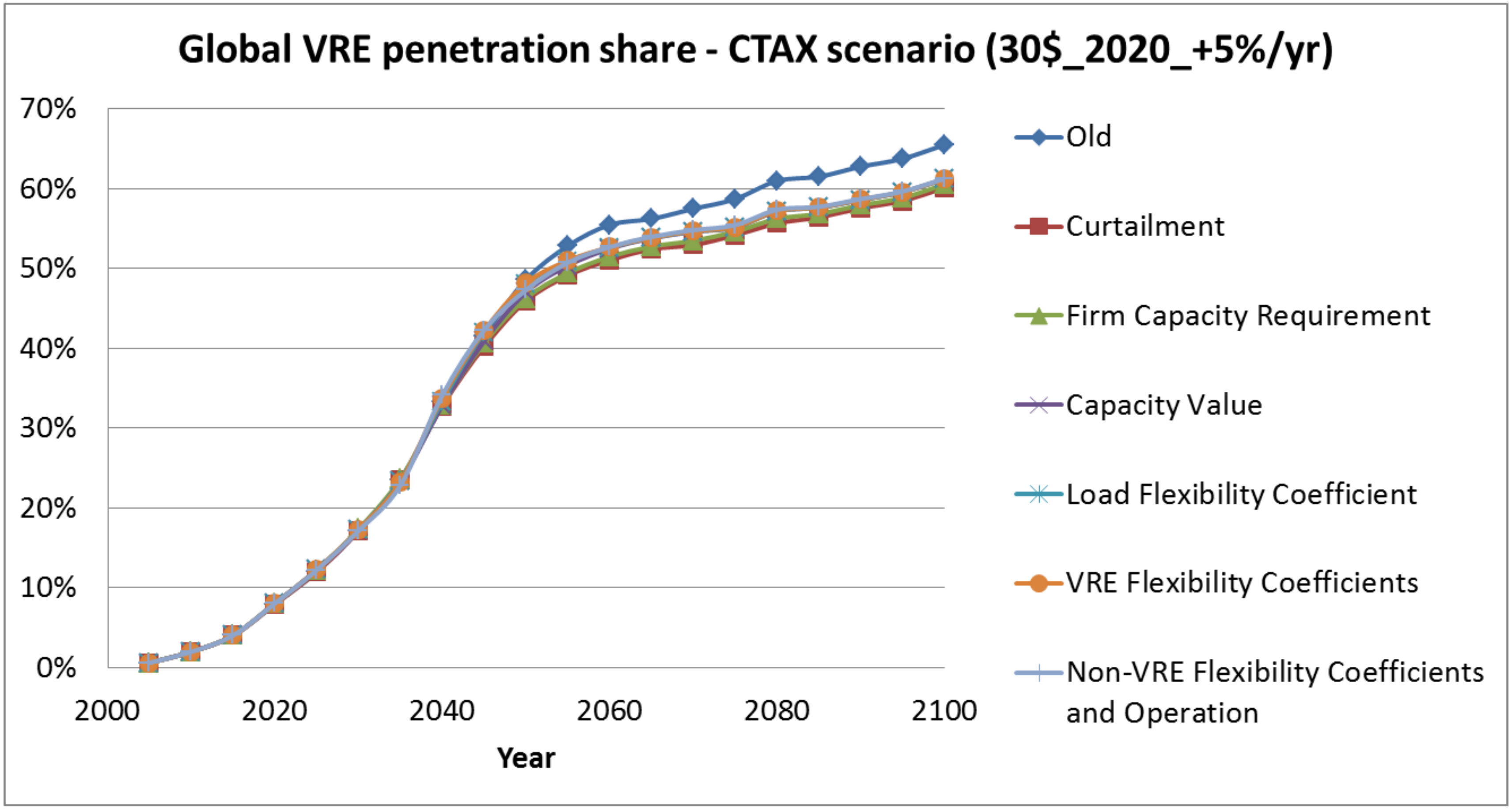
WITCH: New VRE integration – VRE penetration



"Cumulative" scenarios (i.e. each scenario contains all the previous changes as well).

WITCH: New VRE integration – Improvements status

- Update the flexibility and capacity constraints → Region-specific Residual Load Duration Curves (RLDCs) ✓
- Add curtailment ✓
- Revise vintaging modeling O
- Revise expansion constraint ✗
- Improve storage modeling (interaction with curtailment, add technological detail, add seasonal storage, improve Vehicle-to-Grid modeling, etc.) ✗
- Improve grid modeling (add technological detail, improve VRE/power infrastructure expansion relationship, etc.) ✗
- Add electricity trade ✗

✓ = done

O = done but frozen

✗ = to do

WITCH: New VRE integration – Next step: storage

- Implementation of a “real”, yet generic storage technology which absorbs and supplies electricity
- In particular, connection with curtailment, i.e. use of the short-term curtailed electricity to feed storage

  (Seasonal curtailment → hydrogen / methanization?)
- At a later stage, technology differentiation? (pumped hydro, flywheels, compressed air, etc.)
- Additional, potential activity: connection with road transport, i.e. Vehicle-to-Grid
- Complementary part: implementation of combustion turbines in the technology portfolio

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WP1: Interactions and joint applications between WITCH and SWITCH

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WITCH and SWITCH at a glance

Feature	WITCH	SWITCH
Model class	Inter-temporal general equilibrium model	Partial equilibrium electricity system model
Modeling scheme	Inter-temporal optimization with perfect foresight	Inter-temporal optimization with perfect foresight
Temporal resolution	• 5-year time steps (2005-2100) • Average yearly values	• Investments: 10-year time steps (2010-2050) • Dispatch: hourly basis
Spatial resolution	Global (13+ regions)	~ National (+ local load areas)
Electricity demand and fuel prices	Endogenous (model output)	Exogenous (model input)
Model output (among others)	Electricity mix, capacities…	Electricity mix, capacities…

Linkage of WITCH and SWITCH for the EU

WORKFLOW

1. Development of SWITCH-EU
2. Run of WITCH

→ Global optimization

Western EU (+ EFTA) and Eastern EU or Europe as a whole
Input: Electricity demand, fuel prices, etc.
Constraint: regional electricity mix

3. Run of SWITCH with a national detail (32 countries)

→ National detail of load, grid, etc.

Joint applications of WITCH and SWITCH

1) Dynamics of decarbonization (ongoing activity)

Inspired by a work-in-progress paper by Carvallo et al. “A framework to design decarbonization pathways reveals the benefits of early action on emissions reduction” → Study of the effects that different carbon price trajectories can have in defining technological deployment routes for the power sector

2) *To be defined* (Fall 2017)

Likely topic at the moment:
Transport → Decarbonization/electrification pathways, Vehicle-to-Grid modeling, etc.

Dynamics of decarbonization – SWITCH results

- A non-smooth behavior resulting from a set of “tipping points” in decarbonization pathways is found.
- This behavior suggests that a carbon tax calibrated on the specific conditions of the national/regional electricity system should be implemented.
- Carbon prices define specific innovation and environmental pathways for power systems that may be mutually exclusive, which suggests the possibility of locking into sub-optimal low-carbon growth regimes.
- The analysis is also applied to the transmission grid, which further stresses that an earlier and more aggressive carbon price may be a preferred strategy compared to a gradual increase to trigger cost effective decarbonization regimes.

Note: the relevant graphs cannot be shown at the moment due to confidentiality reasons (ongoing submission)

Dynamics of decarbonization – WITCH application

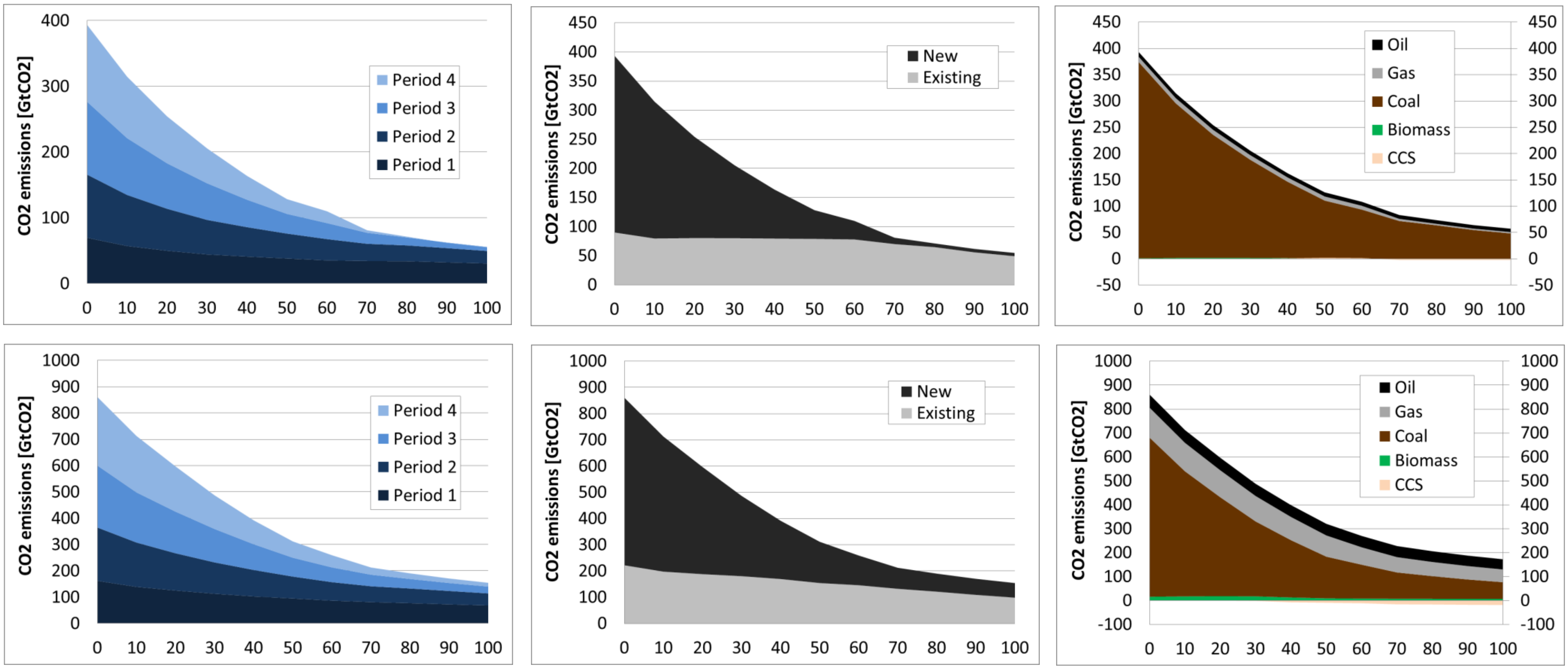
- Same exercise carried out in WITCH

  → Investigation of the dynamics of decarbonization comparing how this is captured by a detailed model of the electric sector (SWITCH) and a more general Integrated Assessment Model (WITCH) → more "technical" paper

- Case studies: China and the World

Dynamics of decarbonization – WITCH results (prelim.)

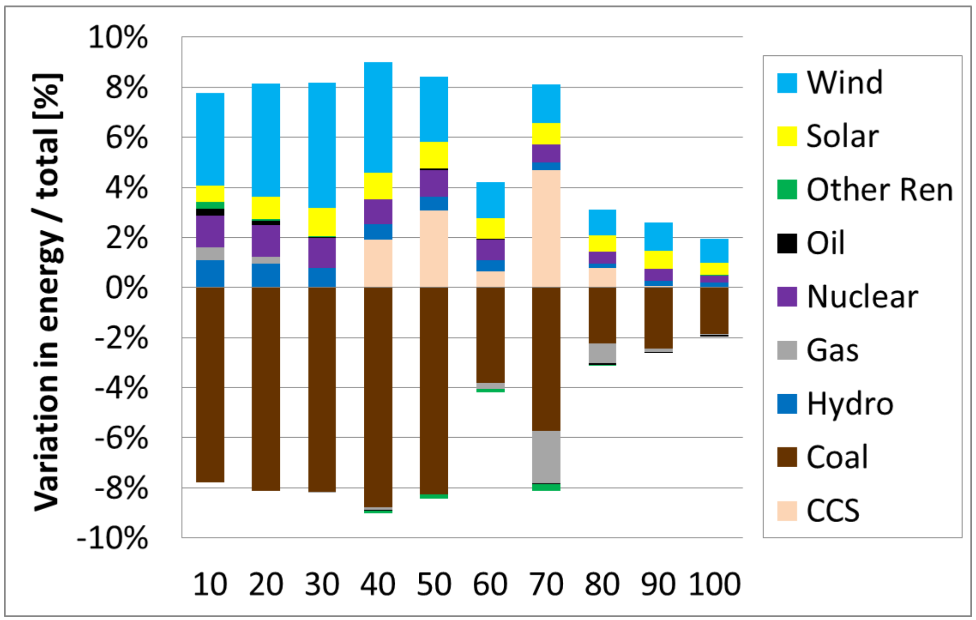
China



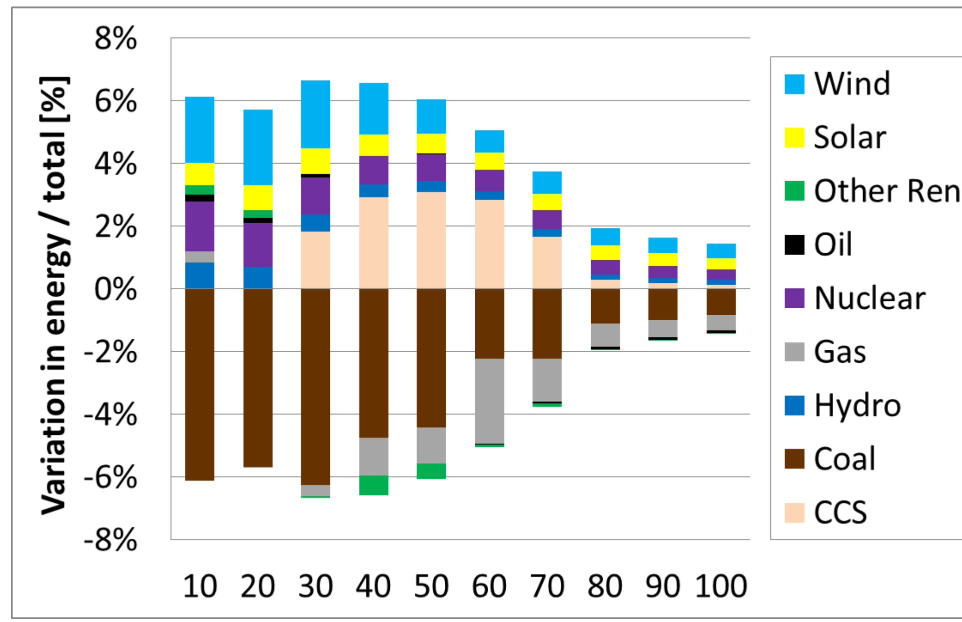
World

x-axis: ctax ($/tCO$_2$)

Dynamics of decarbonization – WITCH results (prelim.)



China



World

x-axis: ctax ($\$/tCO_2$)

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WP2: Learning in solar PV

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.

Objective and Scope

Multi-model exercise

→ Exploring pathways of solar PV learning in Integrated Assessment Models

Study of the evolution of the investment cost associated to different learning rates, analyzing how this influences the penetration of solar PV in the electricity mix, and ultimately the overall electricity mix itself.

Participating models

- IMAGE
- POLES
- REMIND
- WITCH

In this presentation

Preliminary analysis of the first submission results (summary)

Protocol

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

Mitigation → ctax | cumulative 1000 $GtCO_2$ in 2011-2100 in the Ref-Ref scenario

Reference

Witajewski-Baltvilks, J., Verdolini, E., and Tavoni, M. (2015). Bending the learning curve, Energy Economics, Vol. 52, pp. S86-S99

LR = Learning Rate = cost decrease deriving from doubling the installed capacity = $-1 + 2^b$

Empirical estimate → $b = \mu \pm \sigma = -0.254 \pm 0.058$

→ Learning Rate

1) μ = 19.25%
2) $\mu + \sigma$ = 24.14% (+25.4% wrt μ)
3) $\mu + 2\sigma$ = 29.24% (+51.9% wrt μ)
4) $\mu - \sigma$ = 14.55% (-24.4% wrt μ)
5) $\mu - 2\sigma$ = 10.04% (-47.8% wrt μ)

Thus the ±25% and ±50% sensitivity cases

Floor Cost

Investment cost (Learning-by-Doing):

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

Floor cost: hard bound

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

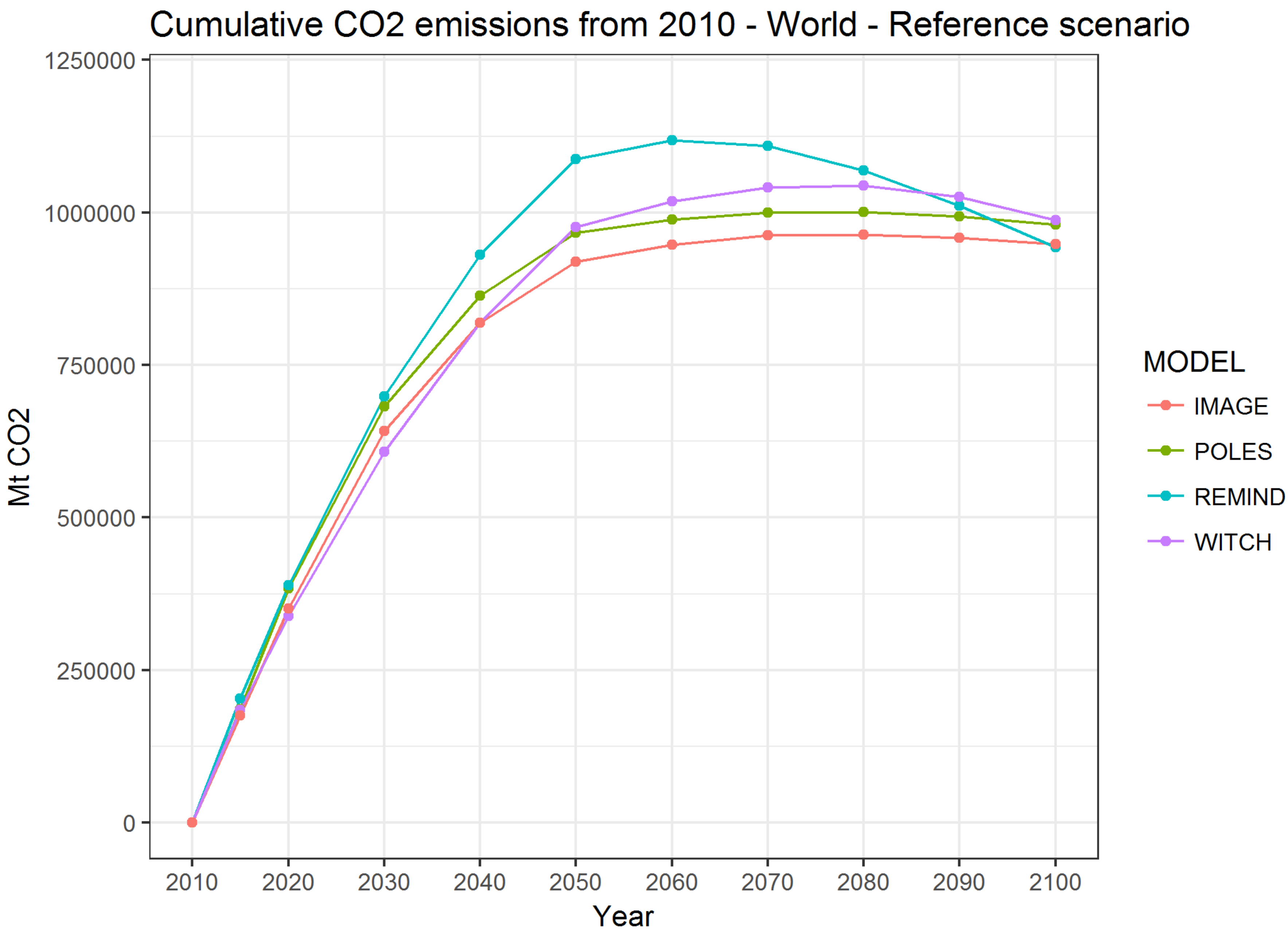
Floor cost: soft bound

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

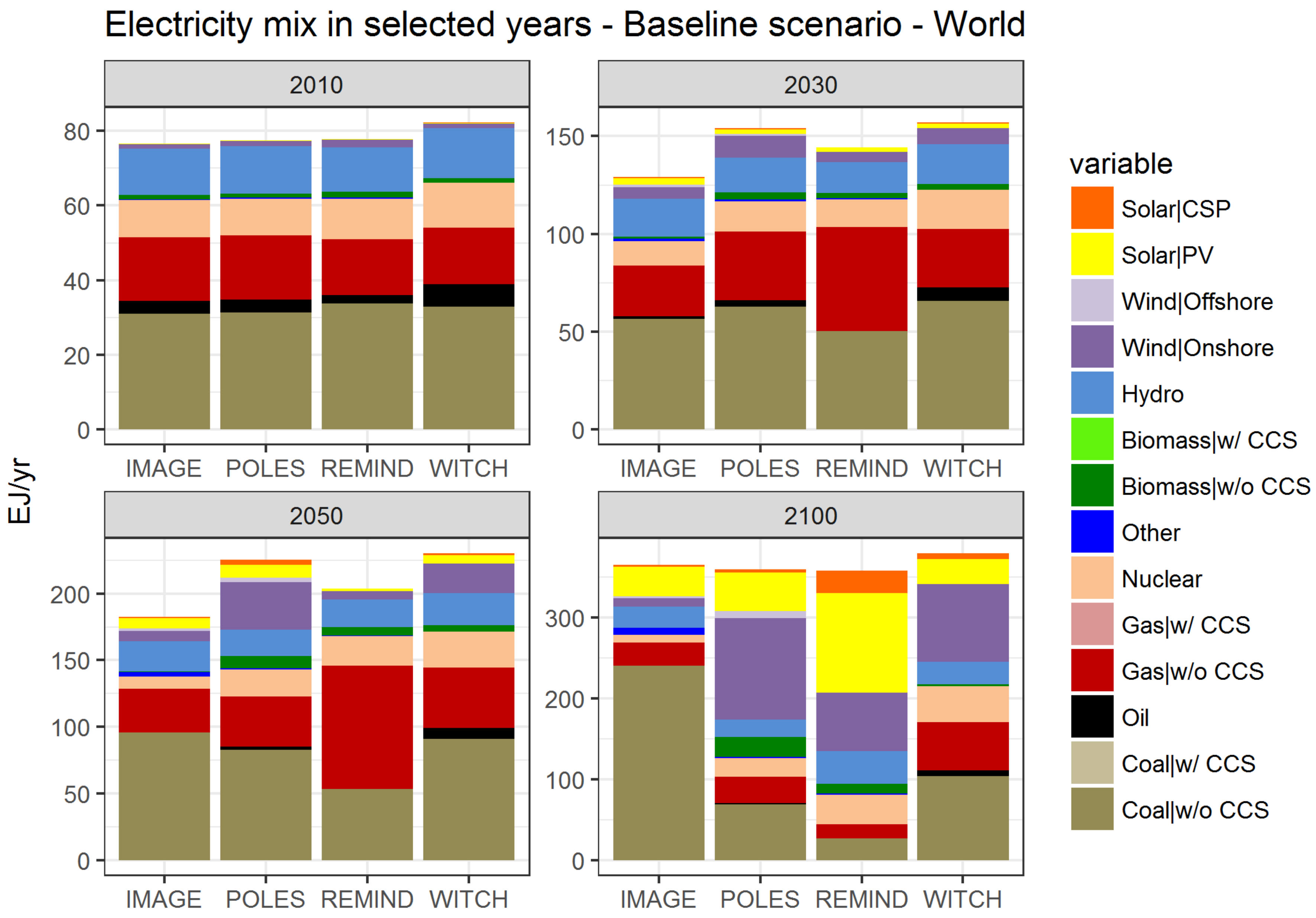
- CC_t = capital cost at time t
- CC_1 = initial capital cost
- K_t = cumulative capacity at time t
- K_1 = initial capacity
- b = a measure of the strength of the learning effect
- FC = floor cost

Modeling assumptions (stocktaking)

	IMAGE	POLES	WITCH	REMIND
Cost calculation	Endogenous			
Type of endogenous modeling	One-factor learning curve (LbD)			
Regional differentiation	No, only one global cost			
Type of floor cost	"Soft bound" (asymptotic floor cost)			
Plant depreciation	Linear	Linear	Exponential	Concave
Depreciation rate	0.1	0.04	0.044	-
Lifetime [years]	25	25	25	30
2005 investment cost [USD2005/kW]	6580	4650	4650	4900
Learning rate	18%	15%	17%	20%
Floor cost [USD2005/kW]	600	500	400	370

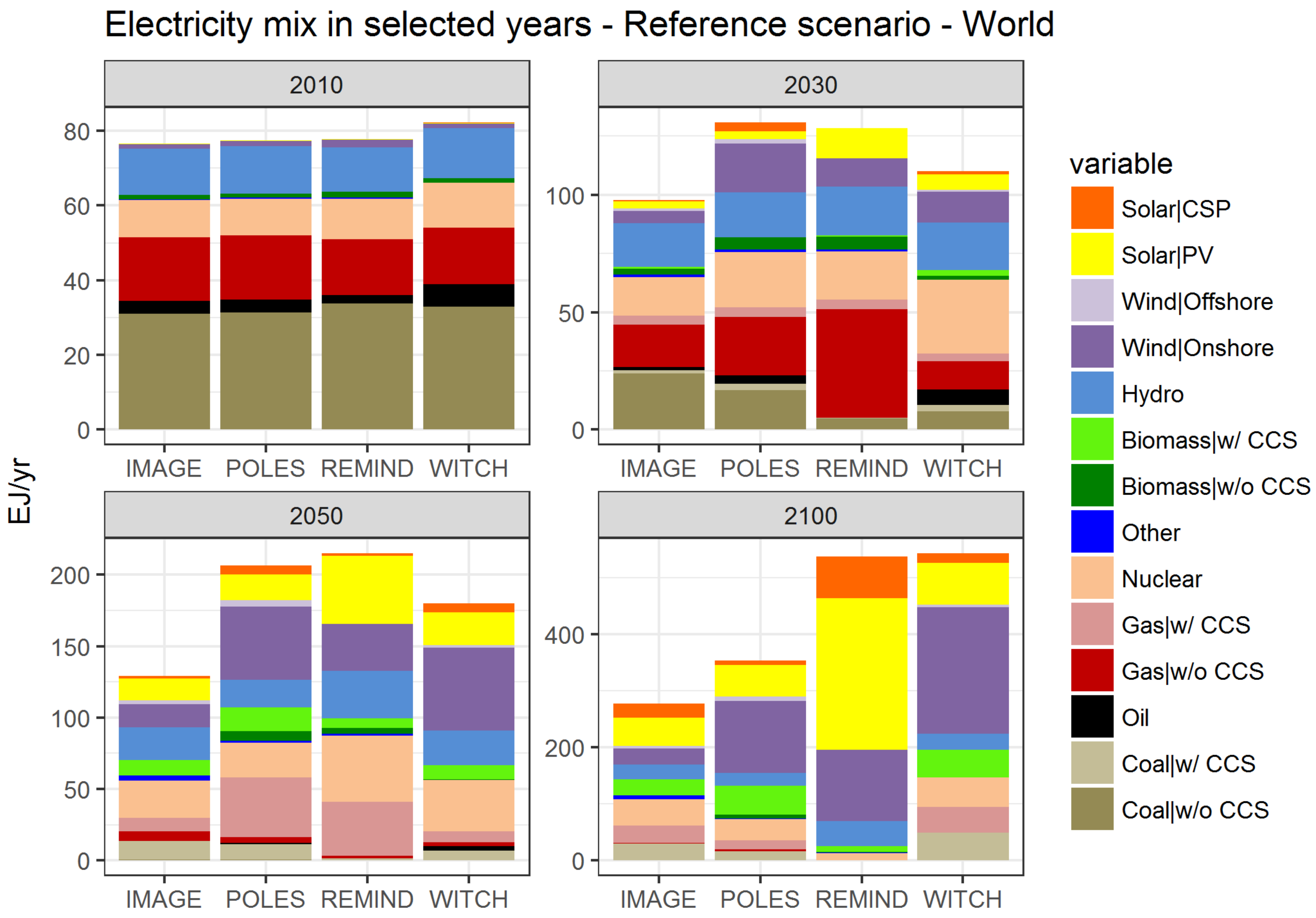


Cumulative CO2 emissions from 2010 - World - Reference scenario
1250000
1000000
750000
500000
250000
0
Mt CO2
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
MODEL
IMAGE
POLES
REMIND
WITCH

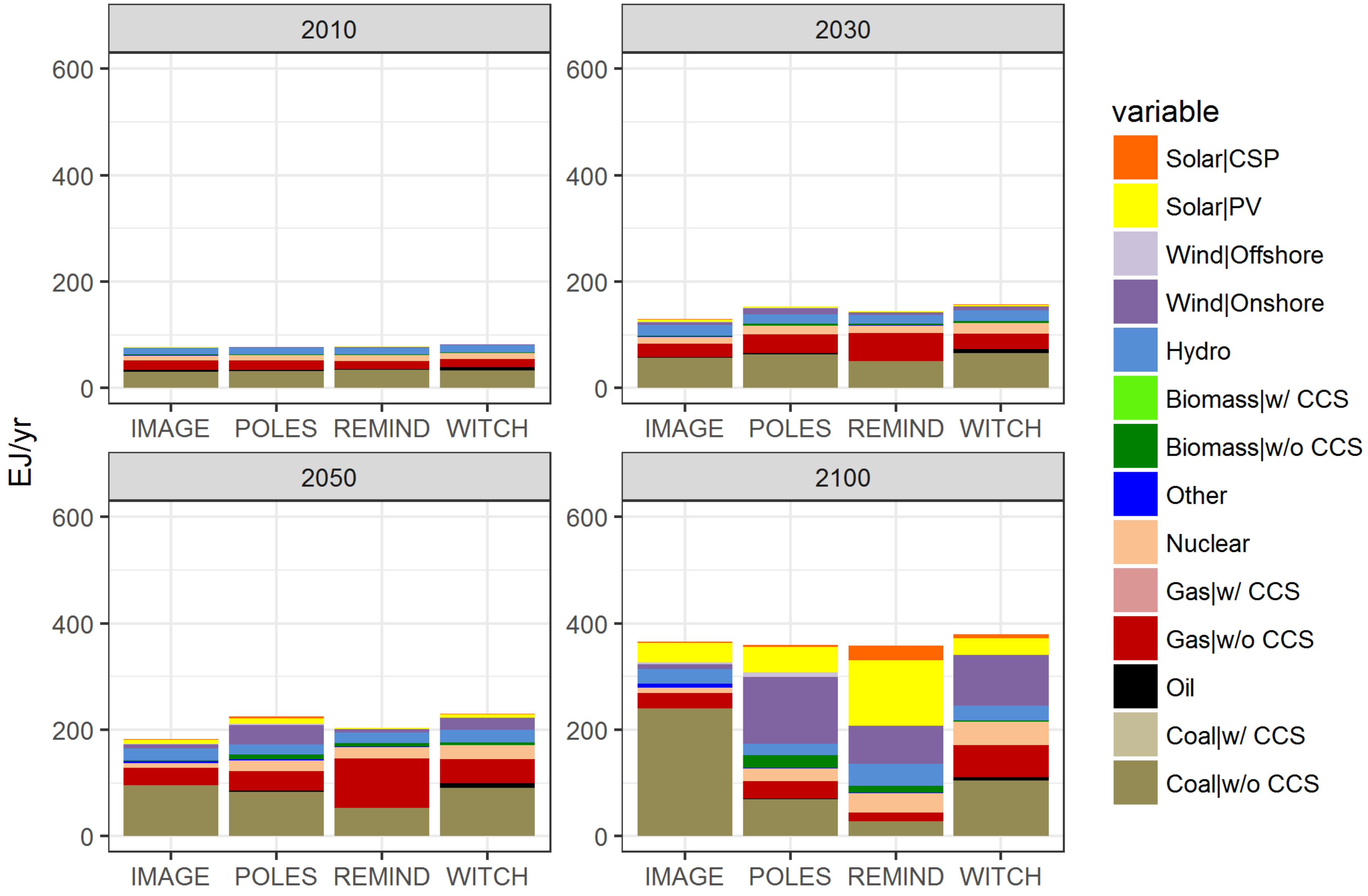


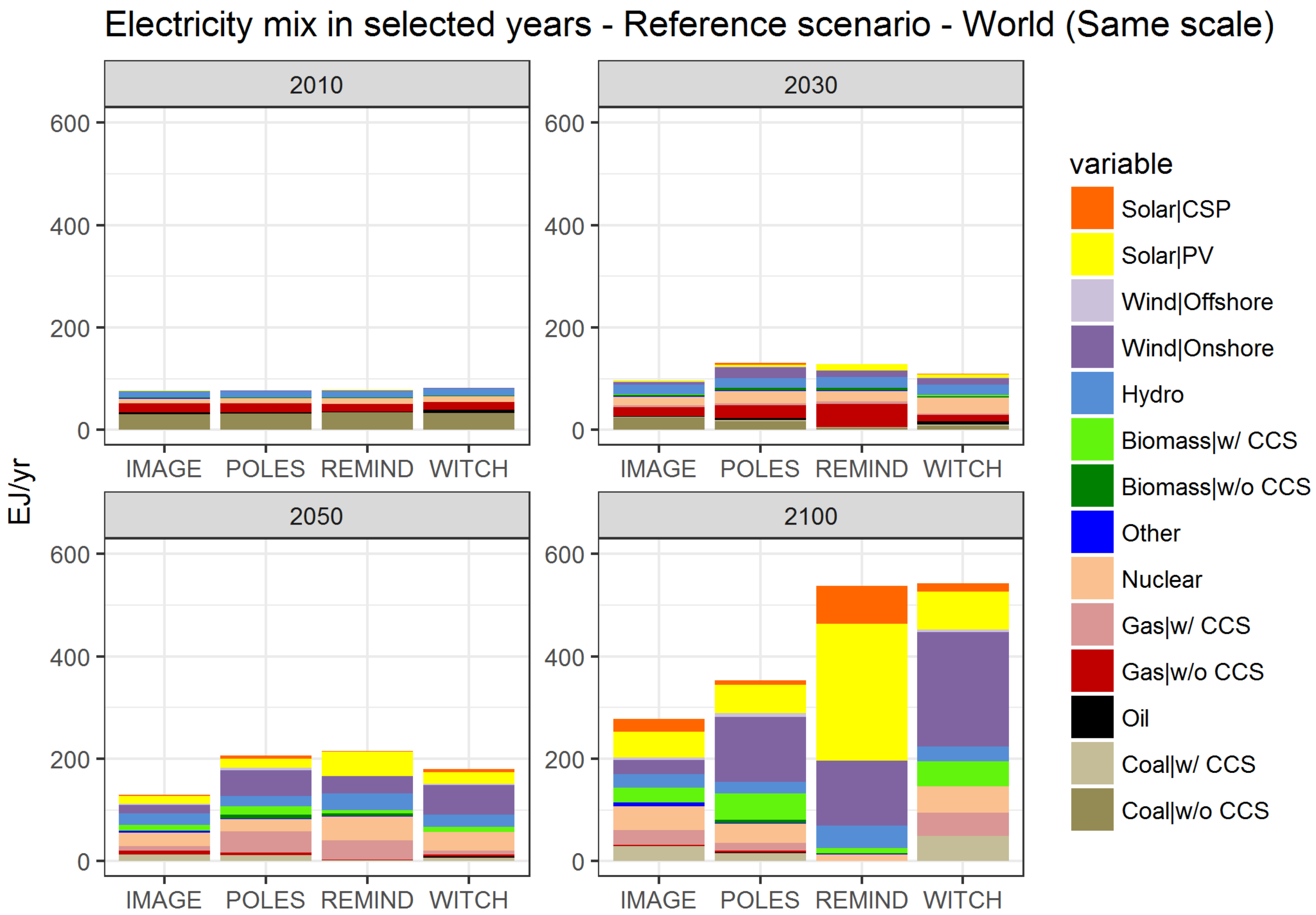
Electricity mix in selected years - Baseline scenario - World
2010
2030
2050
2100
EJ/yr
IMAGE
POLES
REMIND
WITCH
0
20
40
60
80
50
100
150
200
300
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Other
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

MERCURY

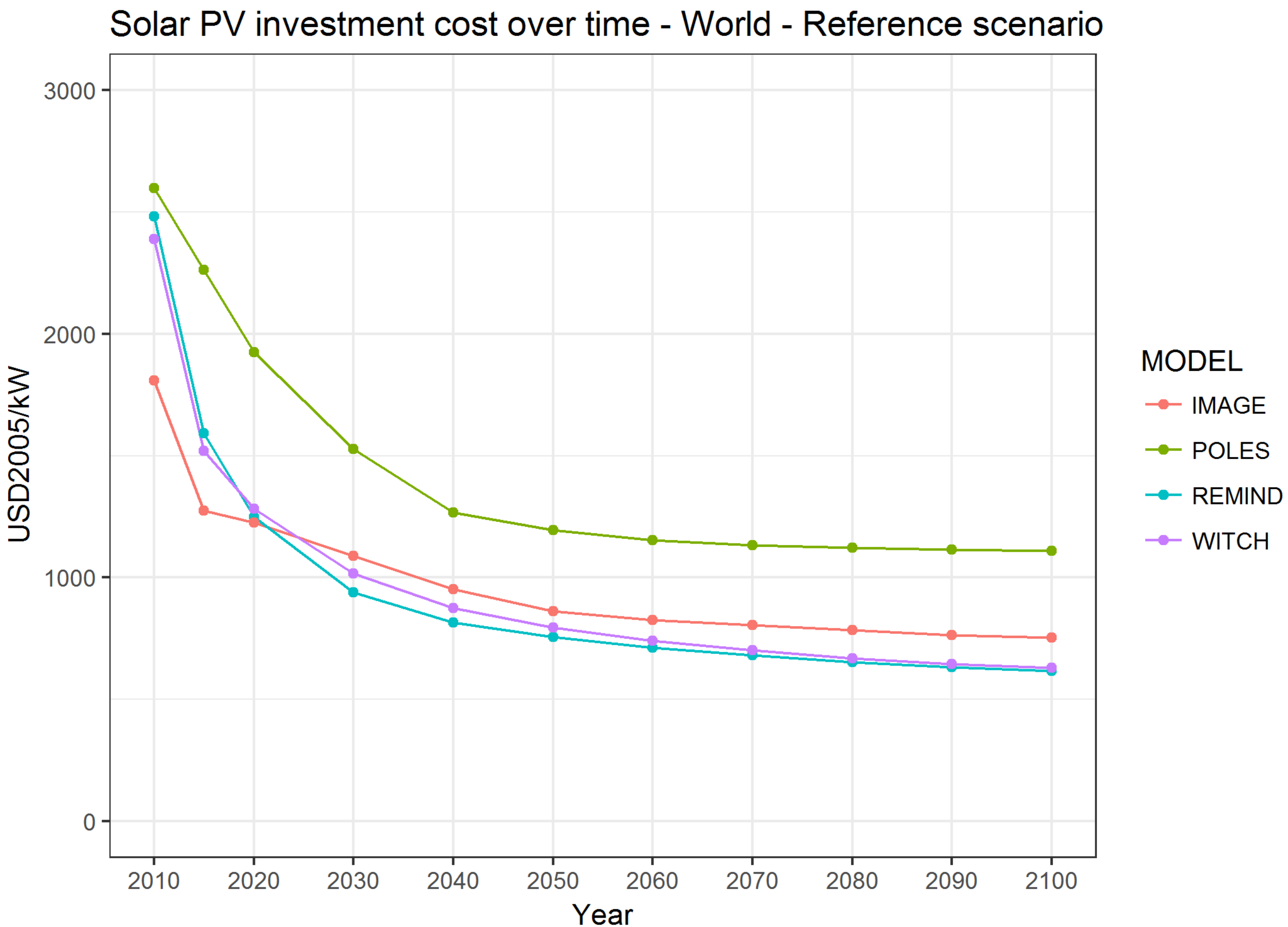

Electricity mix in selected years - Reference scenario - World
2010
2030
2050
2100
EJ/yr
IMAGE
POLES
REMIND
WITCH
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Other
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

Electricity mix in selected years - Baseline scenario - World (Same scale)

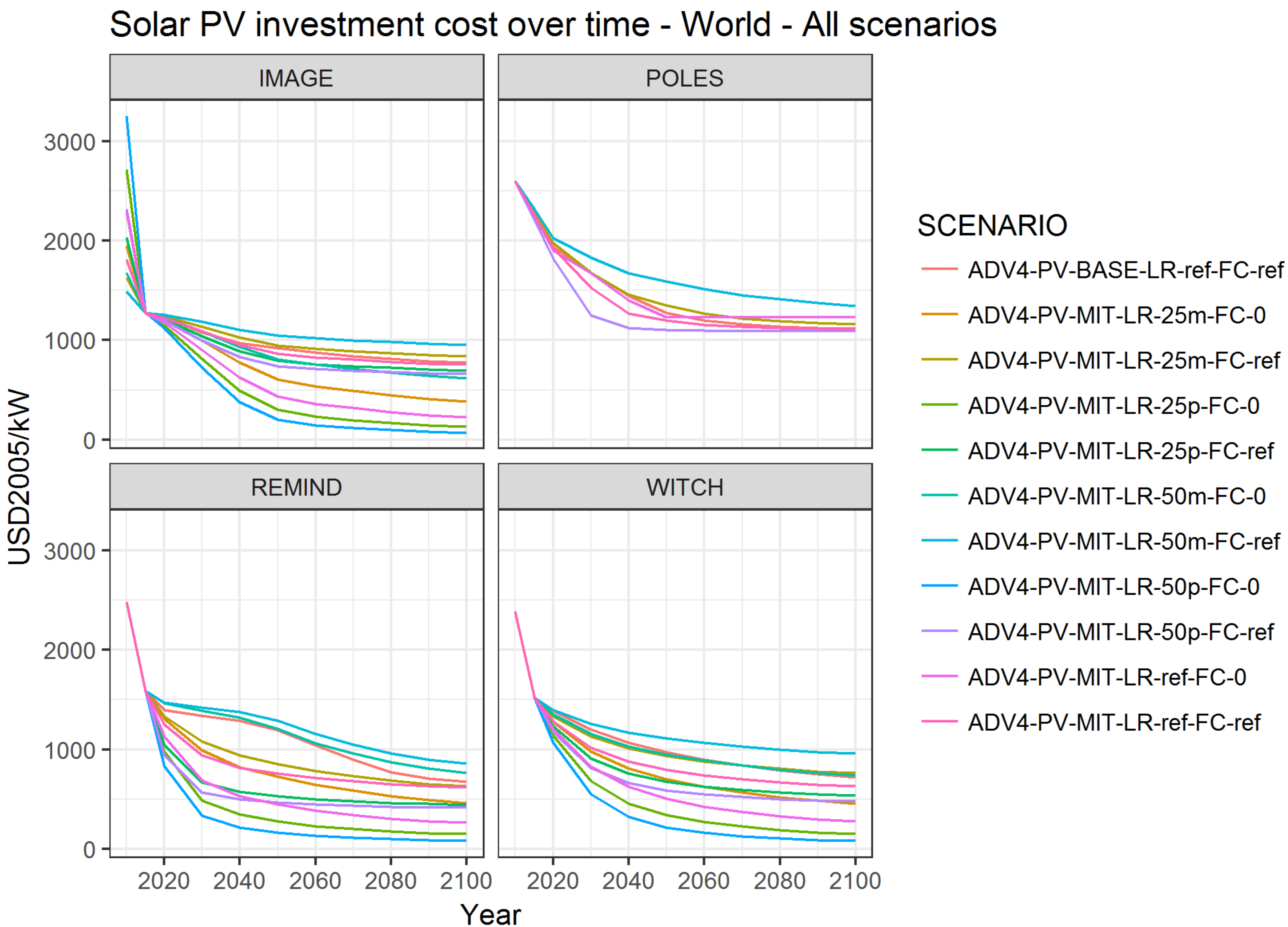




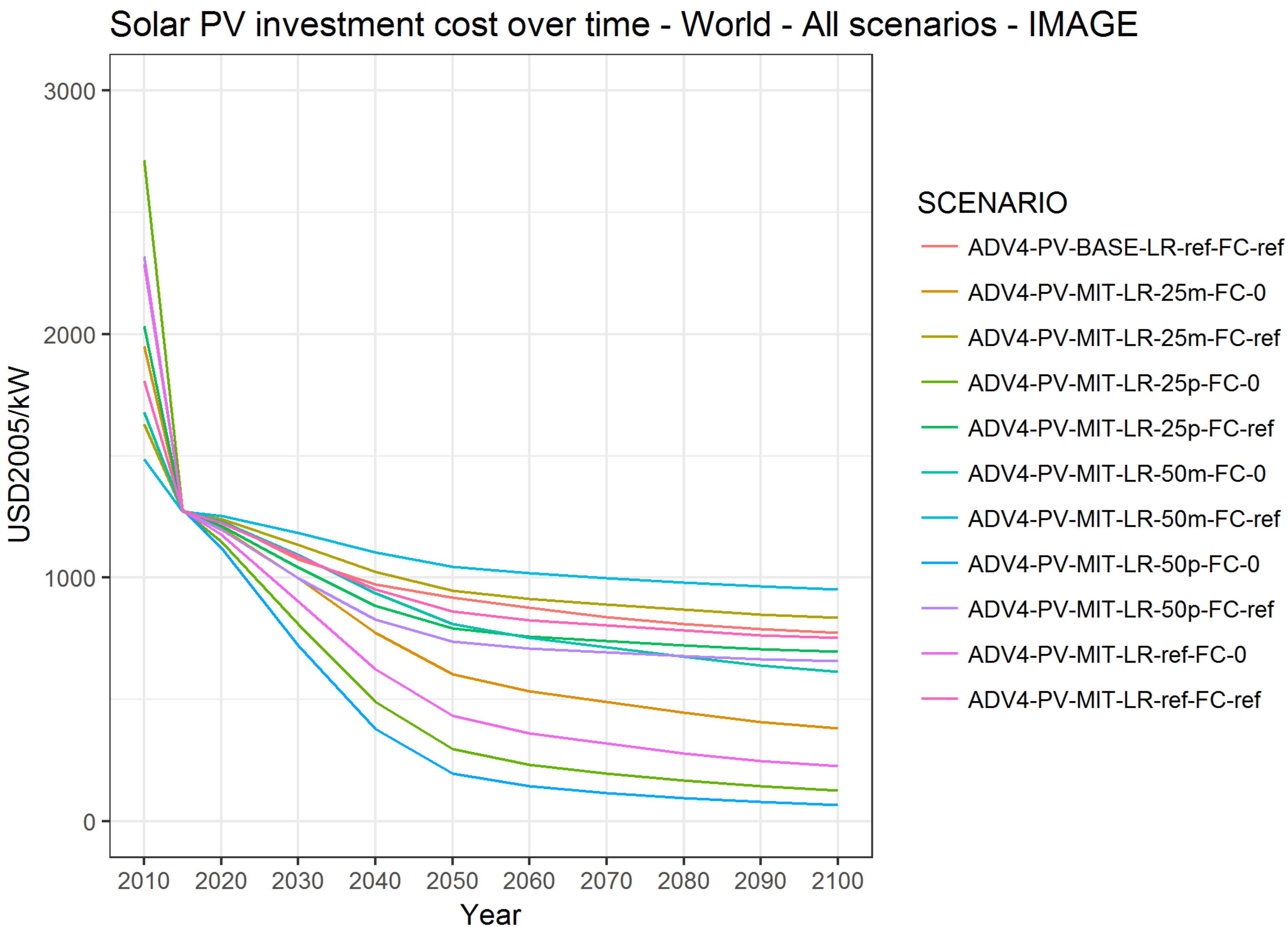
Electricity mix in selected years - Reference scenario - World (Same scale)
2010
2030
2050
2100
600
400
200
0
EJ/yr
IMAGE
POLES
REMIND
WITCH
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Other
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

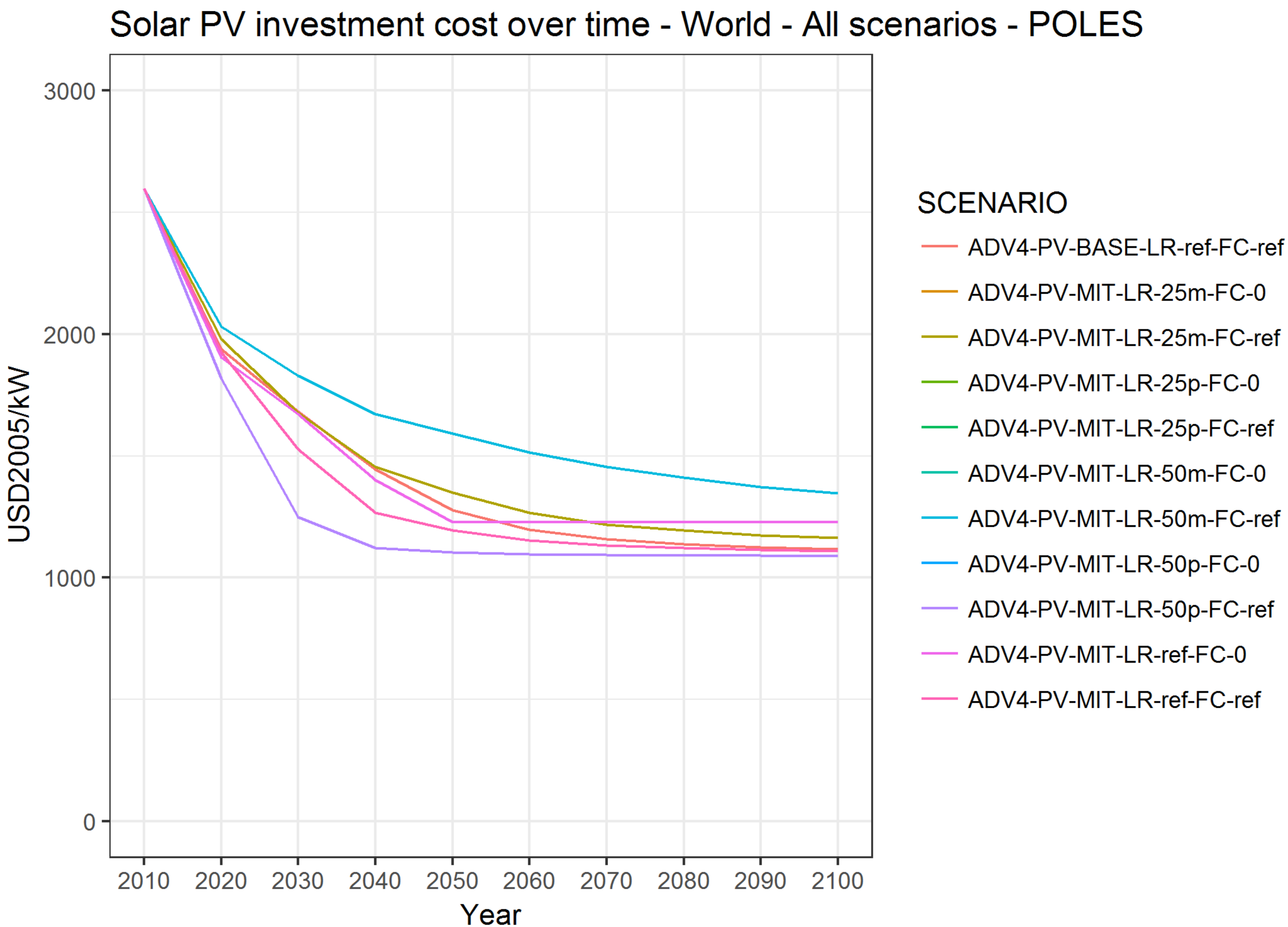


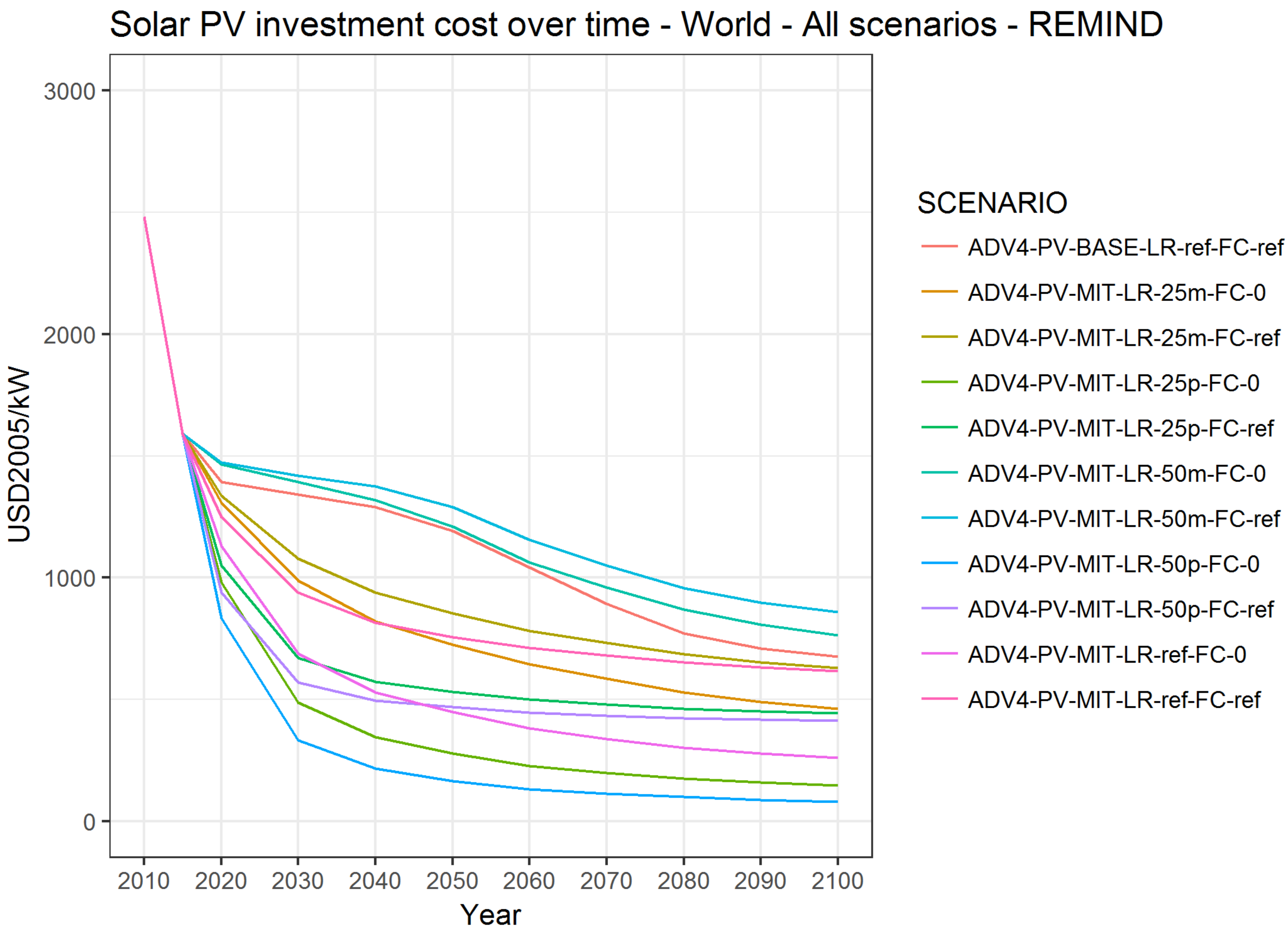
Solar PV investment cost over time - World - Reference scenario
USD2005/kW
3000
2000
1000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
MODEL
IMAGE
POLES
REMIND
WITCH

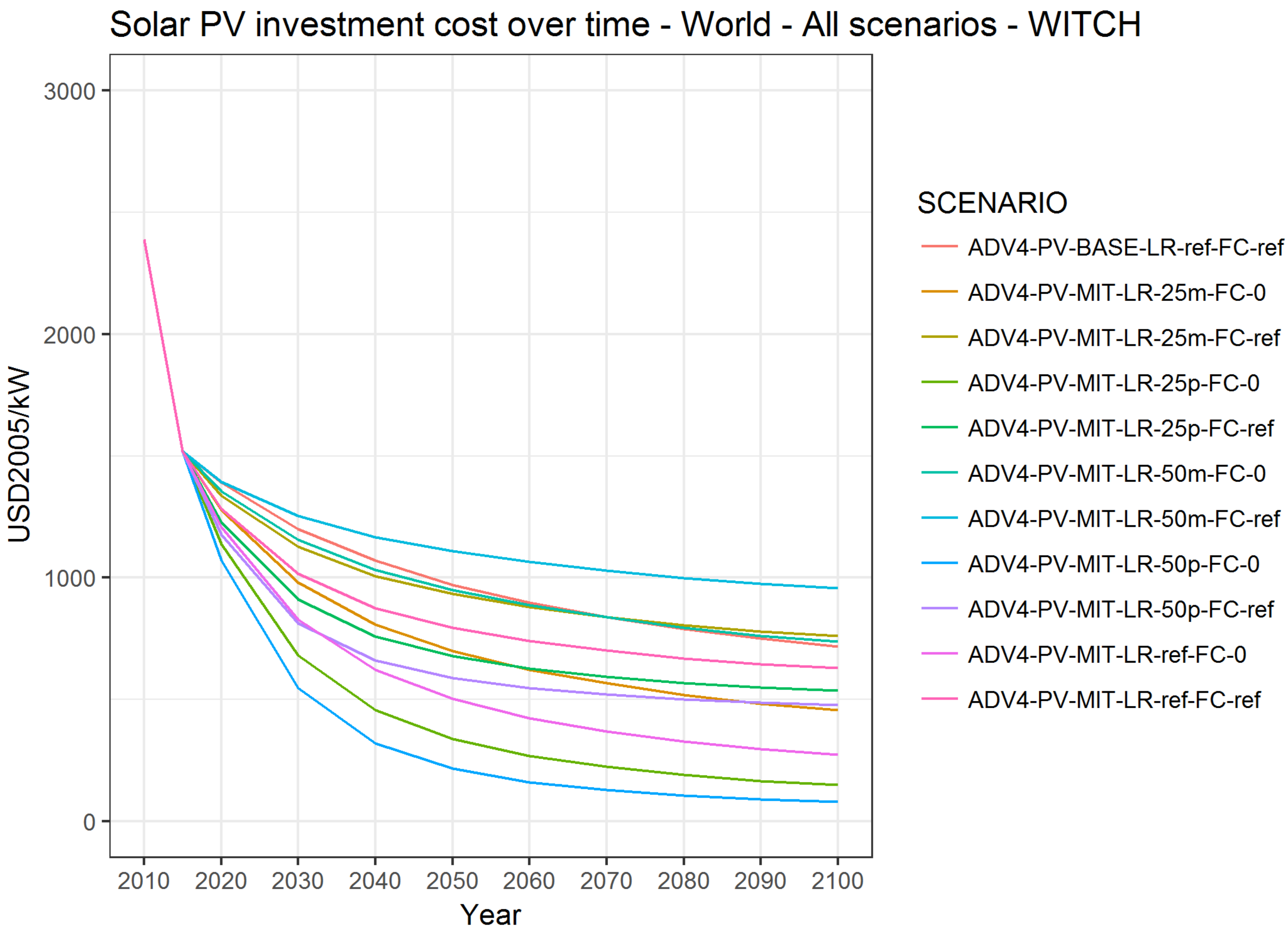


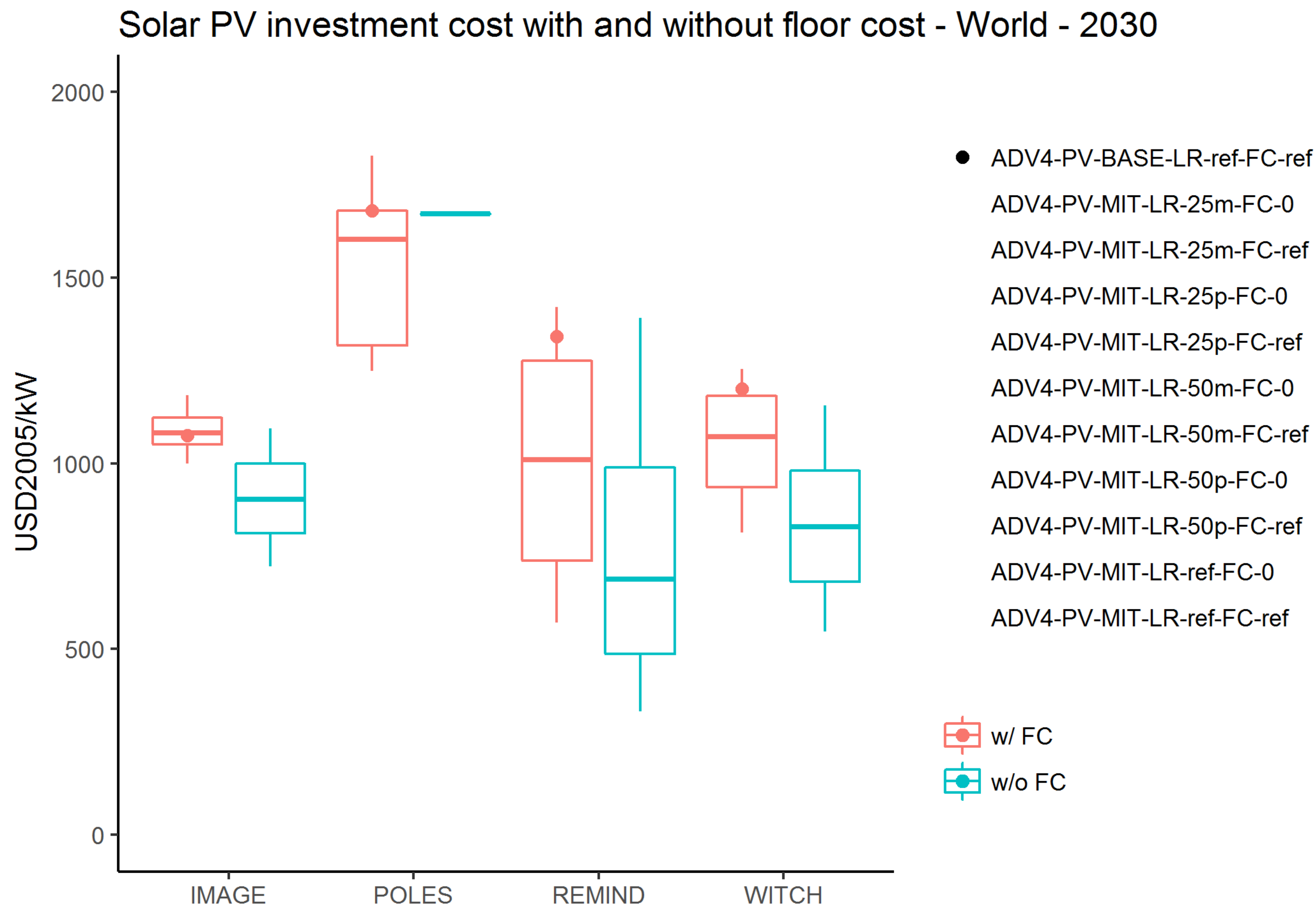
Solar PV investment cost over time - World - All scenarios
IMAGE
POLES
REMIND
WITCH
USD2005/kW
0
1000
2000
3000
2020
2040
2060
2080
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref

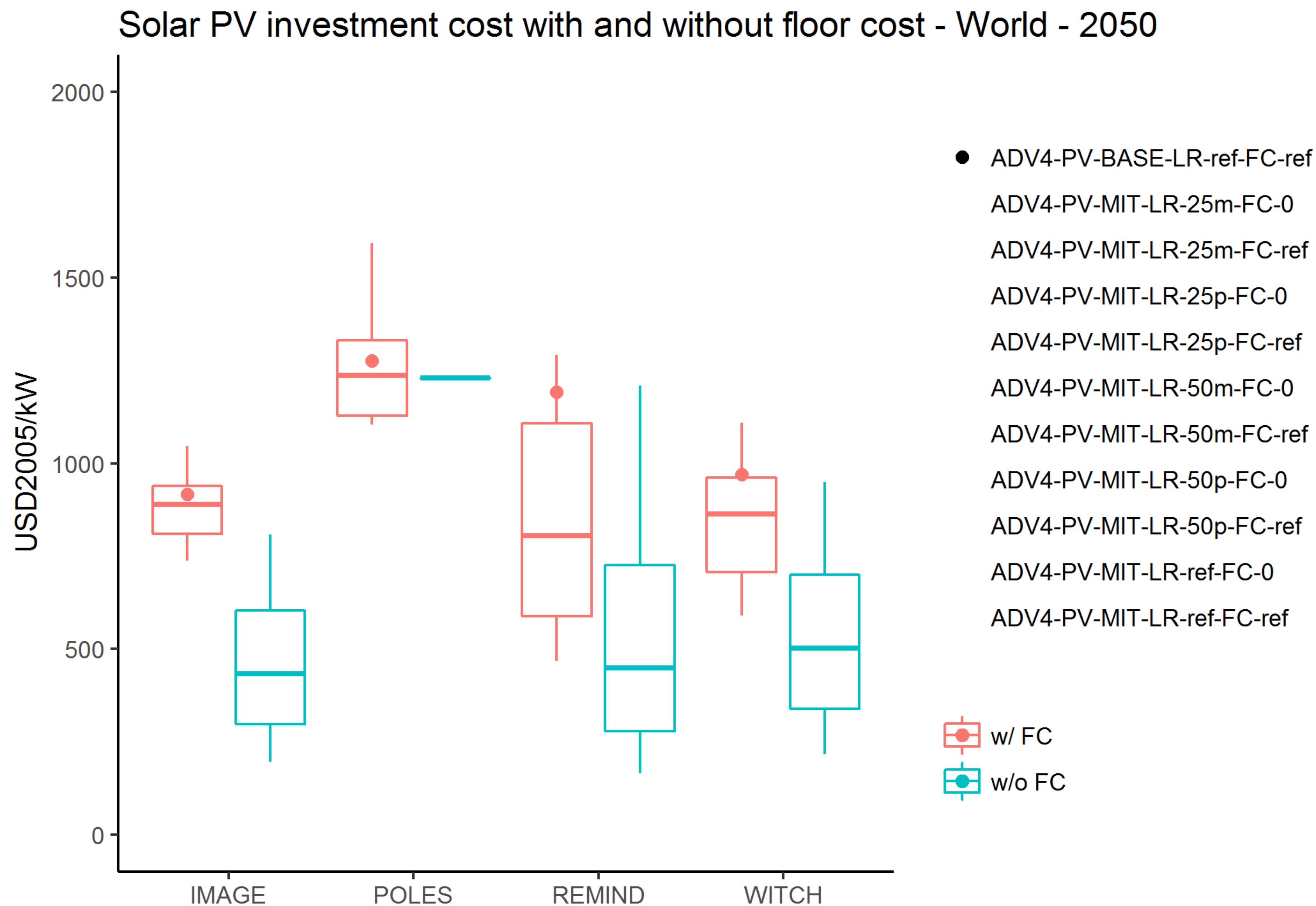

Solar PV investment cost over time - World - All scenarios - IMAGE
USD2005/kW
3000
2000
1000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref

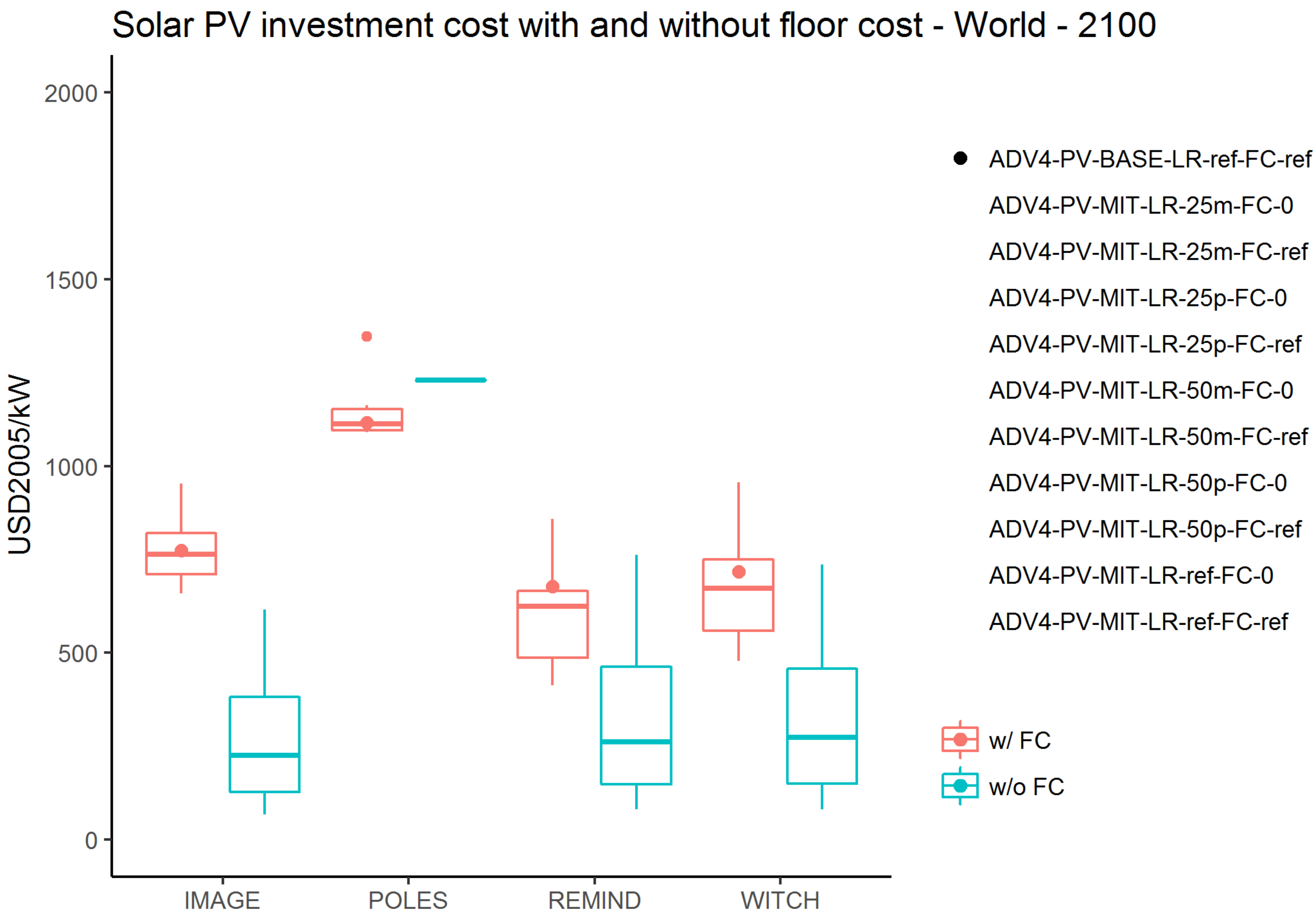

Solar PV investment cost over time - World - All scenarios - POLES
USD2005/kW
3000
2000
1000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref


Solar PV investment cost over time - World - All scenarios - REMIND
USD2005/kW
3000
2000
1000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref

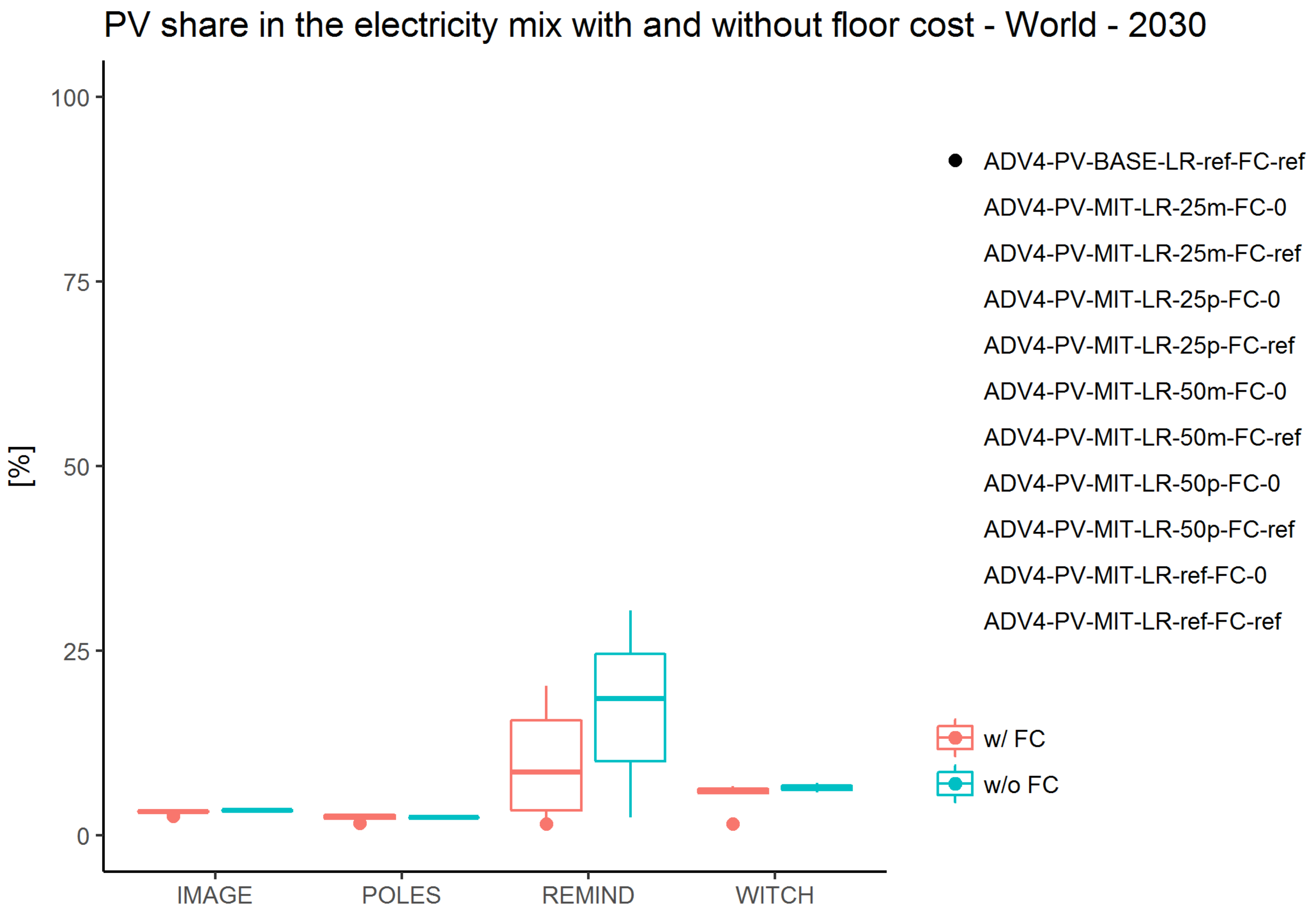

Solar PV investment cost over time - World - All scenarios - WITCH
USD2005/kW
3000
2000
1000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref


Solar PV investment cost with and without floor cost - World - 2030
USD2005/kW
2000
1500
1000
500
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC

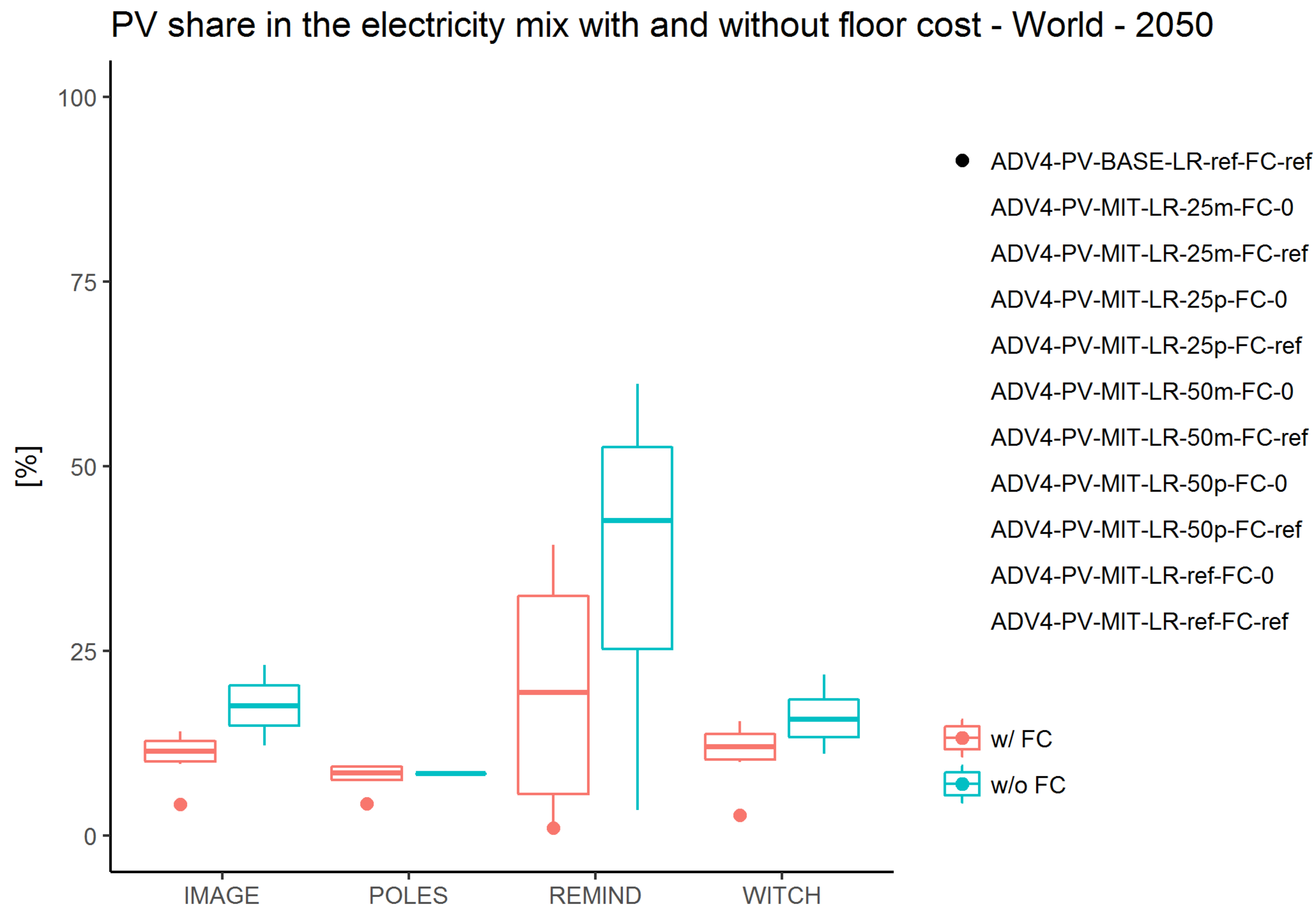

Solar PV investment cost with and without floor cost - World - 2050
USD2005/kW
2000
1500
1000
500
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC

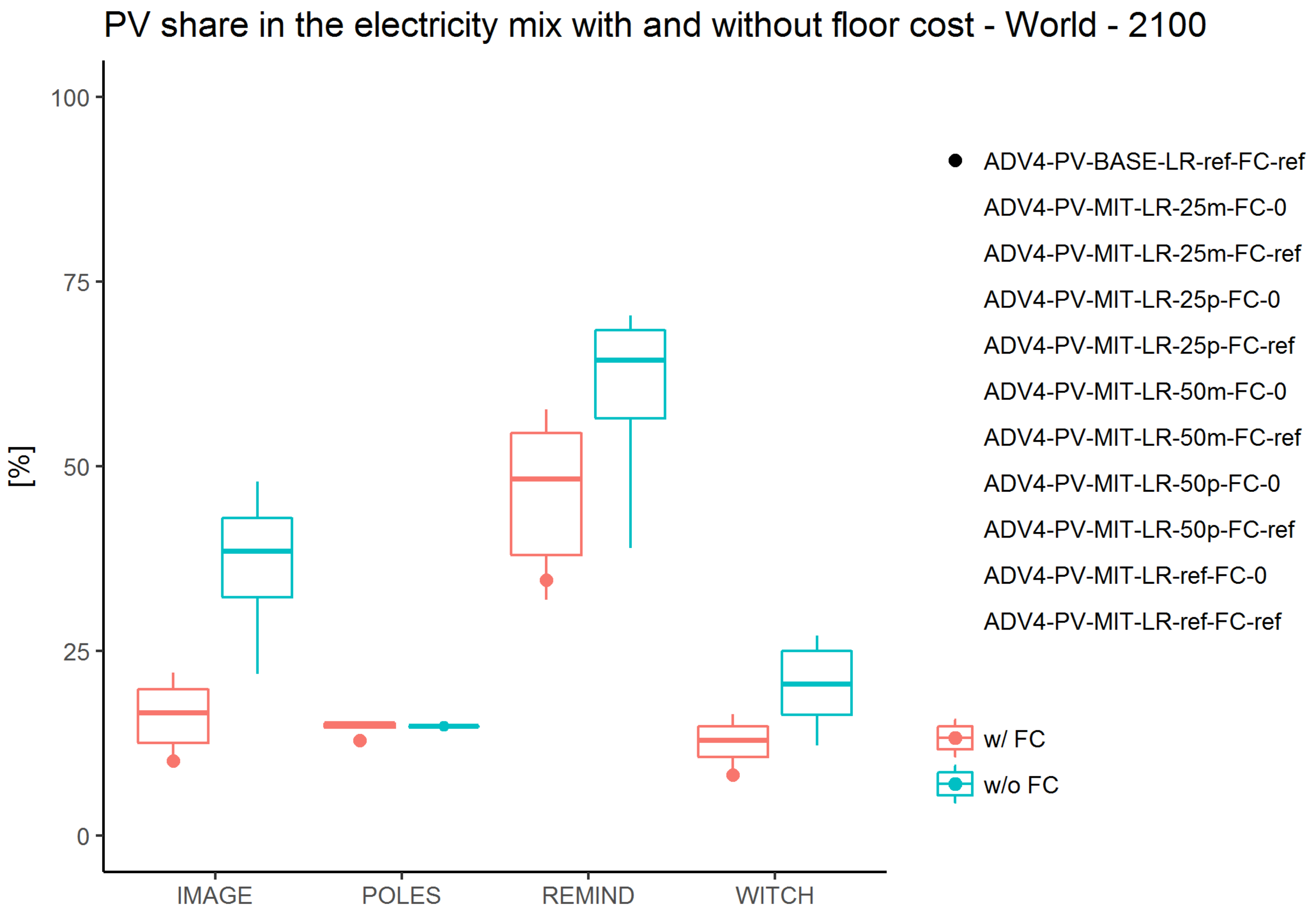


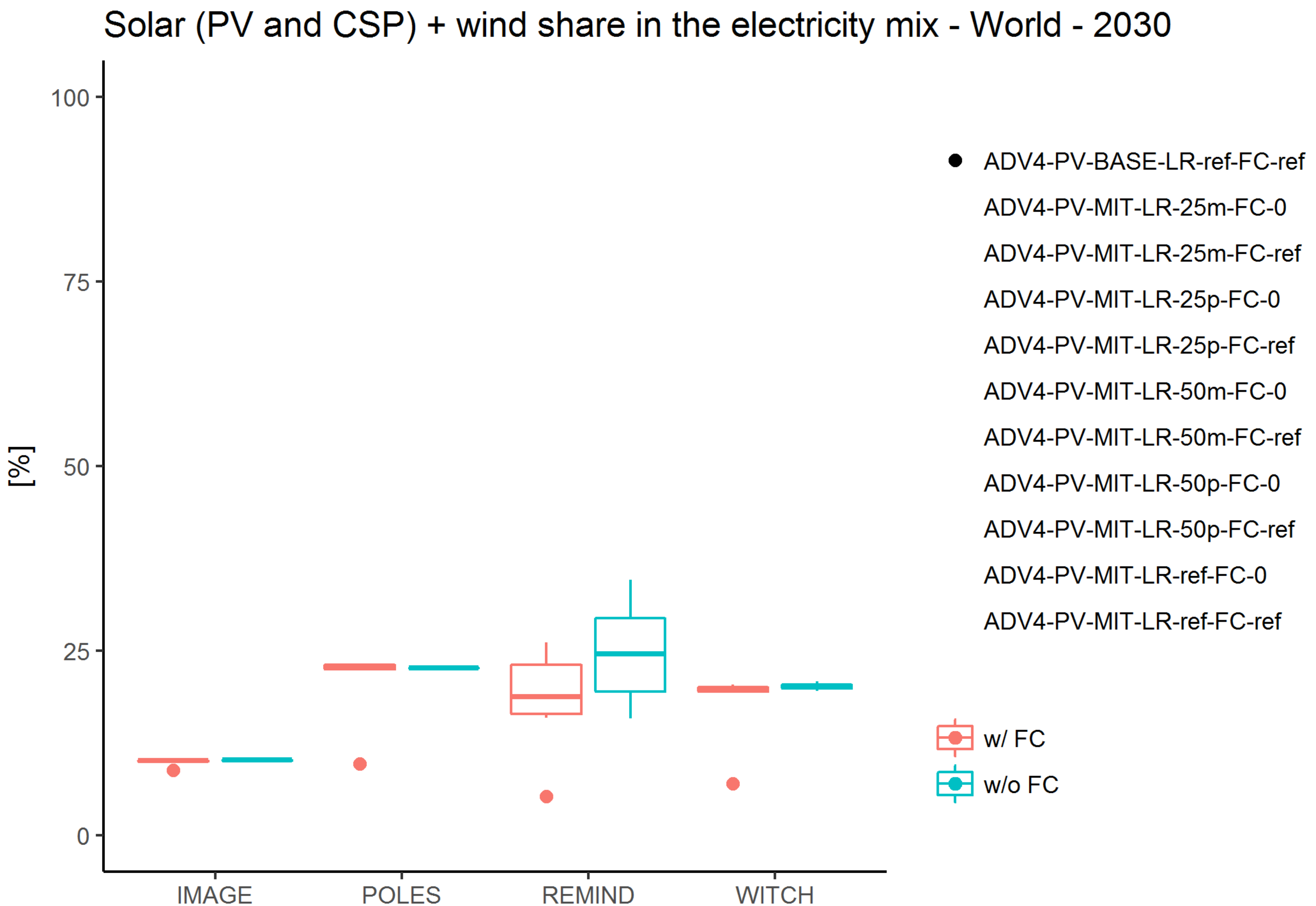
Solar PV investment cost with and without floor cost - World - 2100
USD2005/kW
2000
1500
1000
500
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC



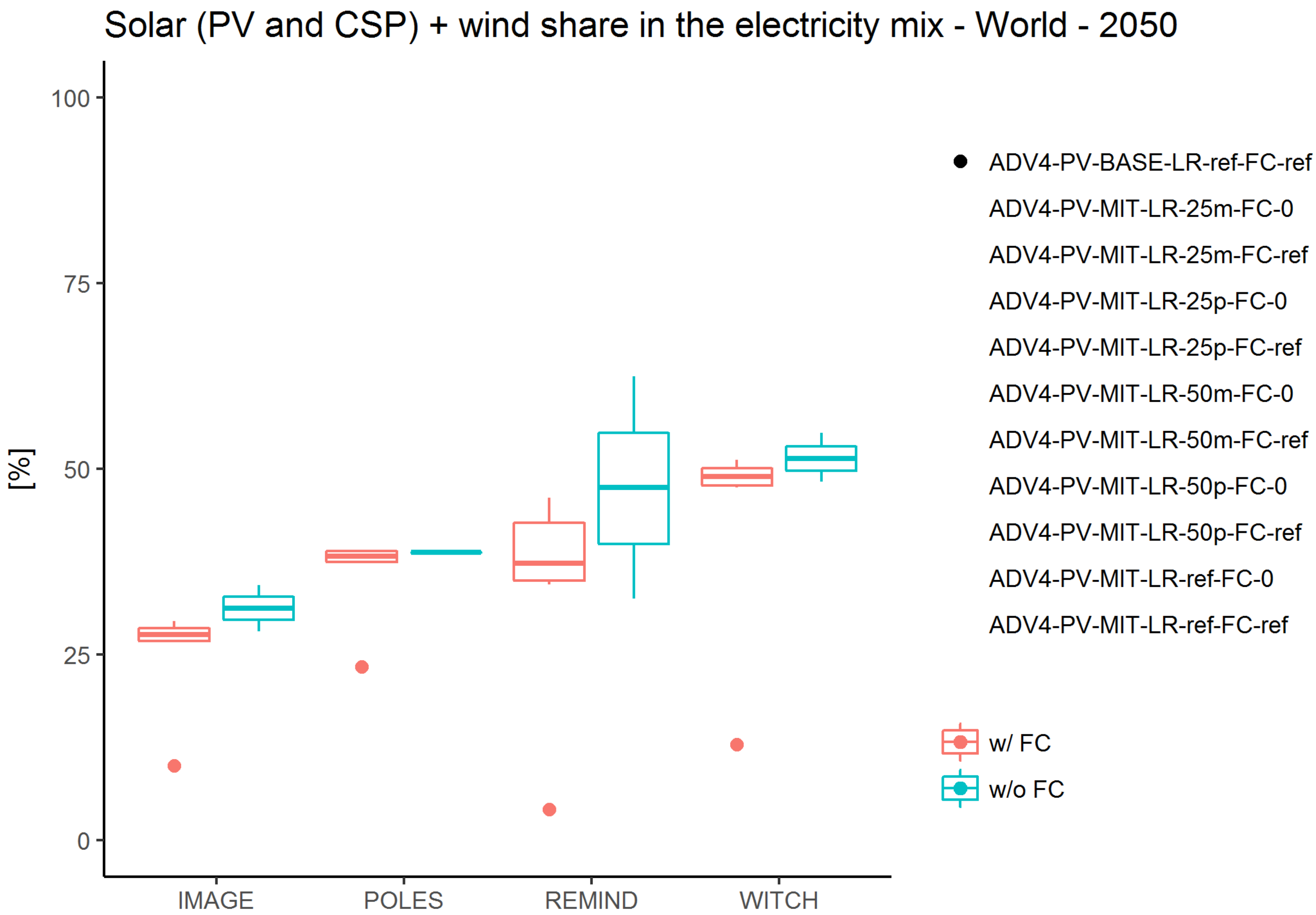
PV share in the electricity mix with and without floor cost - World - 2030
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC

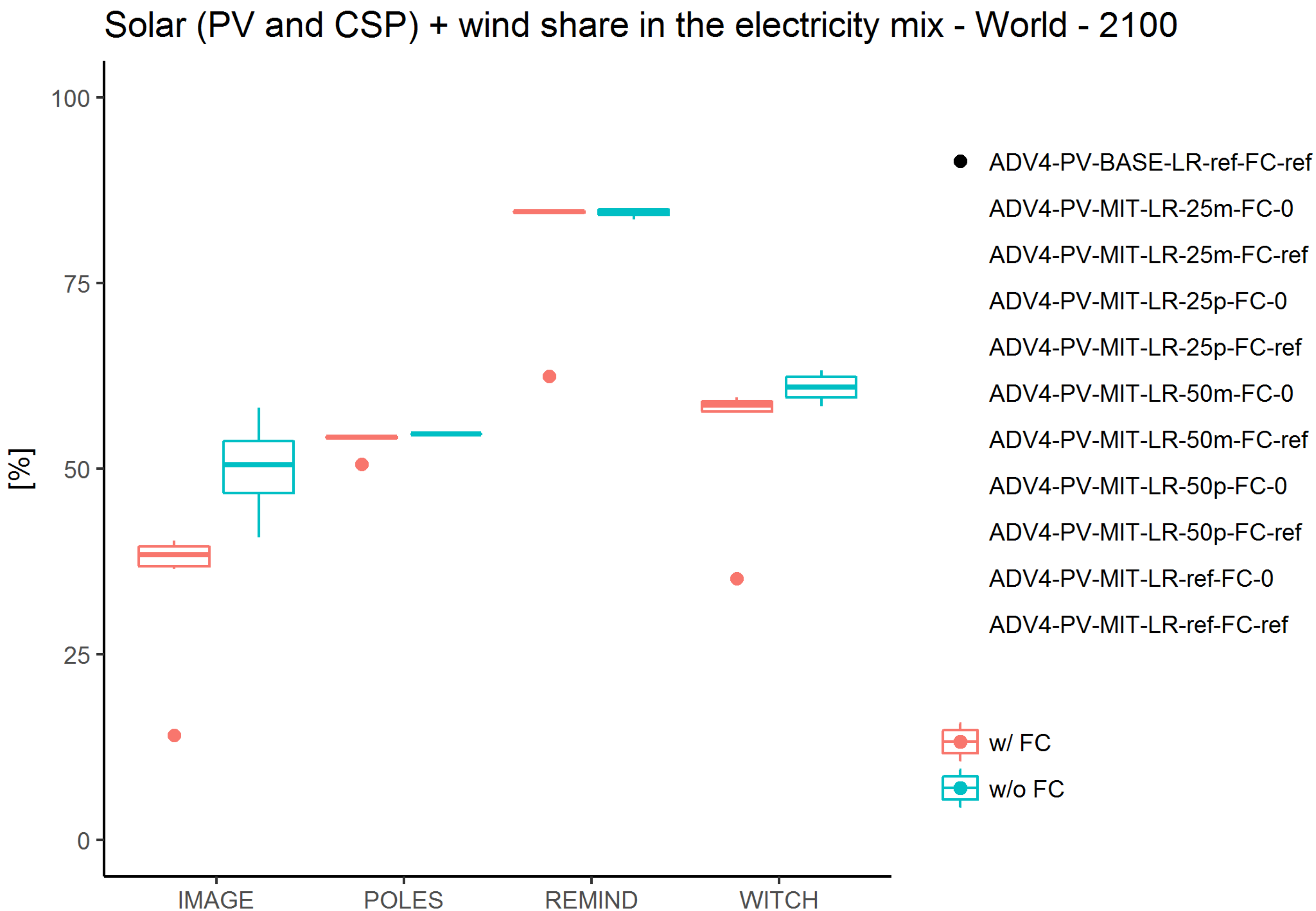

PV share in the electricity mix with and without floor cost - World - 2050
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC

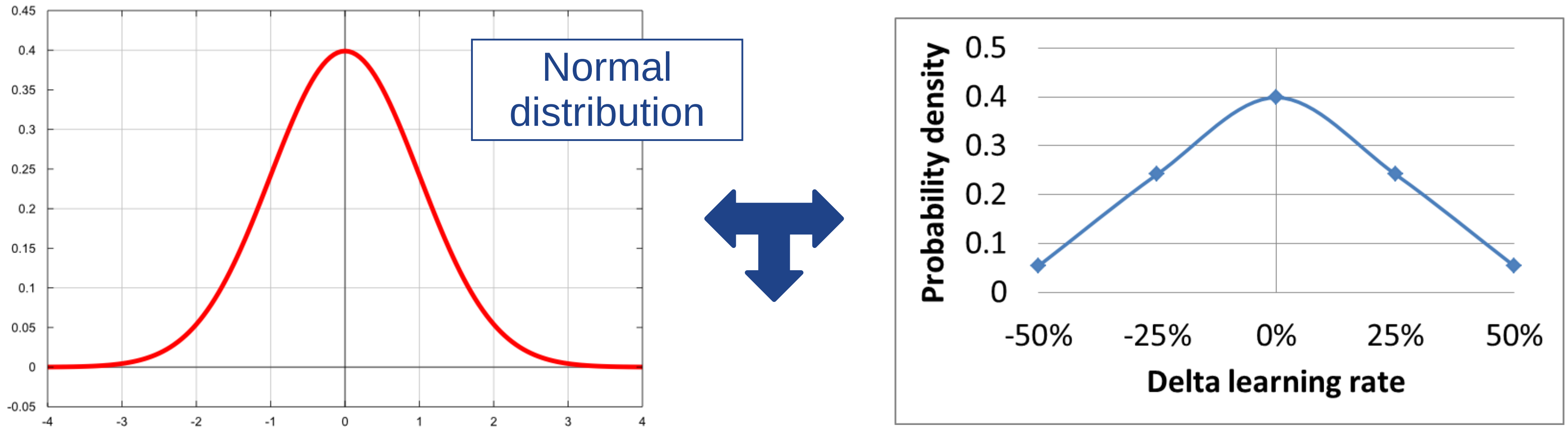

PV share in the electricity mix with and without floor cost - World - 2100
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC

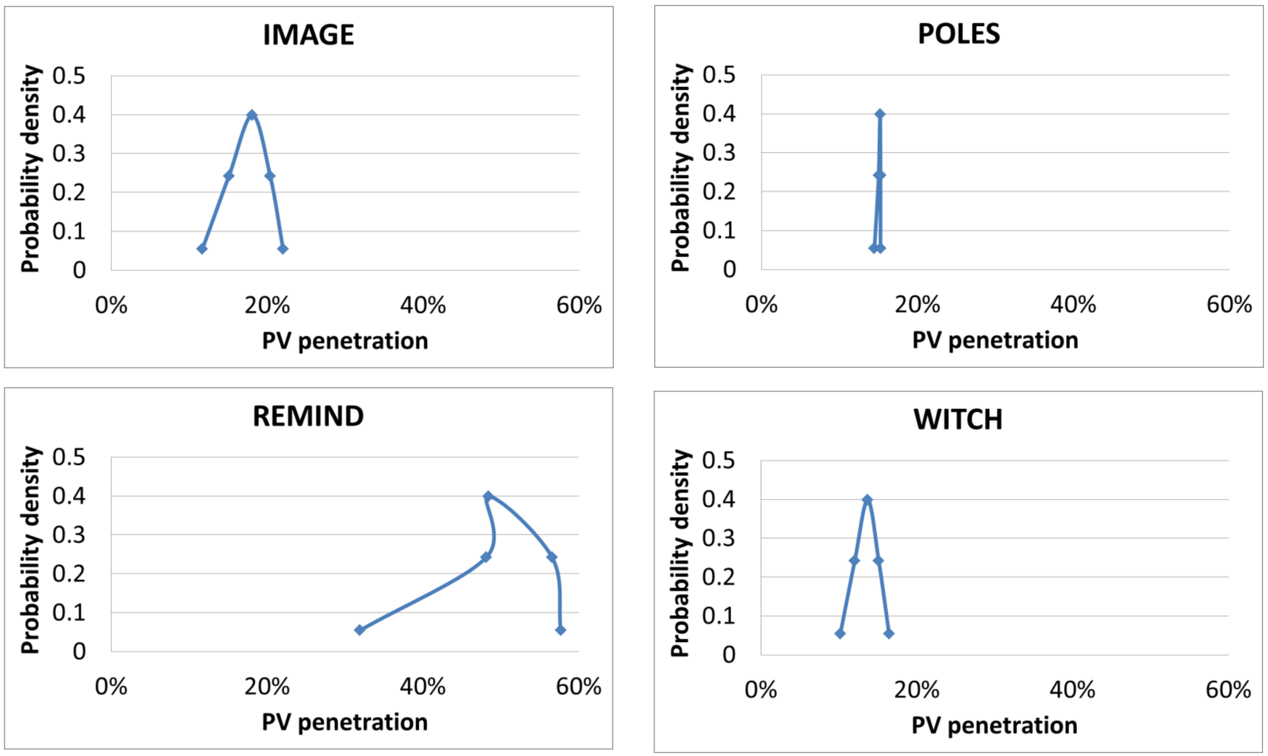


Solar (PV and CSP) + wind share in the electricity mix - World - 2030
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC


Solar (PV and CSP) + wind share in the electricity mix - World - 2050
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC


Solar (PV and CSP) + wind share in the electricity mix - World - 2100
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0
ADV4-PV-MIT-LR-50p-FC-ref
ADV4-PV-MIT-LR-ref-FC-0
ADV4-PV-MIT-LR-ref-FC-ref
w/ FC
w/o FC



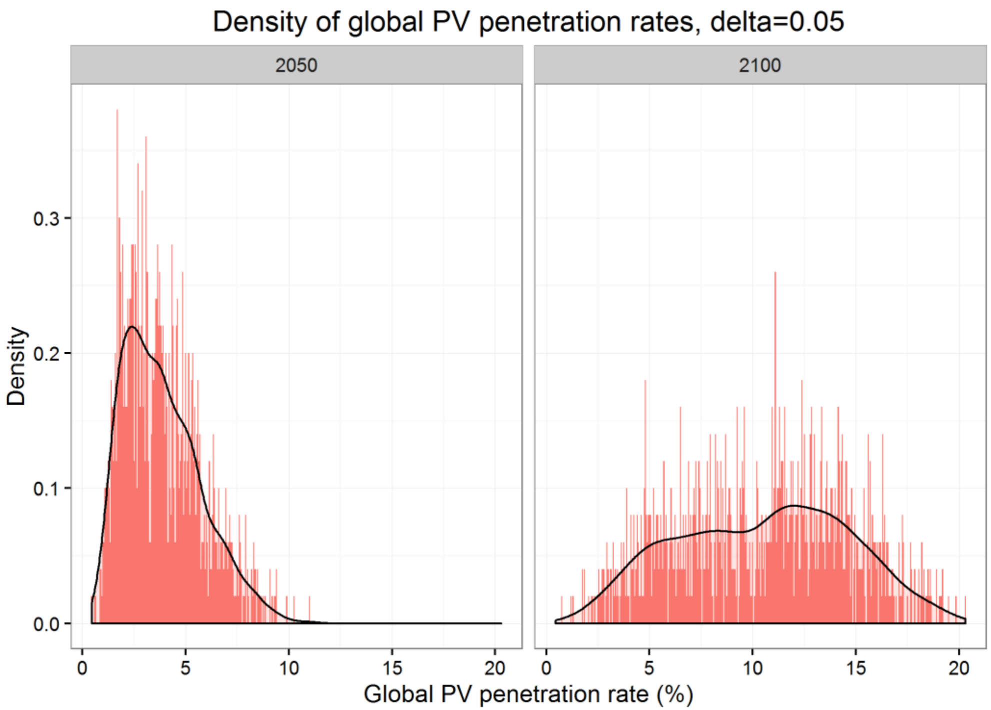


PV share in the ref. case World 2100

Statistical analysis

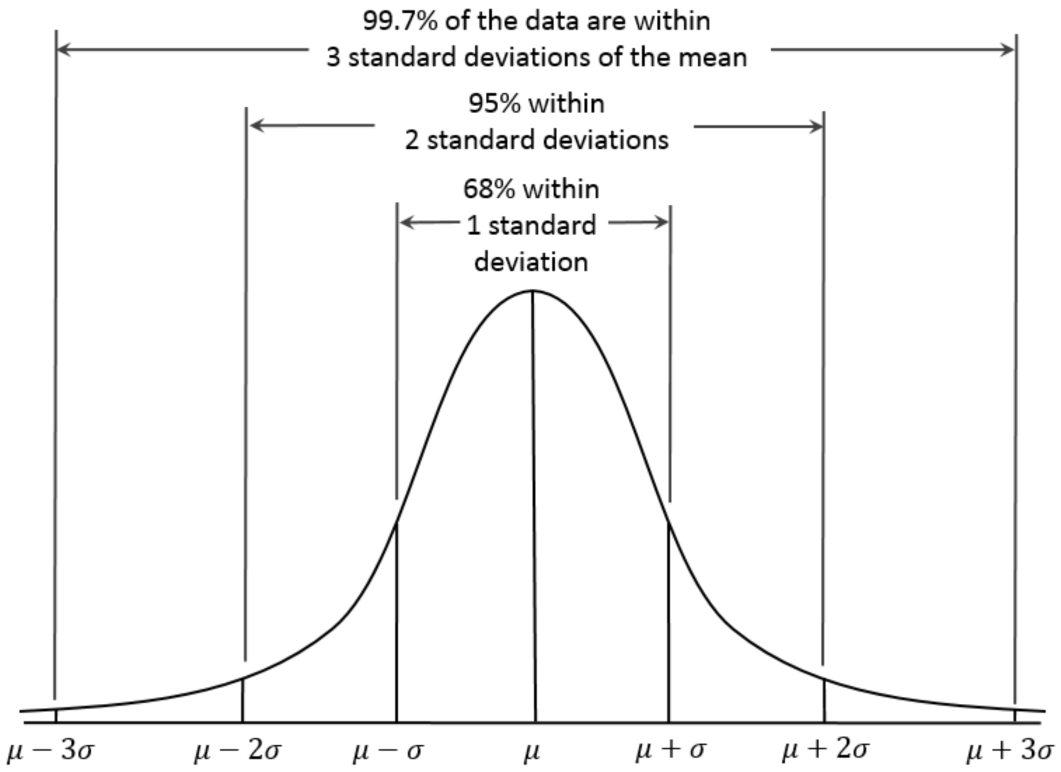
- The previous slide is a draft of what I would like to develop after the next submission.
- The objective is to derive statistical information in order to obtain the “real” penetration, weighting the different PV shares on the probability density of the corresponding learning rate (basing on the assumption that the learning rate profile replicates a normal function).

- The easiest solution would be to carry out a weighted average; a more sophisticated solution would be to derive a statistical distribution like in the example aside (although with much fewer samples).



Additional scenarios

- In the light of what discussed in the previous slide, it will be worth to add the **μ ± 3σ (thus ± 75%) scenarios**, both with and without floor cost, in order to have a more complete statistical picture.



- For the sake of completeness (for instance, in order to have complete charts in box plots), the ADV4-PV-BASE-LR-ref-FC-0 scenario, i.e. a **baseline with no floor cost**, will be added as well.

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

Tentative schedule – Second quarter

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.

Tentative schedule – Second quarter

From	To	Task
Today	*July 14*	*Sam around Europe and the US (work at FEEM and conferences)*
July 15	September 15	• Improvement of storage modeling in WITCH • Dynamics of decarbonization • Learning in solar PV (bilateral checks and definition of the updated protocol and template)
September 16	October 15	• Improvement of grid modeling in WITCH • Second WITCH-SWITCH joint application (activity definition) • Learning in solar PV (second submission)
October 16	November 30	• Modeling of electricity trade in WITCH • Second WITCH-SWITCH joint application (actual activity) • Learning in solar PV (result analysis)
December 1	January 15	Backup weeks, wrap up activities, deliverables drafting

THANK YOU
FOR YOUR ATTENTION

www.mercury-energy.eu

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.
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