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 in Integrated Assessment Models

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Joint Global Change Research Institute of Pacific Northwest National Laboratory (PNNL) and University of Maryland (UMD), College Park, MD, USA

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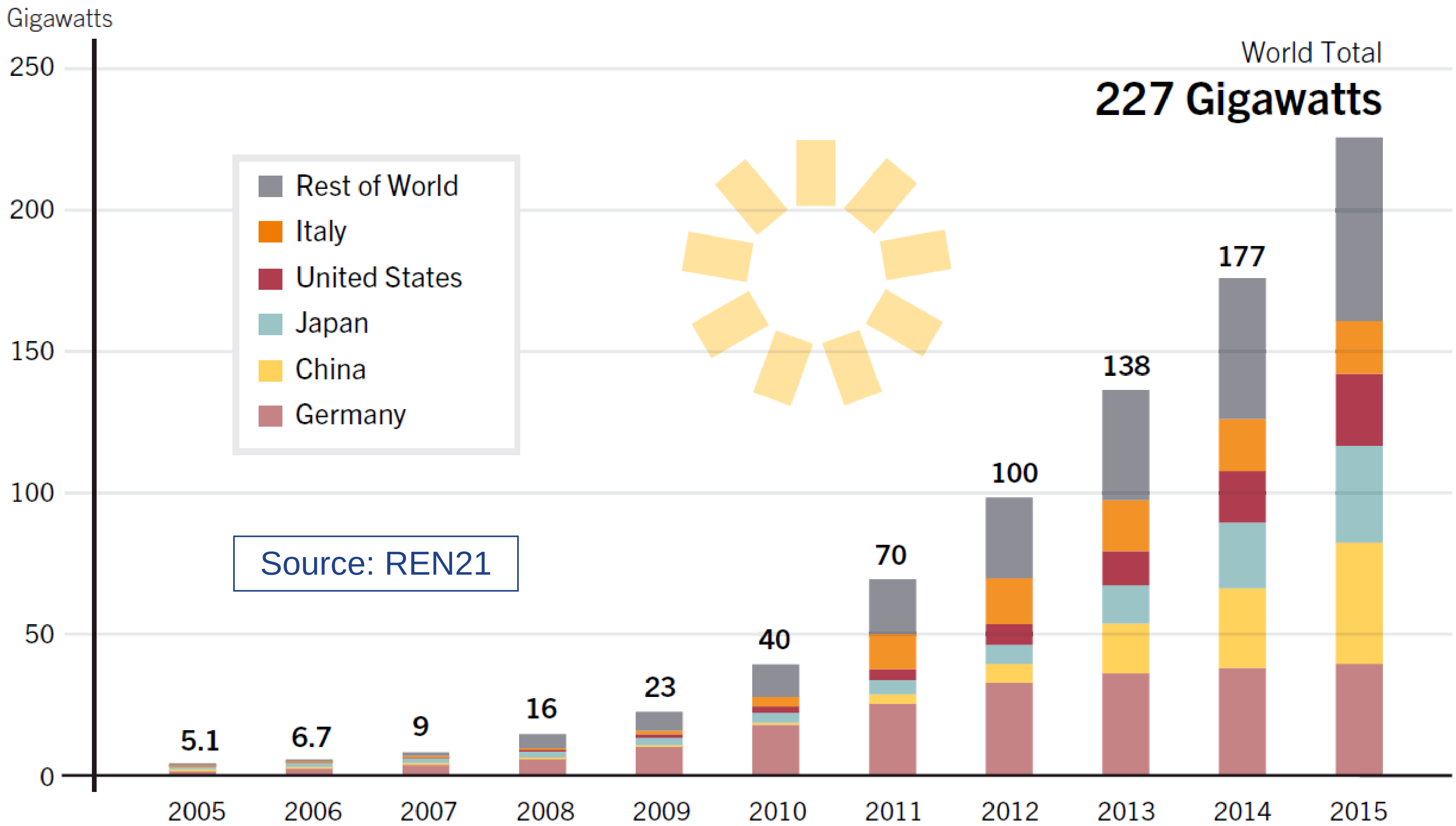
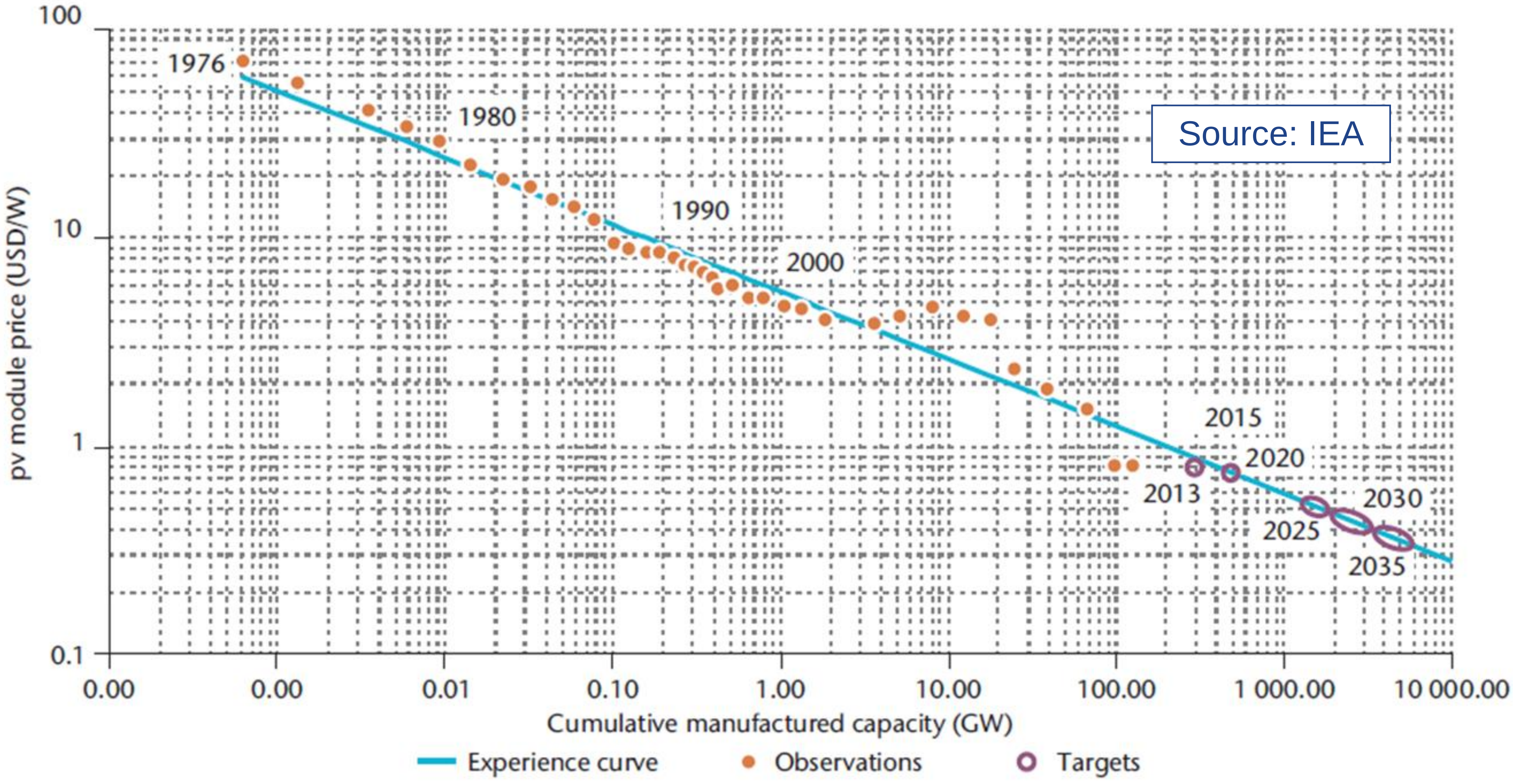
# Motivation and scope I – PV global capacity




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-relevancy 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 VRE (Variable Renewable Energies) system integration modeling

- IMAGE
- POLES

} Recursive dynamic partial equilibrium models

- REMIND
- WITCH

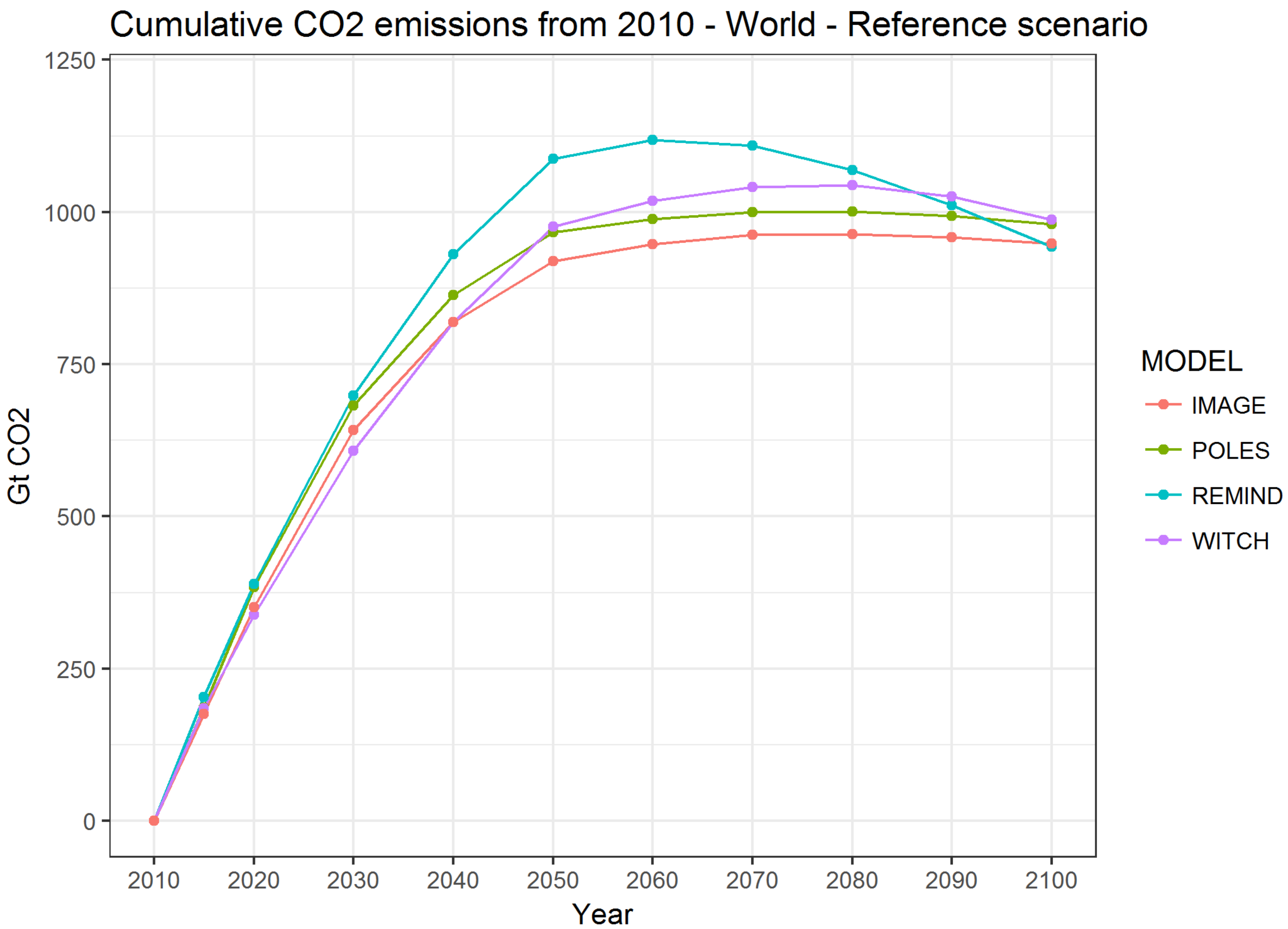
} Intertemporal optimal-growth general equilibrium models

**In this presentation** → Preliminary analysis of the first submission results

# 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 → 2°C


Cumulative CO2 emissions from 2010 - World - Reference scenario
1250
1000
750
500
250
0
Gt CO2
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
MODEL
IMAGE
POLES
REMIND
WITCH

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

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

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

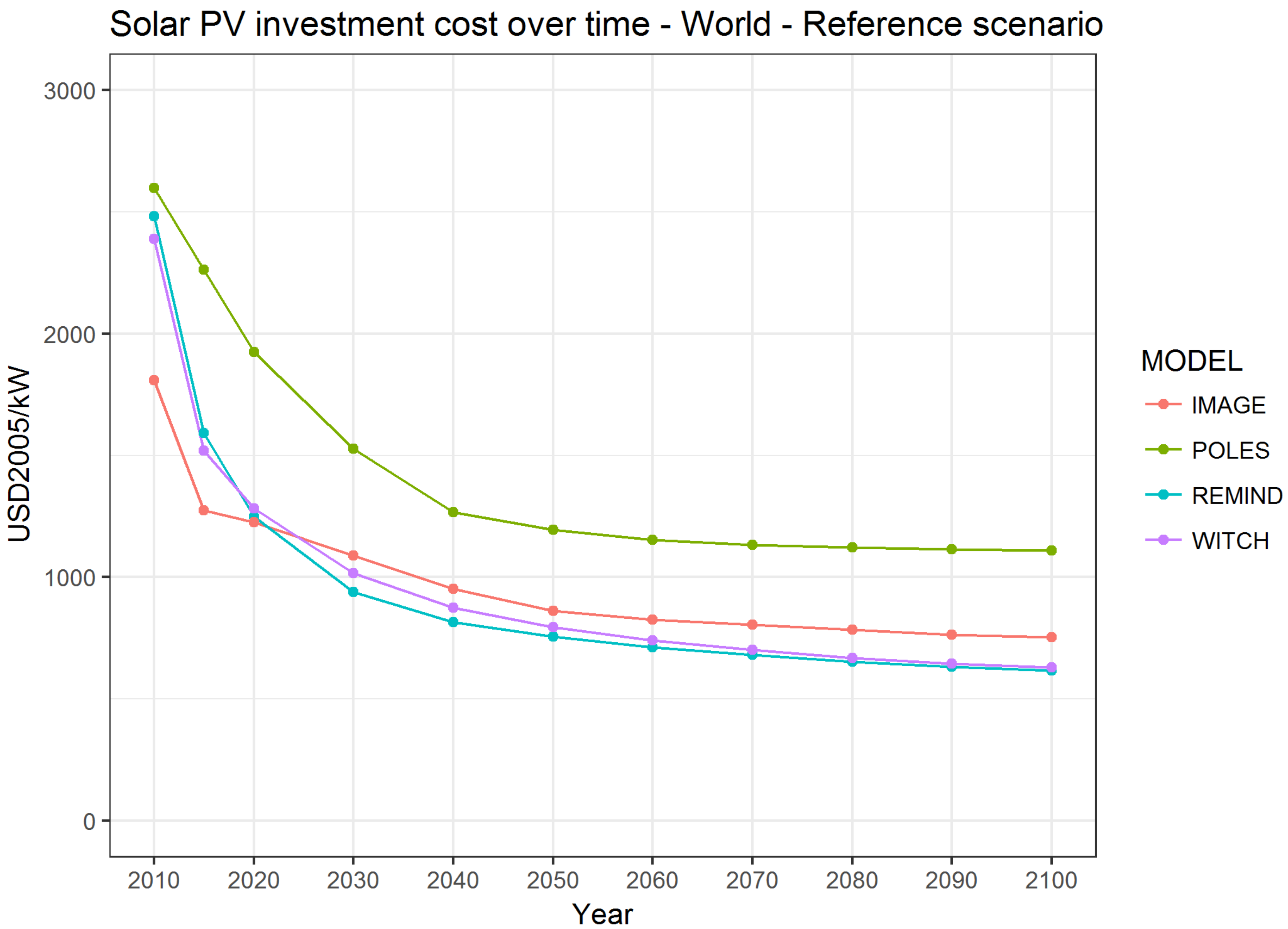
Floor cost: soft bound

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

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

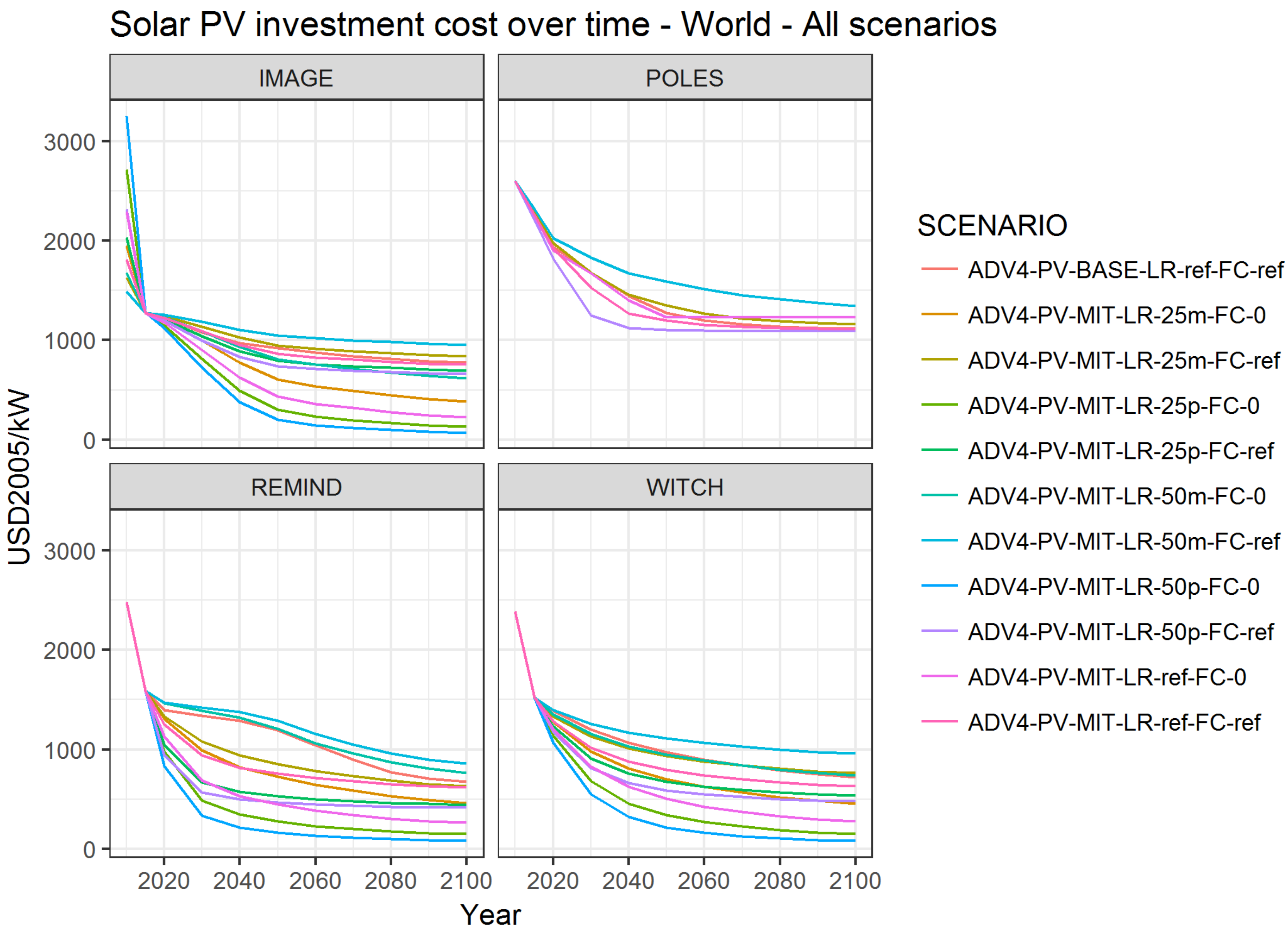
# Modeling assumptions (stocktaking)

| | 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 |


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

# PV investment costs (Reference scenario) – Comments

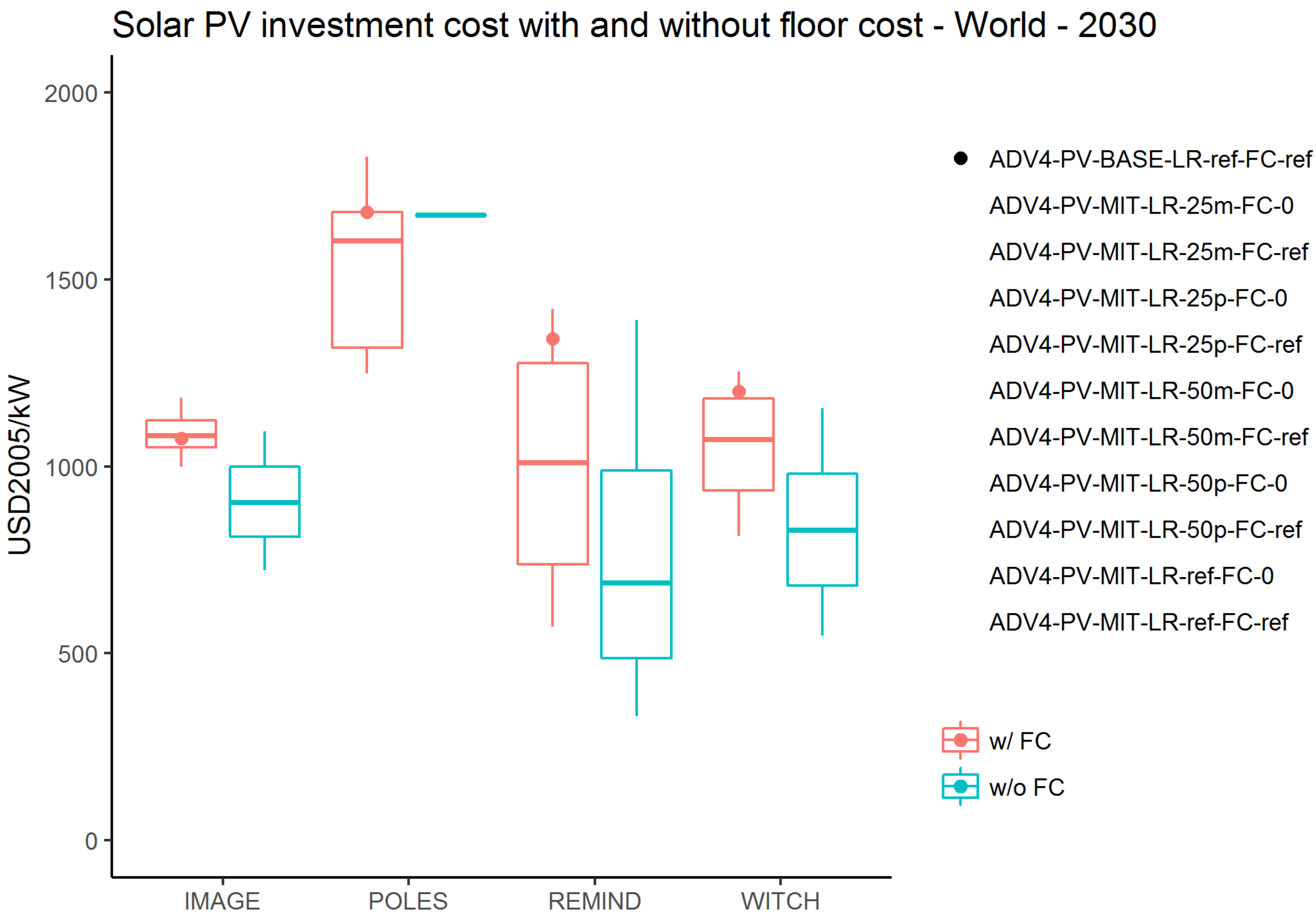
- In general, good calibration across models in 2010 and 2015, but IMAGE appears too low in 2010, POLES too high in 2015.
- The evolution over time is markedly higher in POLES with respect to the other models which are mutually in line, instead.

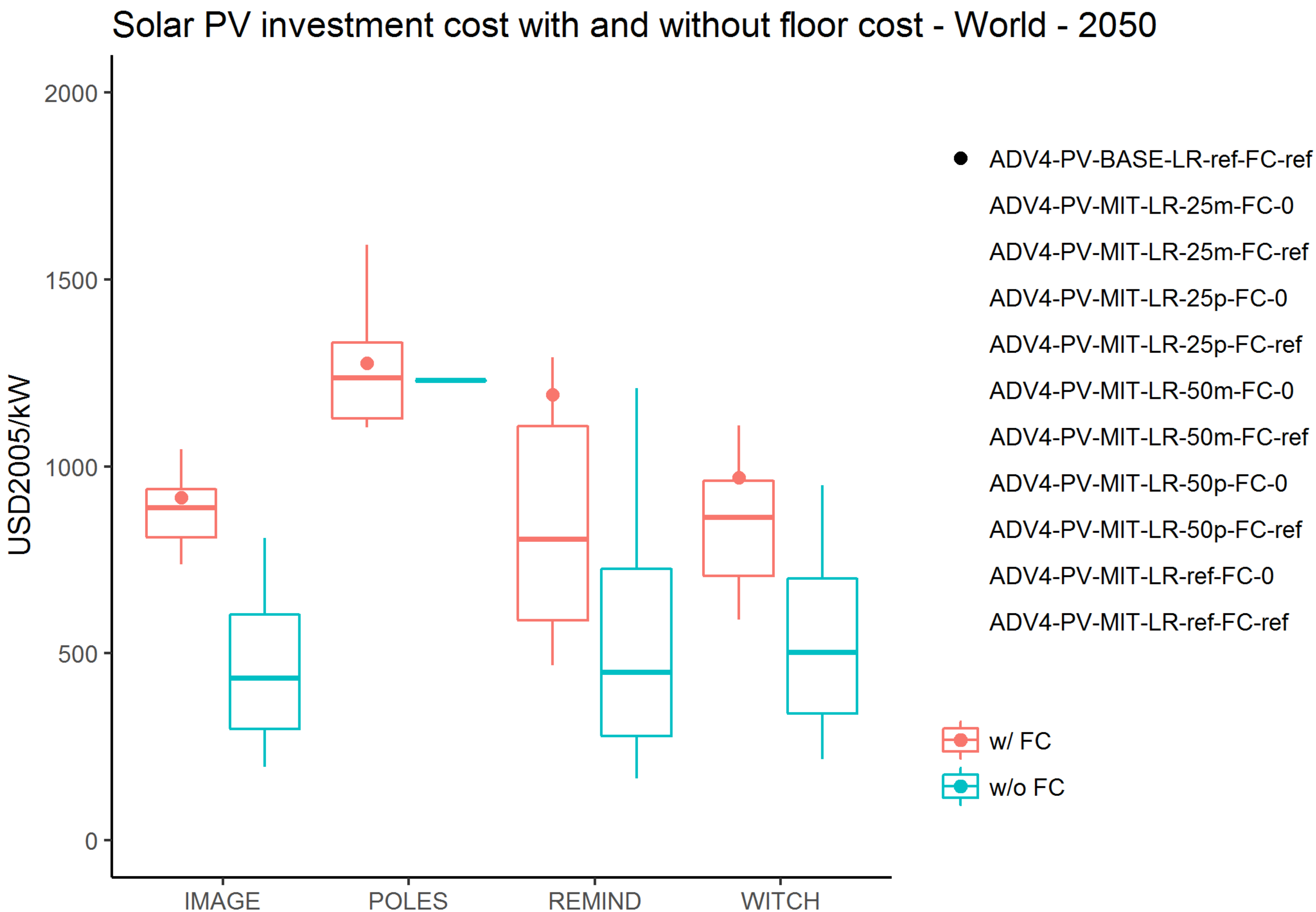


Solar PV investment cost over time - World - All scenarios
IMAGE
POLES
REMIND
WITCH
USD2005/kW
0
1000
2000
3000
2020
2040
2060
2080
2100
Year
SCENARIO
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0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

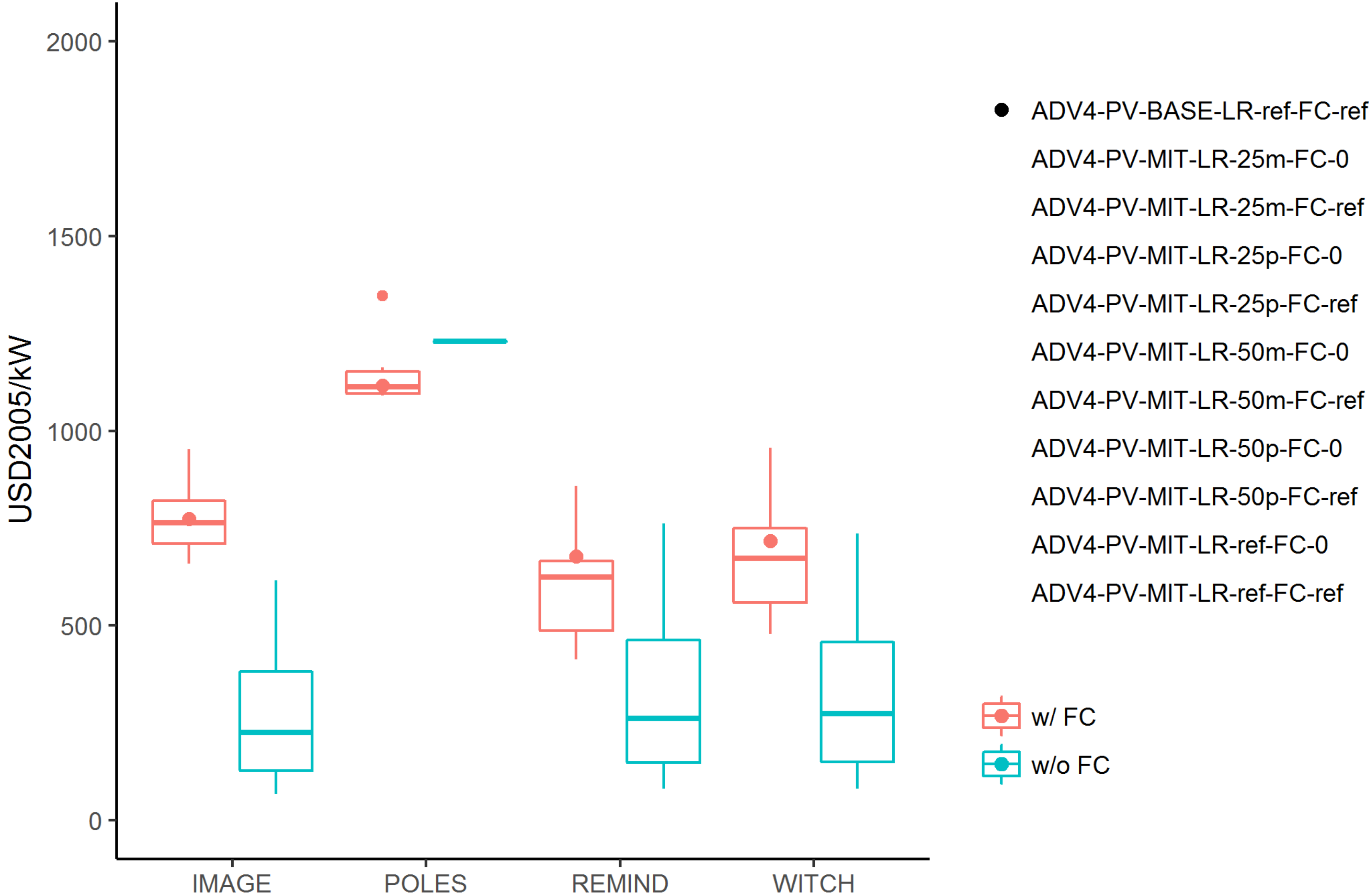
# PV investment costs (all scenarios) – Comments

- A problematic behavior is found in POLES, as all scenarios without floor cost i) report the very same cost pattern, which cannot be, and ii) do have a hard floor cost → implementation issues.
- Graphs show that the PV cost evolution across scenarios in IMAGE, REMIND, and WITCH is coherent: all models span a range of about 80-1000 USD/kW in 2100.


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

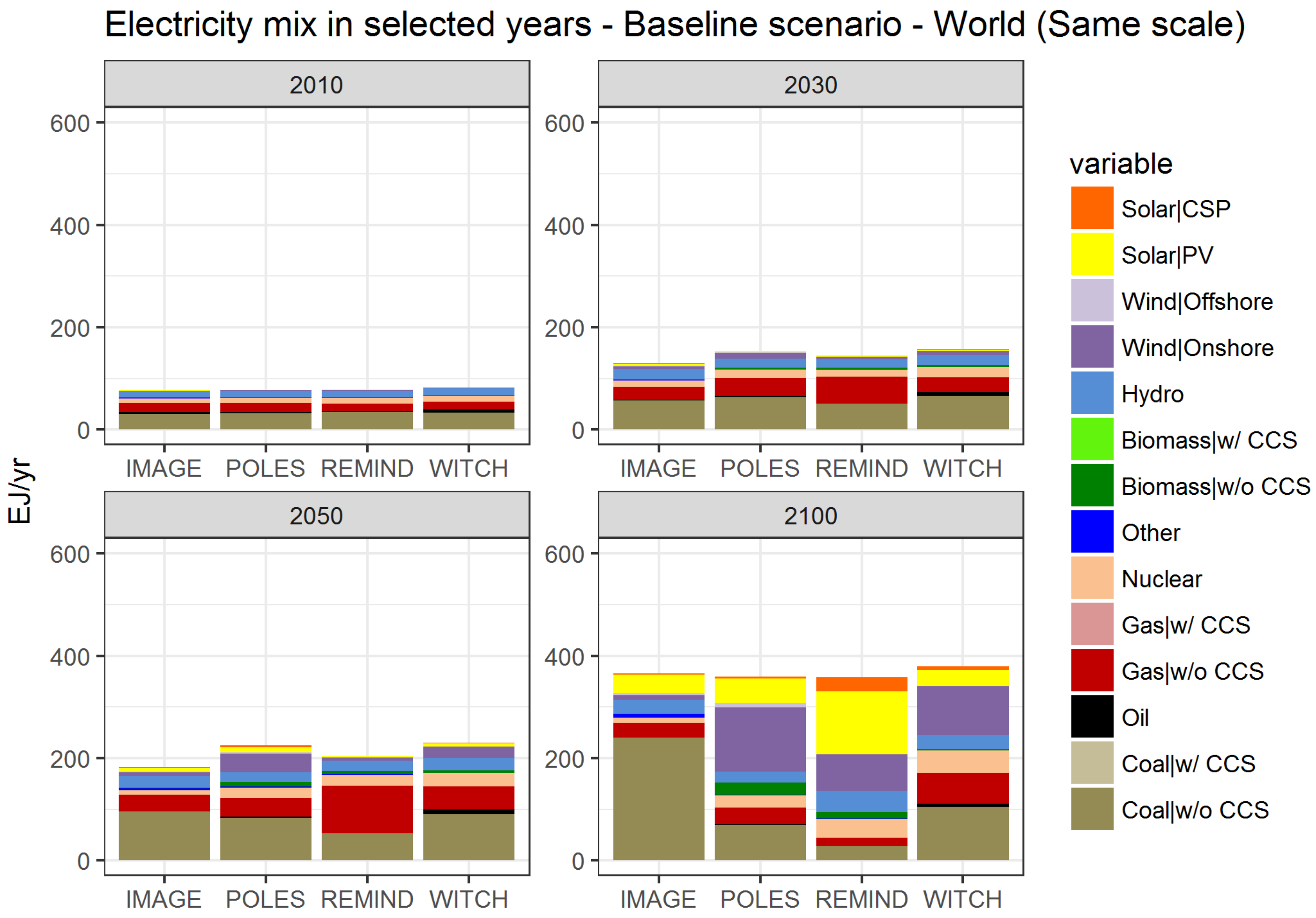

Solar PV investment cost with and without floor cost - World - 2050
USD2005/kW
0
500
1000
1500
2000
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref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



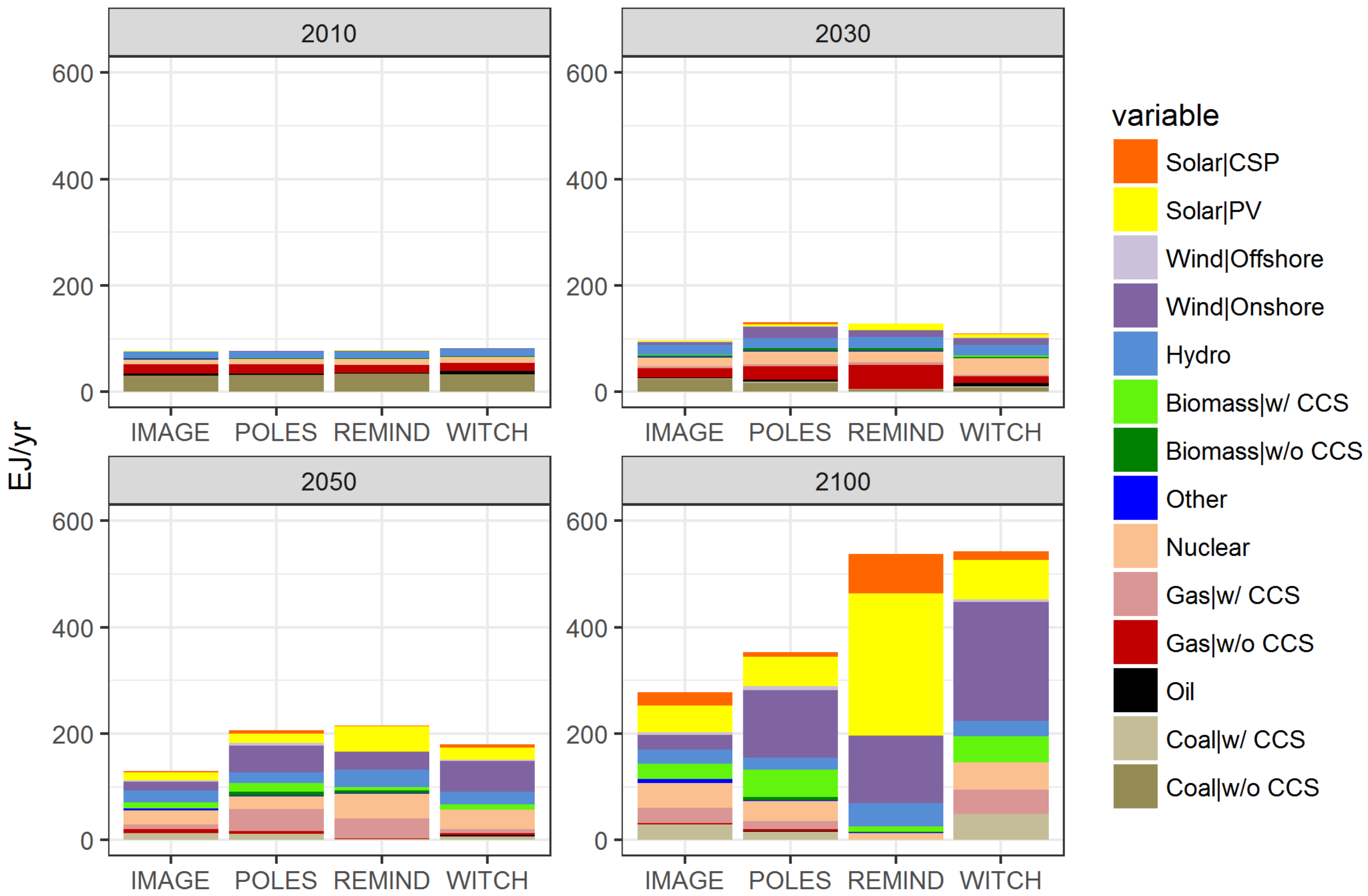
# PV investment costs (box plot) – Comments

- This graph allows analyzing the cost “width” across scenarios, distinguishing between the cases with and without floor cost.
- The dot represents the baseline case; the box plots refer to the mitigation cases: the line extremes are the ±50% cases, the rectangle edges are the ±25% cases, while the “median” is the reference case.
- The graph highlights the cost issues in POLES.
- Apart from POLES, the distribution is most compact in IMAGE, then comes WITCH and finally REMIND.
- As already noted, the latter three models are substantially in line with each other.



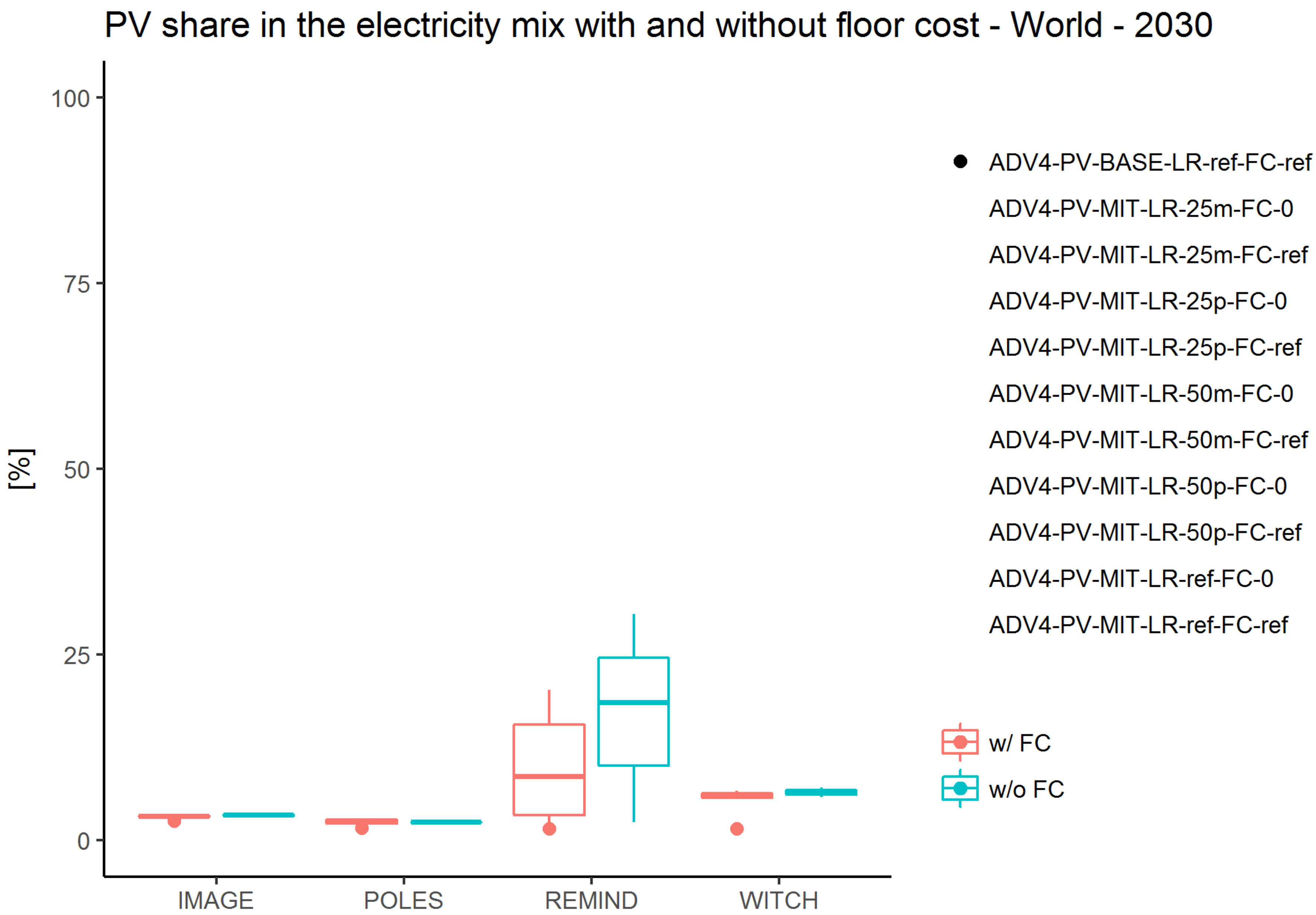
Electricity mix in selected years - Baseline scenario - World (Same scale)
2010
2030
2050
2100
EJ/yr
600
400
200
0
IMAGE
POLES
REMIND
WITCH
variable
Solar|CSP
Solar|PV
Wind|Offshore
Wind|Onshore
Hydro
Biomass|w/ CCS
Biomass|w/o CCS
Other
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS

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

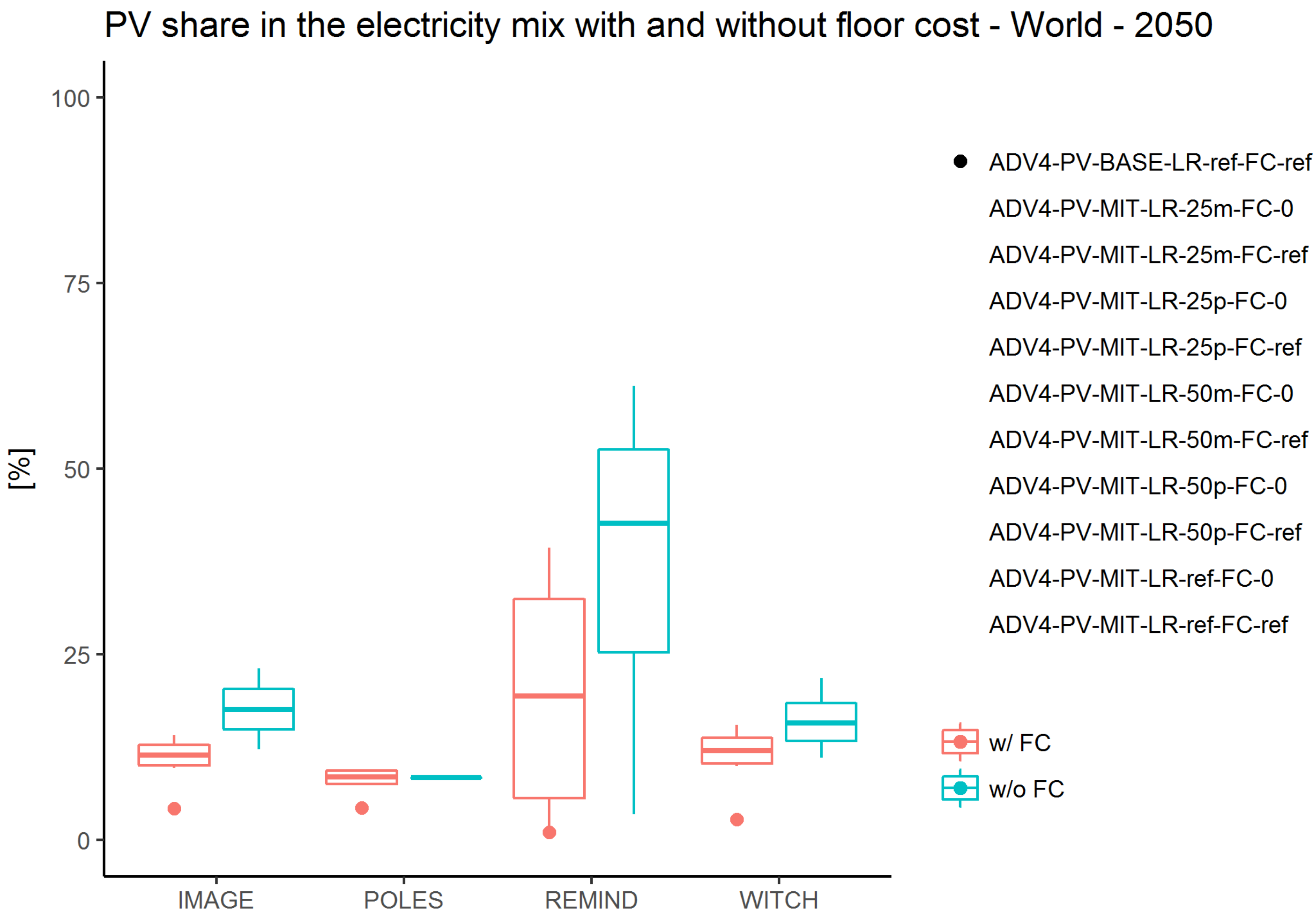


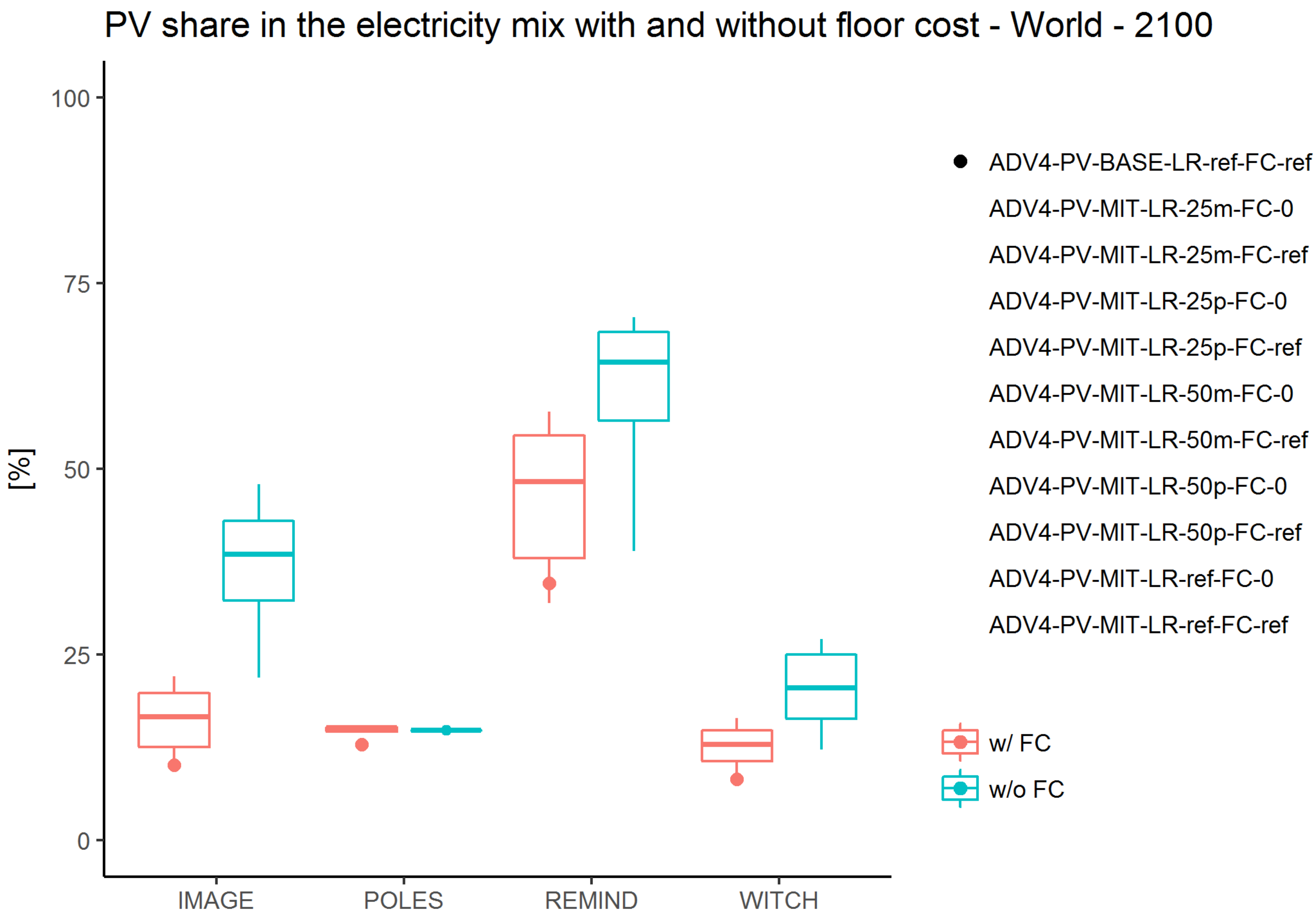
# Electricity mix (Base. and Ref. scenarios) – Comments

- Compared to the baseline scenario, in the reference scenario the total electricity generation decreases in IMAGE, it remains substantially constant in POLES, while it increases in REMIND and WITCH → energy efficiency vs. electrification
- Despite the cost evolution similarities, PV penetration in REMIND is way higher than in the other models, which are mutually similar.



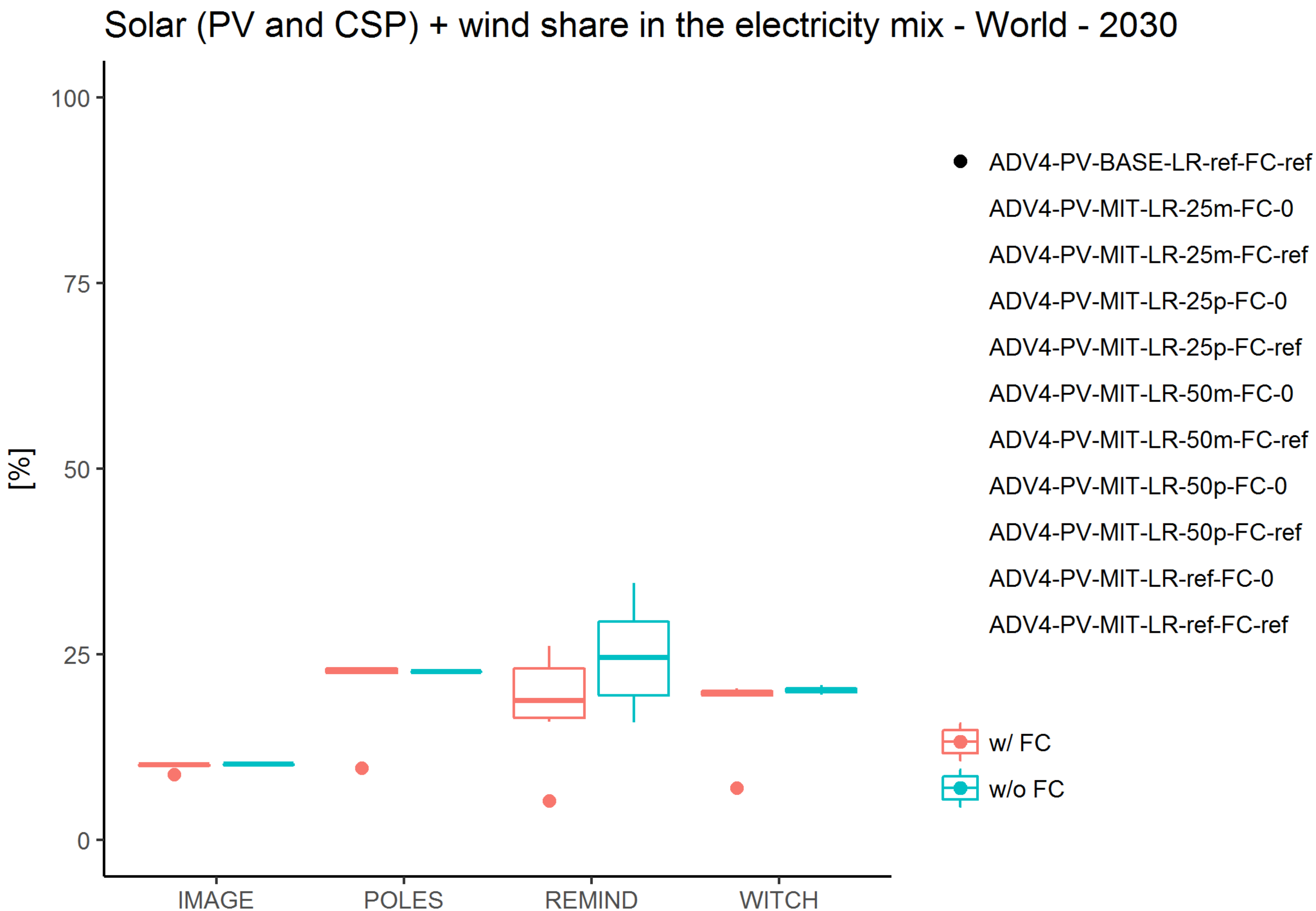
PV share in the electricity mix with and without floor cost - World - 2030
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0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

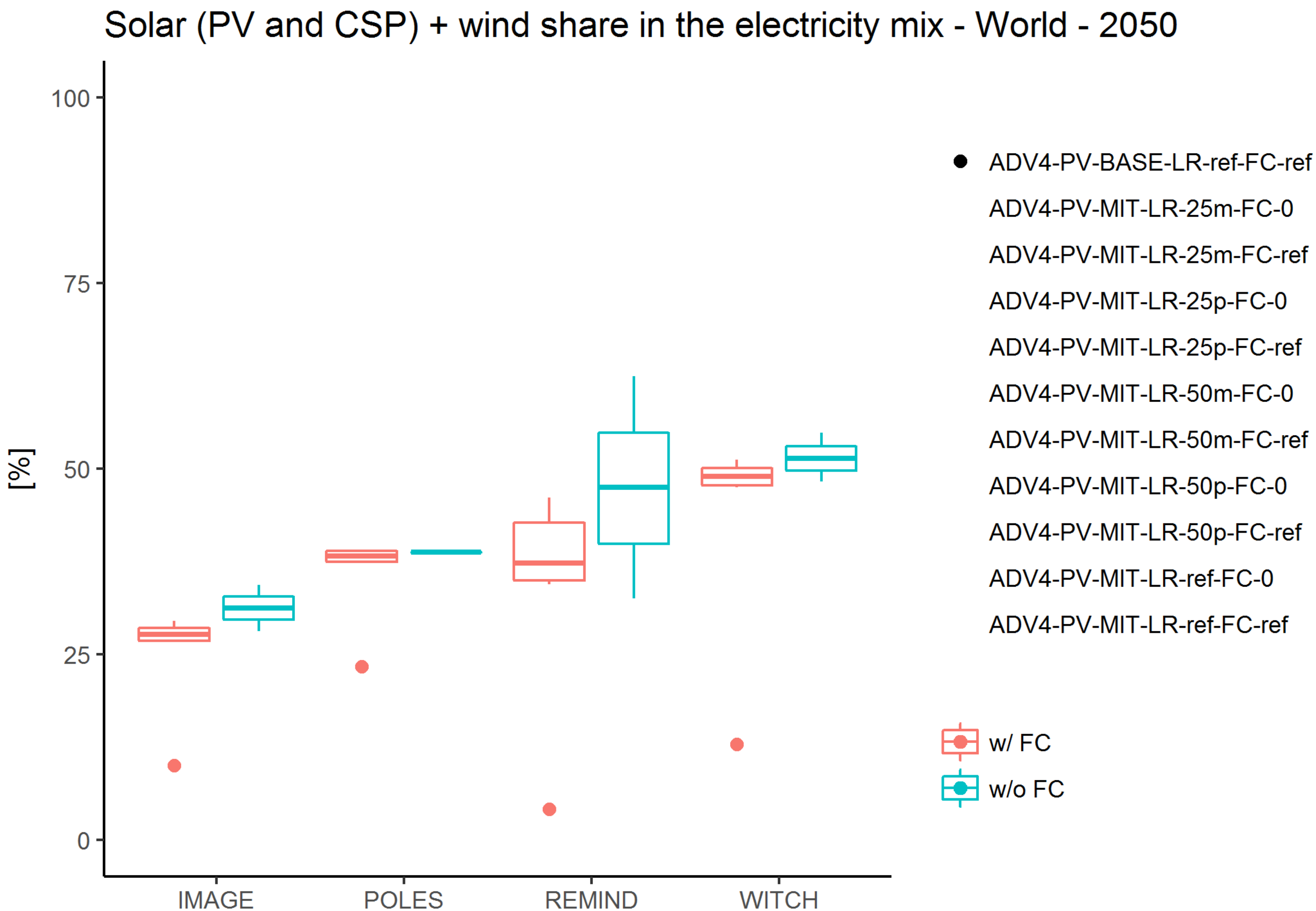

PV share in the electricity mix with and without floor cost - World - 2100
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0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

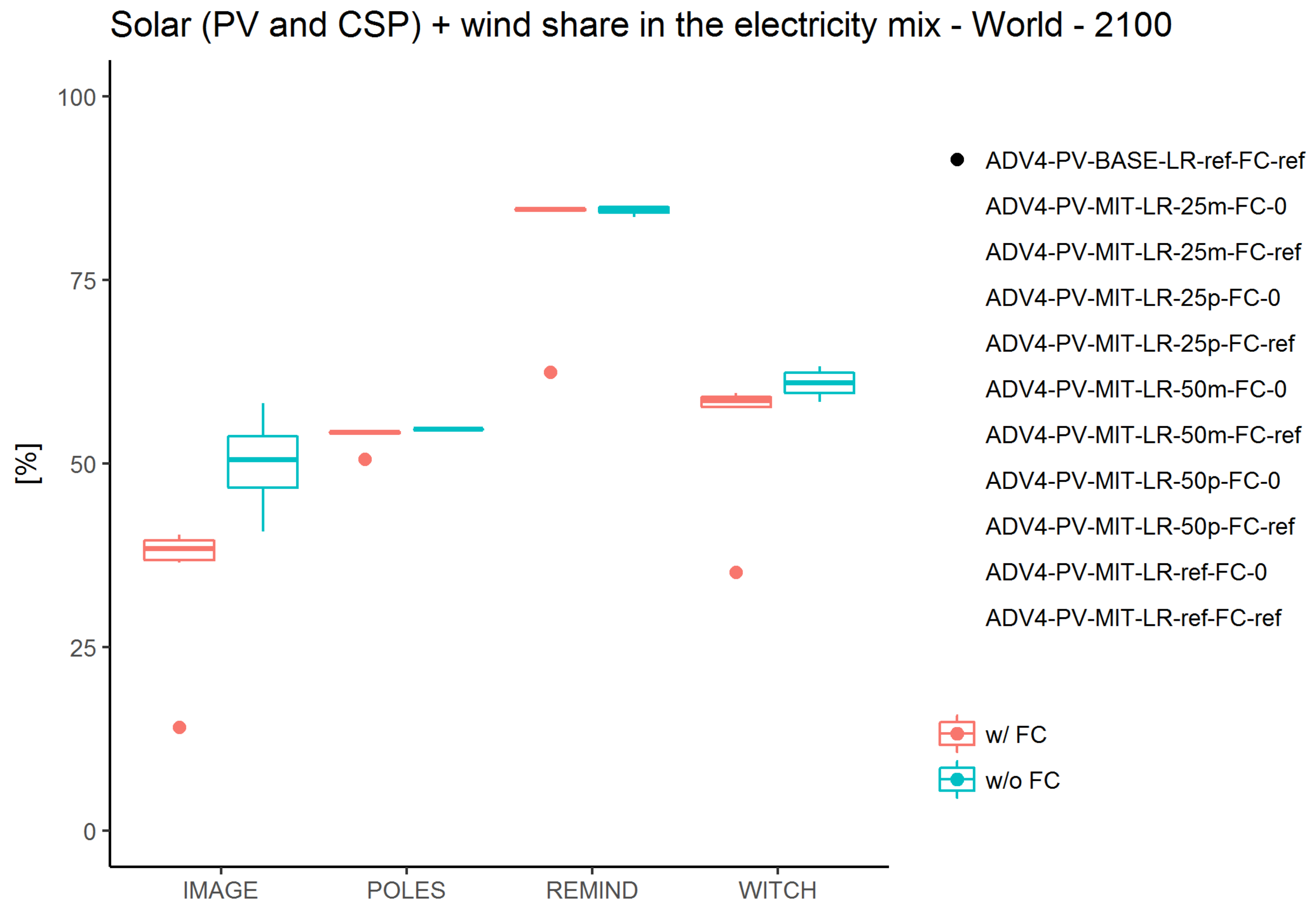
# PV share – Comments

- PV penetration is obviously higher without floor cost, except for POLES.
- As said, REMIND shows the highest PV share across models. Then we have IMAGE, WITCH, and finally POLES.
- The same "model rank" applies to sensitivity as well: REMIND shows the largest one (especially in 2050, while this diminishes in 2100), followed by IMAGE, WITCH, and finally POLES.
- In particular, REMIND shows sensitivity to the learning rate already in 2030, while all the other models show differences in penetration in 2050 and 2100 only.
- POLES is basically insensitive to the different learning rates.
- IMAGE shows the highest sensitivity to the removal of the floor cost.



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

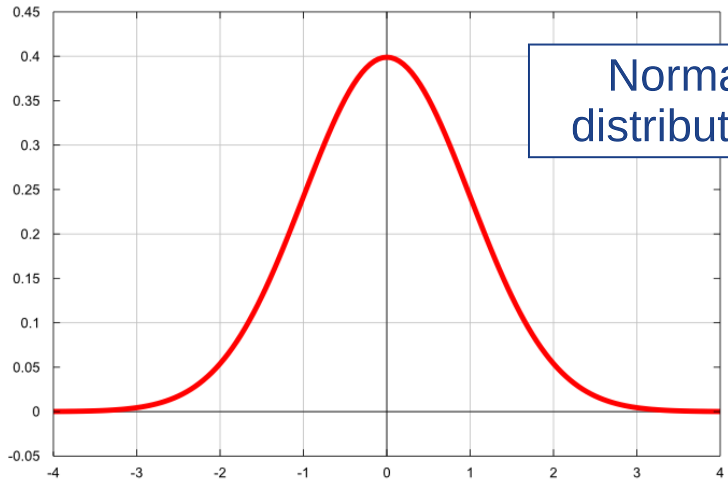

Solar (PV and CSP) + wind share in the electricity mix - World - 2050
100
75
50
25
0
[%]
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0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



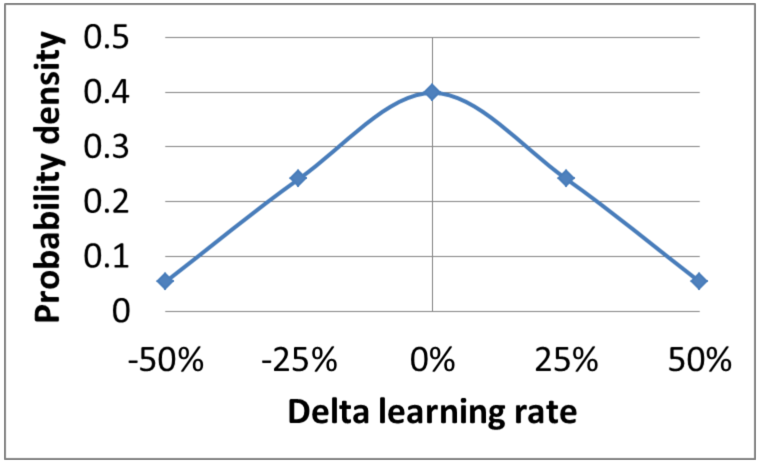
Solar (PV and CSP) + wind share in the electricity mix - World - 2100
[%]
100
75
50
25
0
IMAGE
POLES
REMIND
WITCH
ADV4-PV-BASE-LR-ref-FC-ref
ADV4-PV-MIT-LR-25m-FC-0
ADV4-PV-MIT-LR-25m-FC-ref
ADV4-PV-MIT-LR-25p-FC-0
ADV4-PV-MIT-LR-25p-FC-ref
ADV4-PV-MIT-LR-50m-FC-0
ADV4-PV-MIT-LR-50m-FC-ref
ADV4-PV-MIT-LR-50p-FC-0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

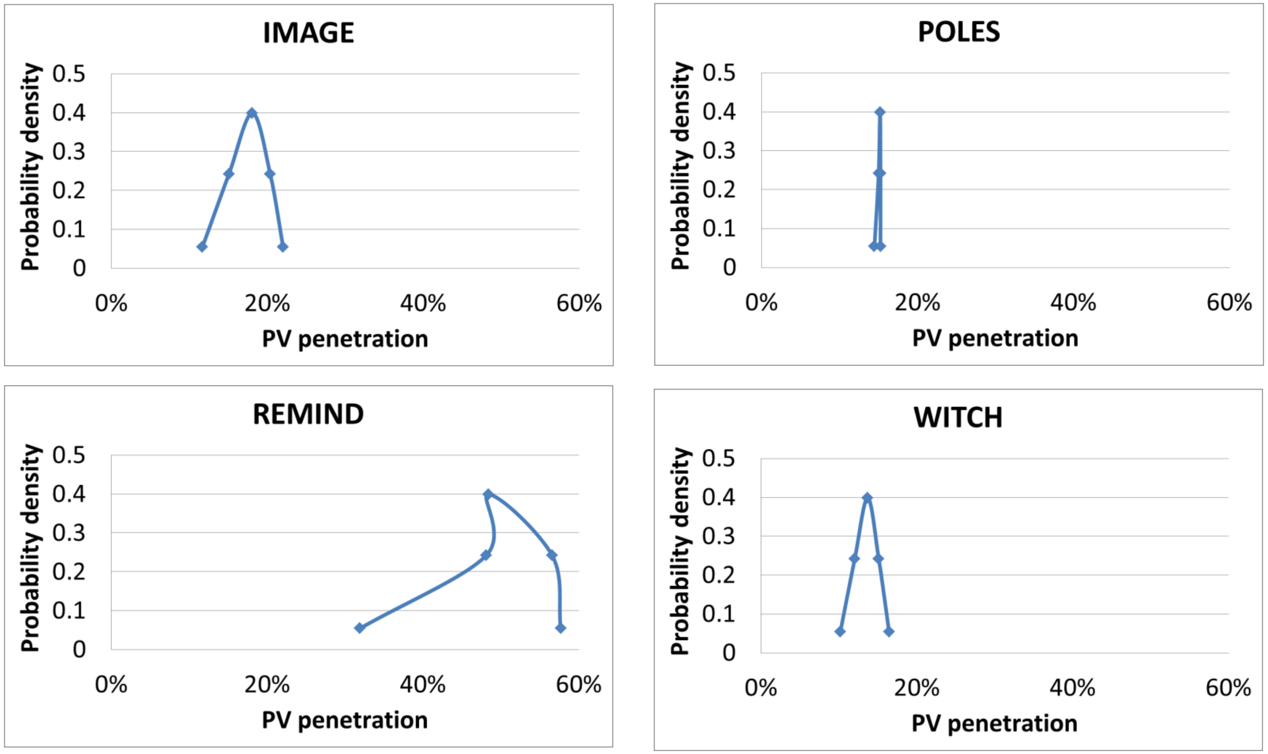
# PV + CSP + wind share – Comments

- If we sum solar PV, CSP and wind, the sensitivity markedly reduces in all models, except partly for IMAGE.
- A similar behavior (though less “extreme”) would be found if we considered wind only.
- This means that the higher/lower PV penetration associated to the different learning rates primarily occurs to the detriment/benefit of wind and CSP.
- This is particularly clear in WITCH, which basically shows no sensitivity (similarly to POLES, but the latter did not show sensitivity in the PV penetration alone either).
- In particular, REMIND seems to have reached a “Variable Renewable Energy threshold” around 80-85% in 2100.
- The same substantially applies to POLES (~ 55%) and WITCH (~ 60%).




Normal distribution

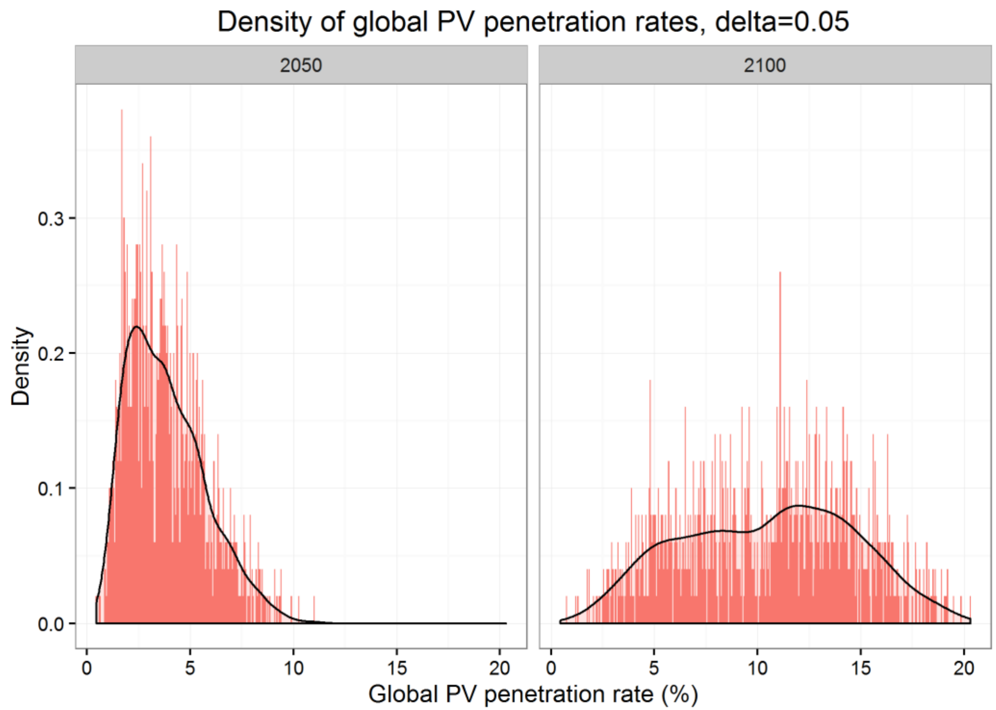



PV share in the ref. case World 2100

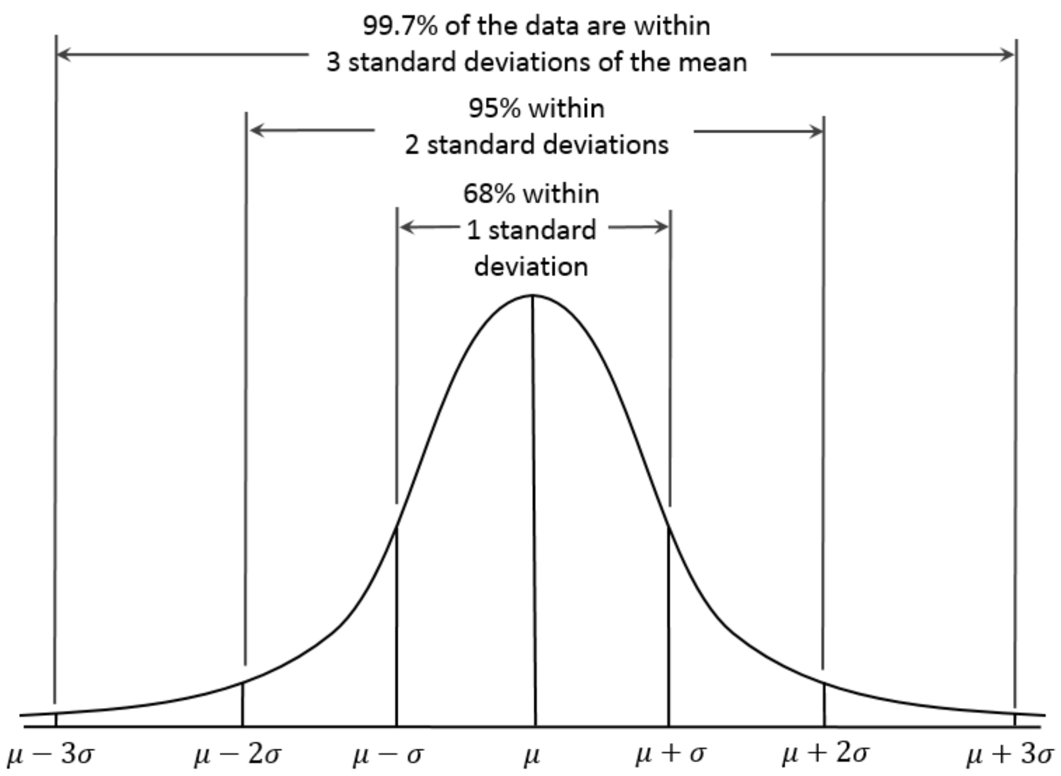
# Statistical analysis

- 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.

# THANK YOU
# FOR YOUR ATTENTION

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