



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

Samuel Carrara (... and many others!)

Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

Renewable & Appropriate Energy Laboratory (RAEL), Energy & Resources Group (ERG), University of California, Berkeley, USA

International Association for Energy Economics (IAEE) – 15th European Conference
September 3-6, 2017 – Hofburg Congress Center, Vienna, Austria



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

List of authors

Carrara S.^{1,2,3}, Bevione M.^{1,4}, de Boer H.S.⁵, Gernaat D.⁵, Mima S.⁶, Pietzcker R.C.⁷, and Tavoni M.^{1,2,8}

¹ Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

² Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy

³ Renewable and Appropriate Energy Laboratory (RAEL) and Energy and Resources Group (ERG), University of California, Berkeley, USA

⁴ INRIA, Grenoble, France

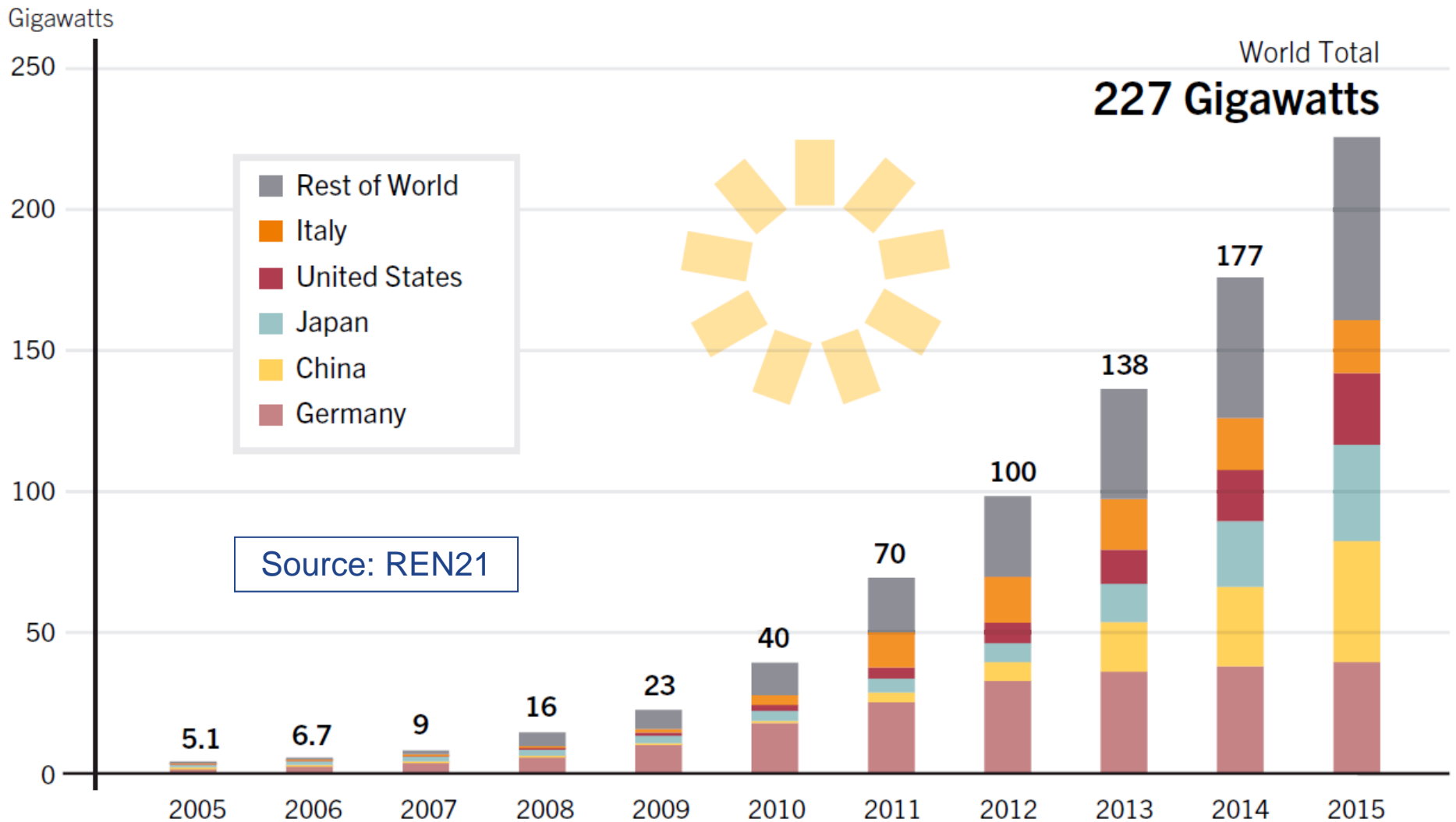
⁵ PBL Netherlands Environmental Assessment Agency, Den Haag, the Netherlands

⁶ Univ. Grenoble Alpes, CNRS, Grenoble INP, INRA, GAEL, Grenoble, France

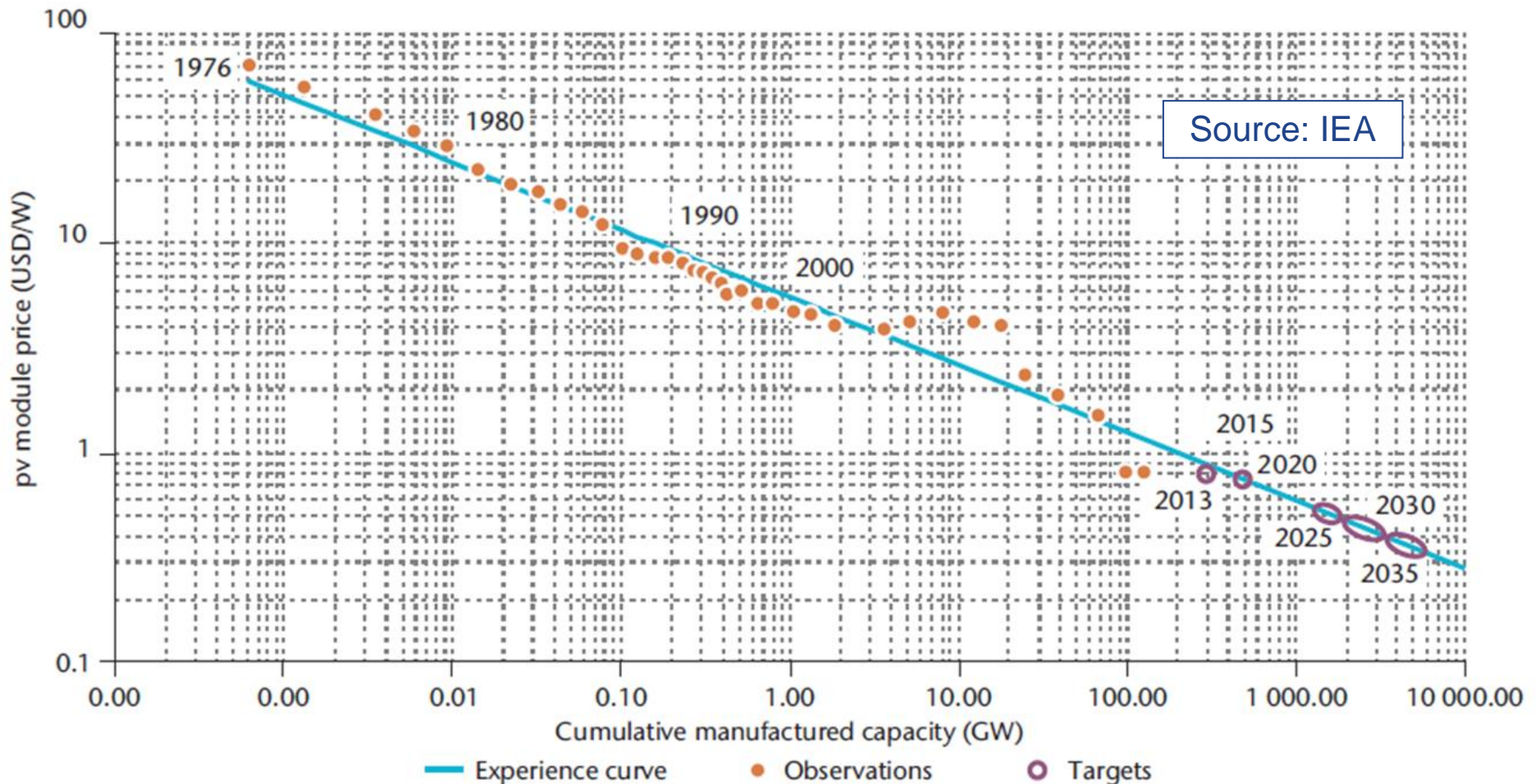
⁷ PIK Potsdam Institute for Climate Impact Research, Potsdam, Germany

⁸ Politecnico di Milano, Milan, Italy

Motivation and Scope I – PV global capacity



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 system integration modeling)

- **IMAGE**
 - **POLES**
 - **REMIND**
 - **WITCH**
- } Recursive dynamic partial equilibrium models
- } 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 GtCO₂ in 2011-2100 in the Ref-Ref scenario → 2°C

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

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

- 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

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 $\rightarrow b = \mu \pm \sigma = -0.254 \pm 0.058$



Learning Rate

- 1) $\mu = 19.25\%$
- 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)

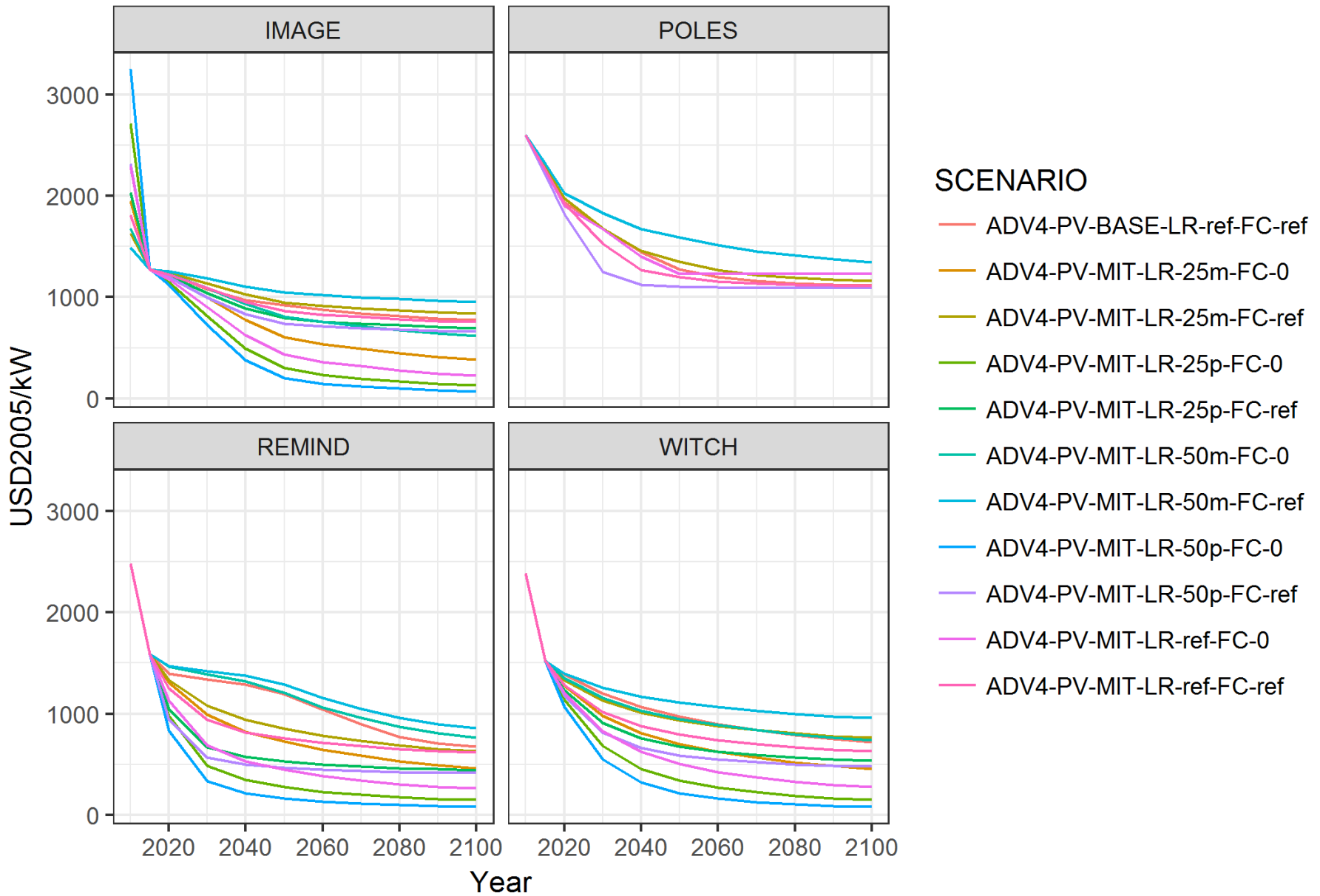


Thus the $\pm 25\%$ and $\pm 50\%$ sensitivity cases

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

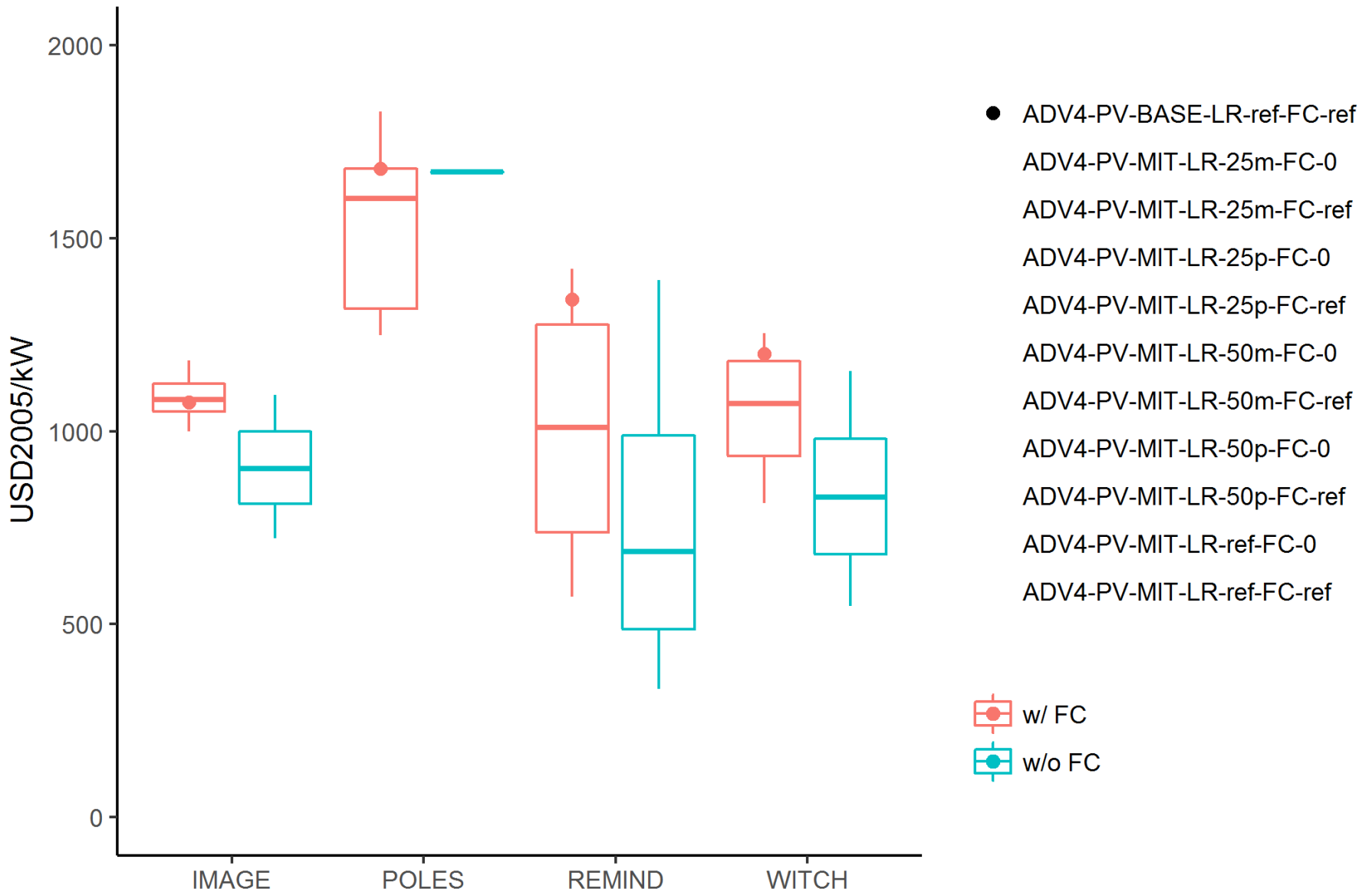
Solar PV investment cost over time - World - All scenarios



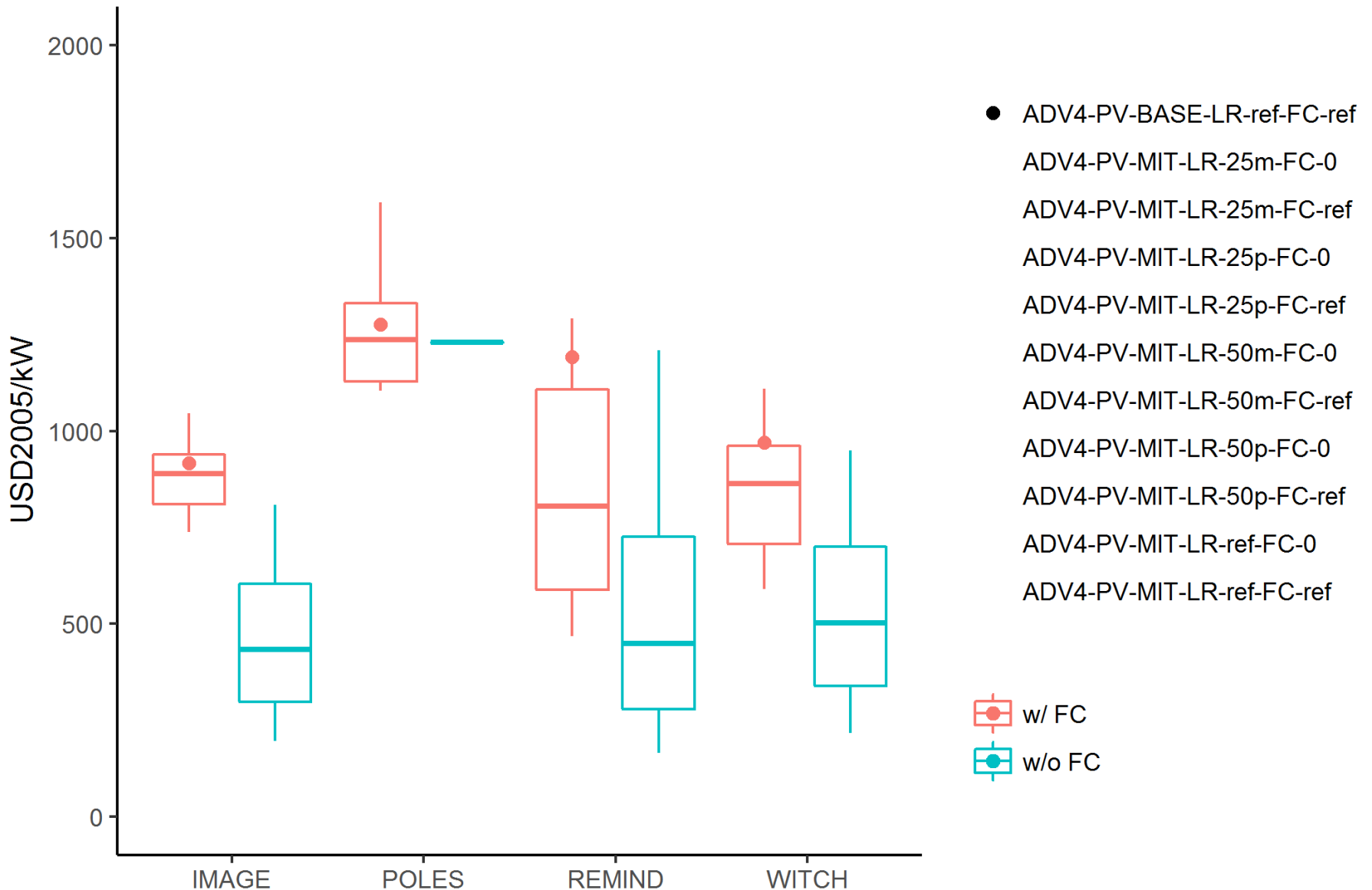
PV investment costs – Comments

- 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.

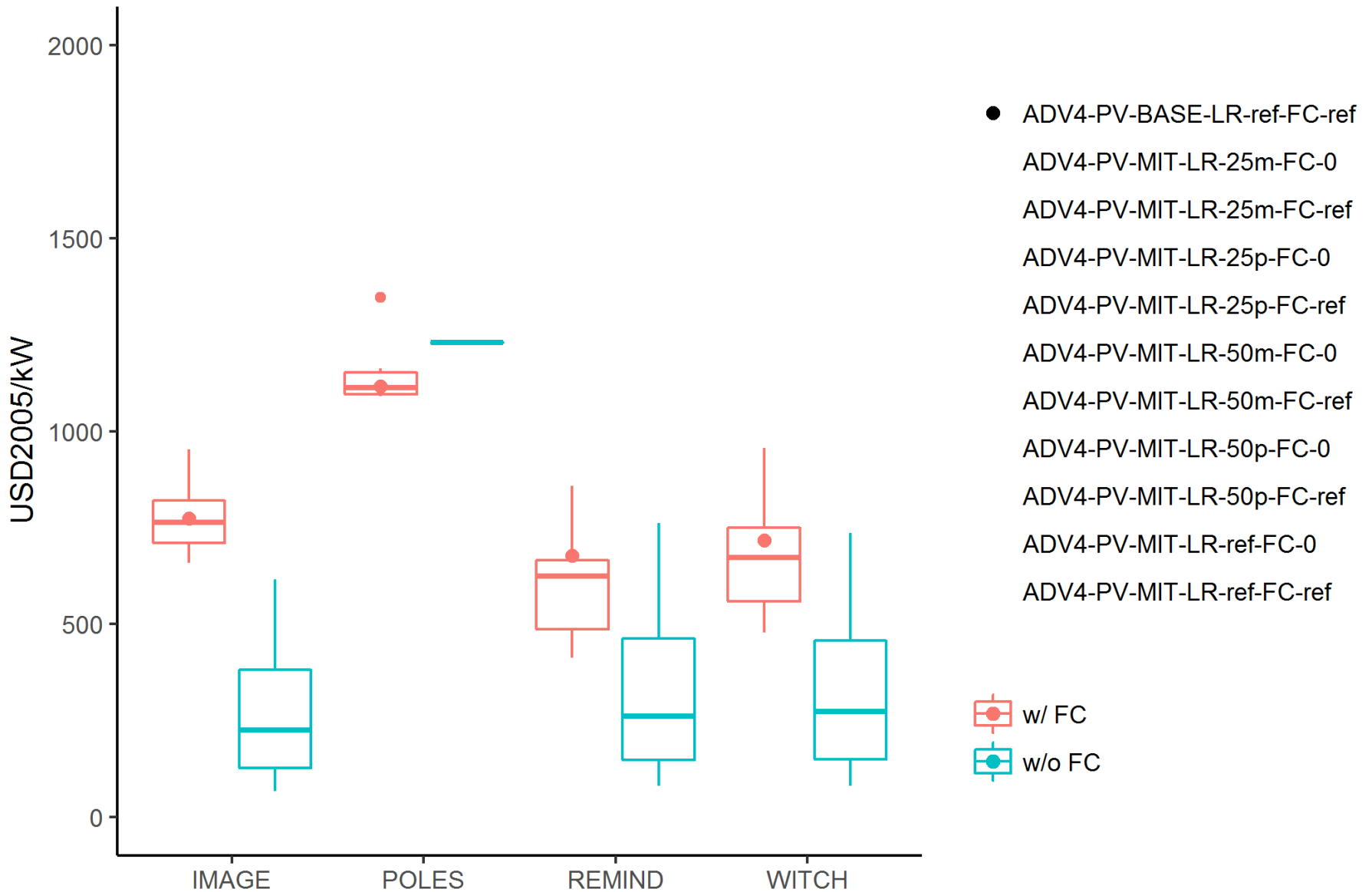
Solar PV investment cost with and without floor cost - World - 2030



Solar PV investment cost with and without floor cost - World - 2050



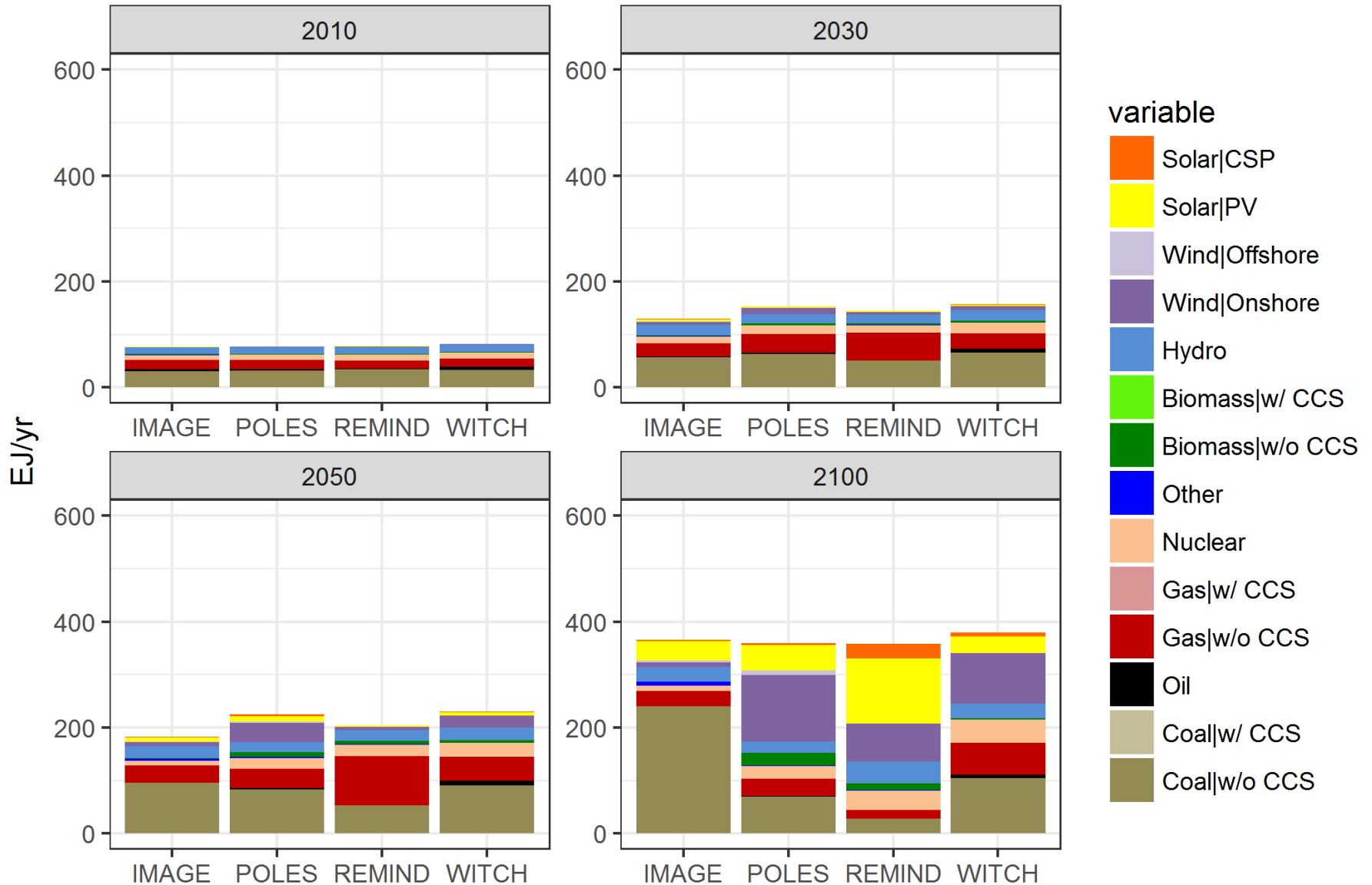
Solar PV investment cost with and without floor cost - World - 2100



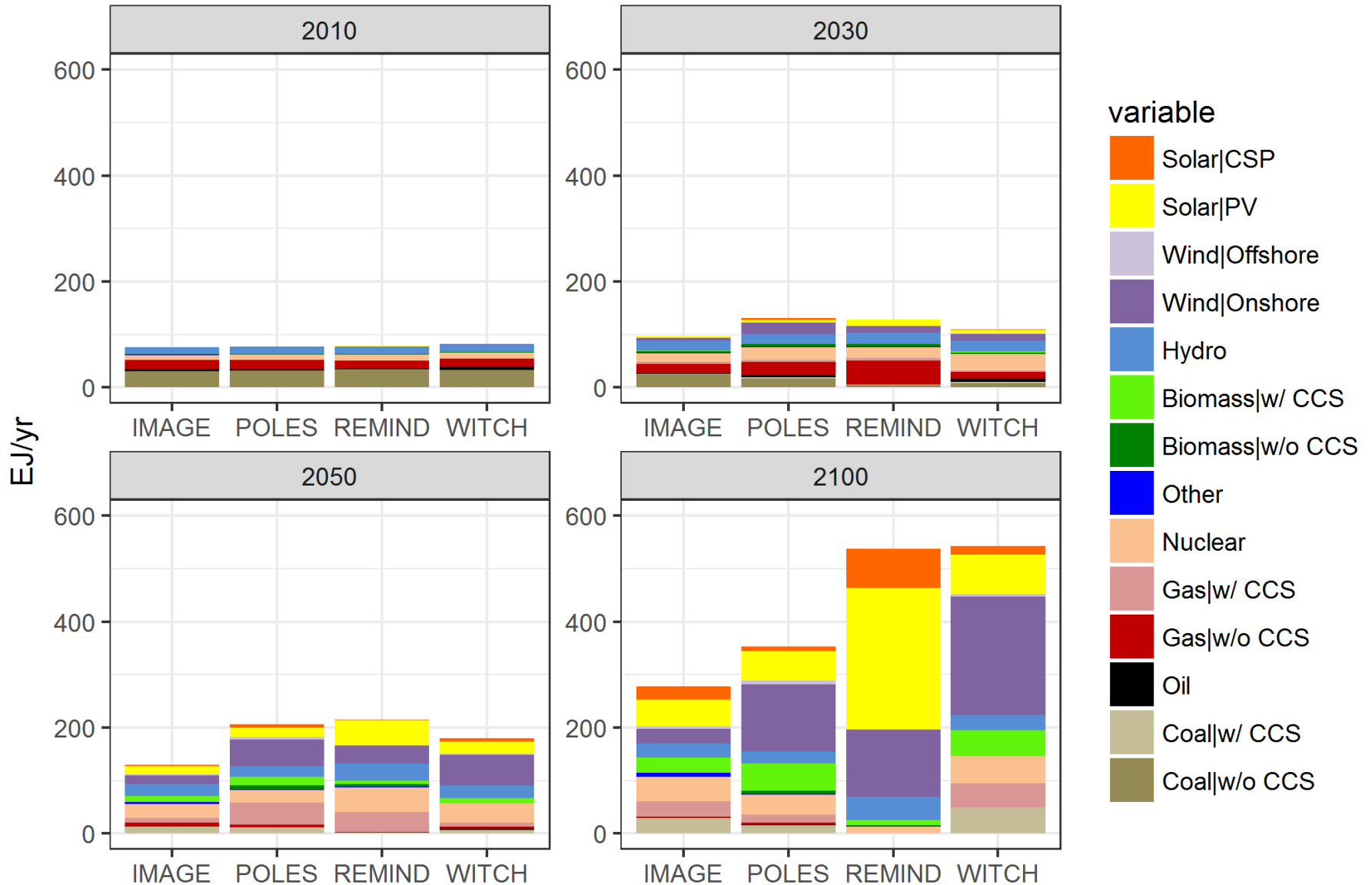
PV investment costs (box plot) – Comments

- 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 $\pm 50\%$ cases, the rectangle edges are the $\pm 25\%$ 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)



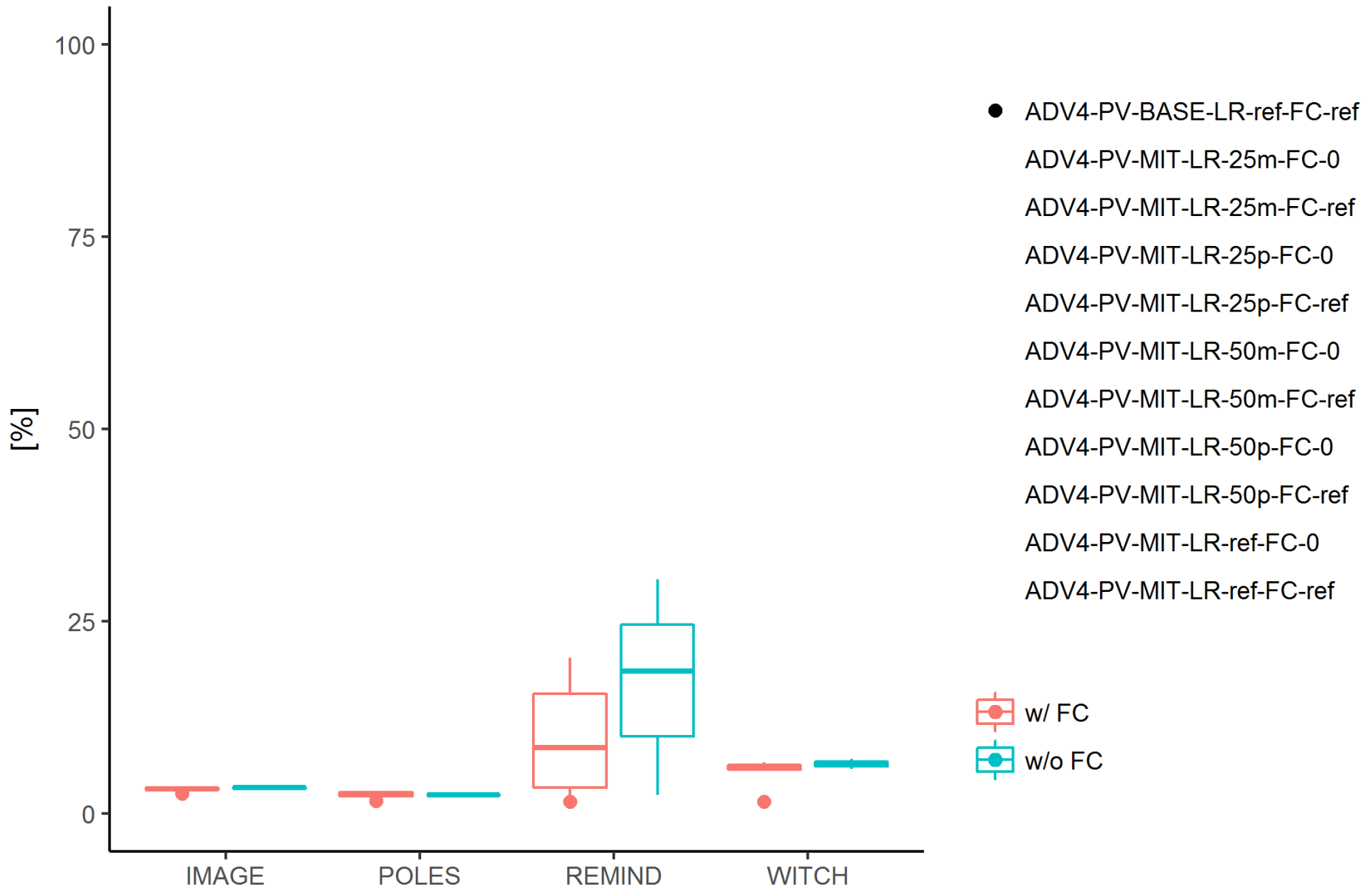
Electricity mix in selected years - Reference scenario - World (Same scale)



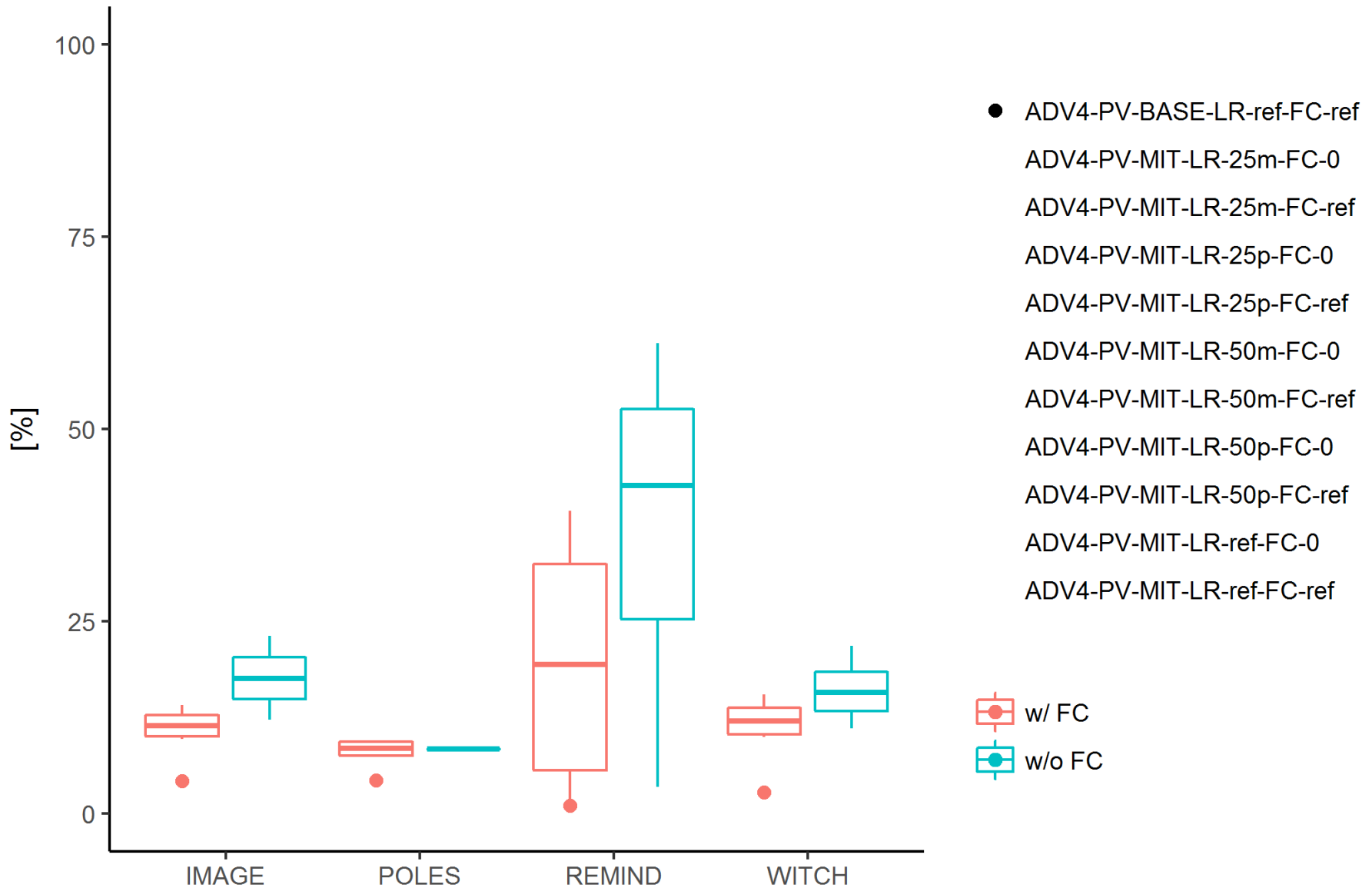
Electricity mix (Base. and Ref. scenarios) – Comments

- Compared to the baseline scenario, in the reference scenario the total electricity generation decreases in **IMAGE**, 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.

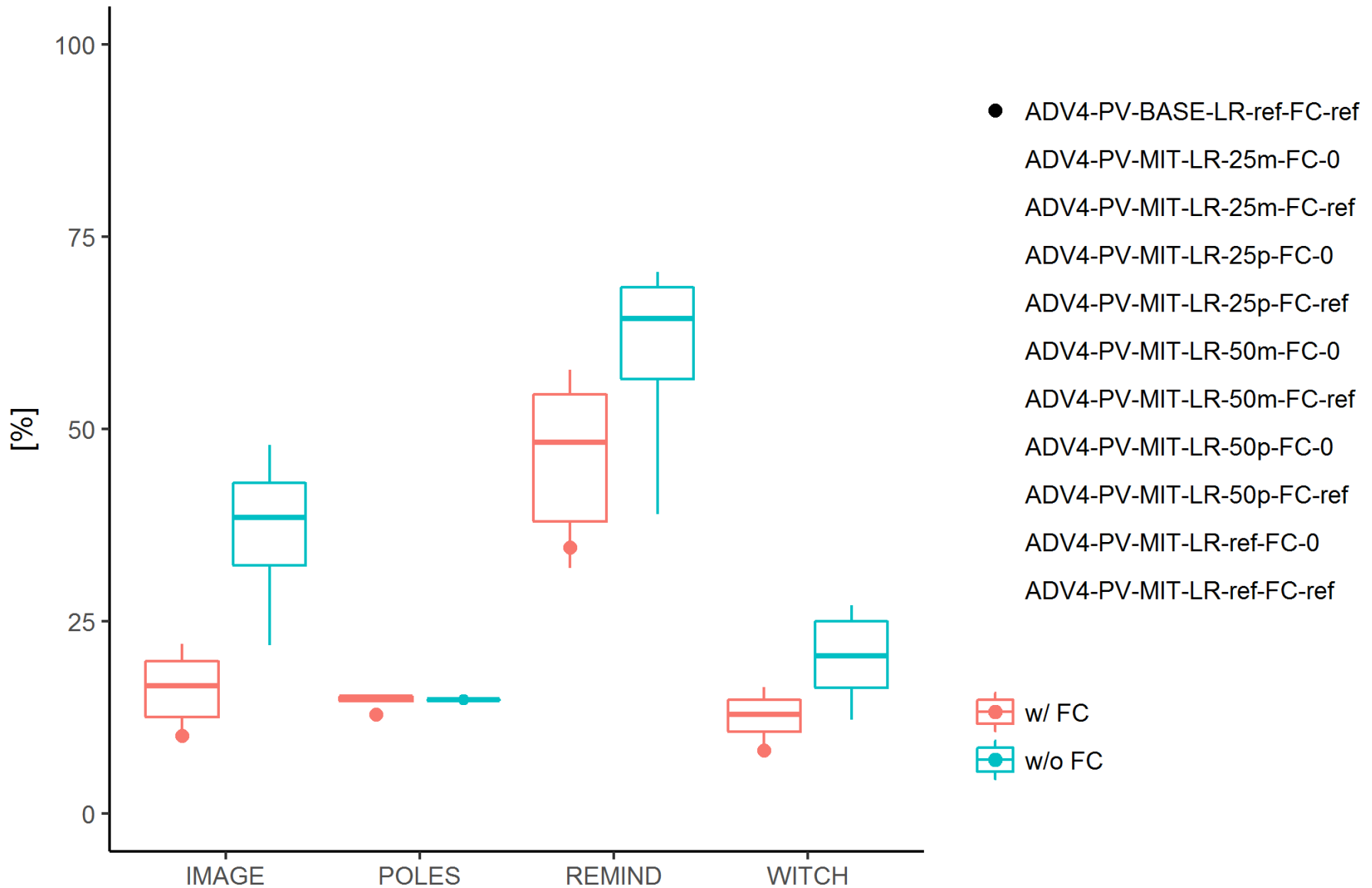
PV share in the electricity mix with and without floor cost - World - 2030



PV share in the electricity mix with and without floor cost - World - 2050



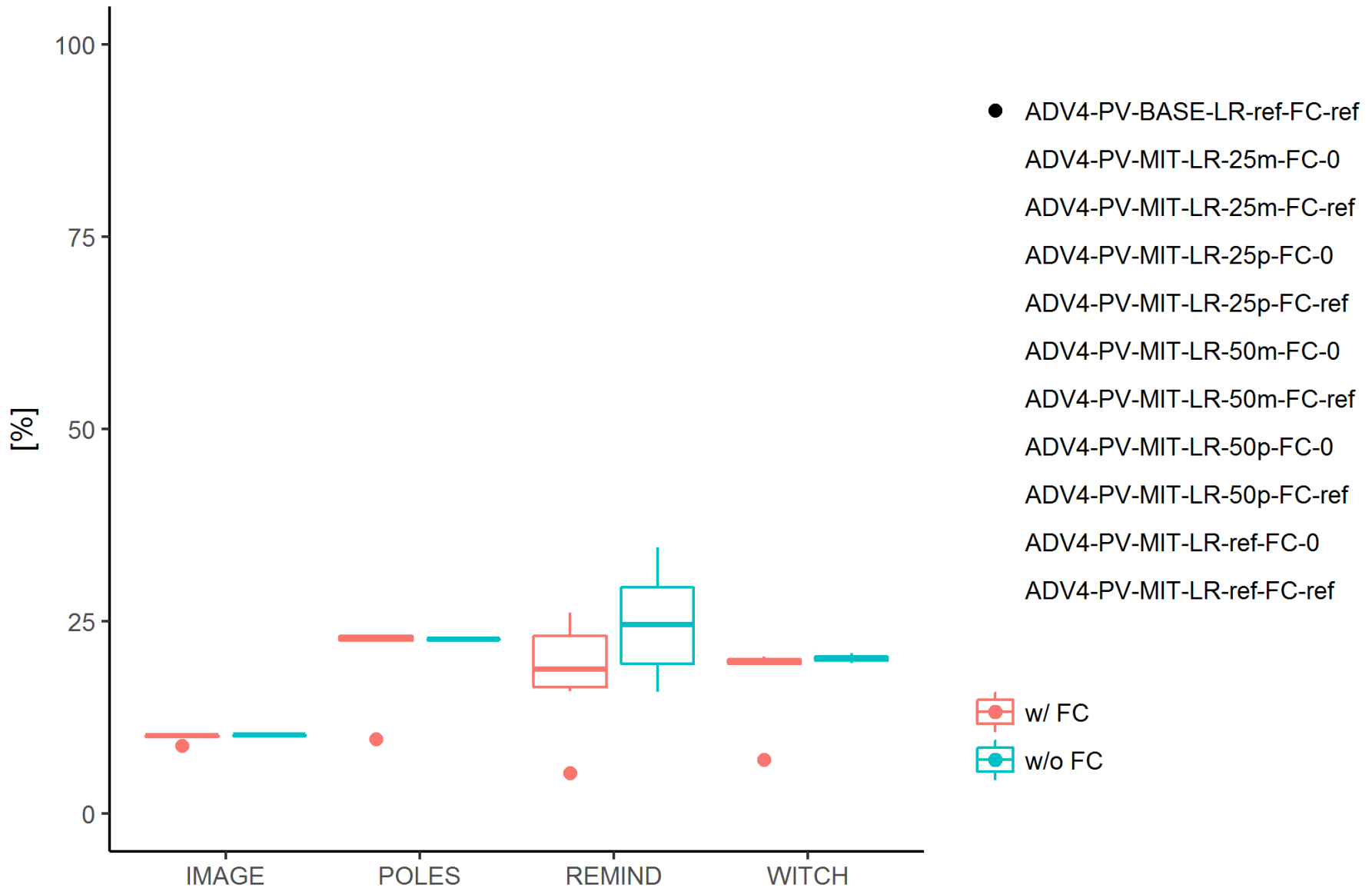
PV share in the electricity mix with and without floor cost - World - 2100



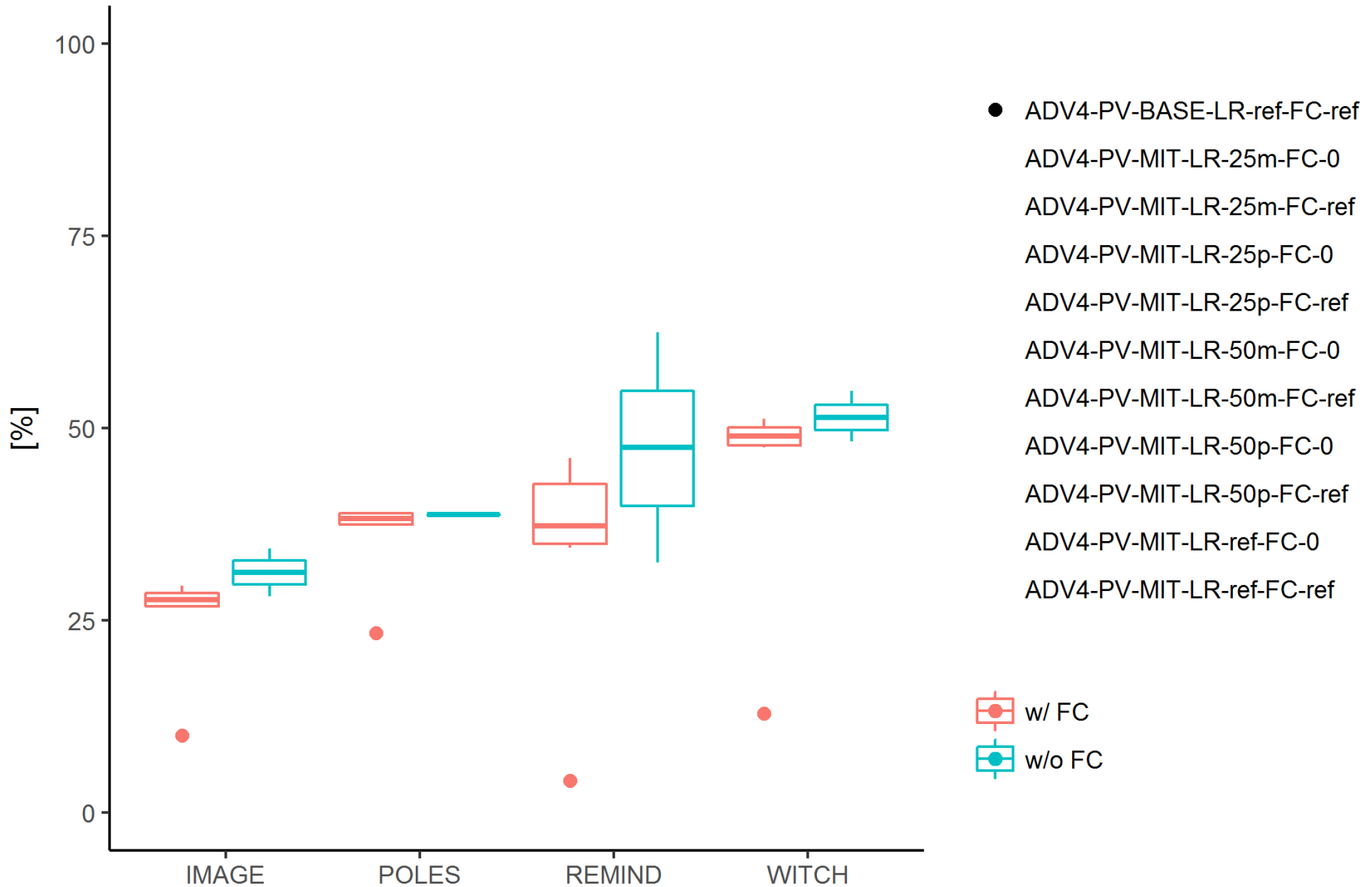
PV share – Comments

- 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.

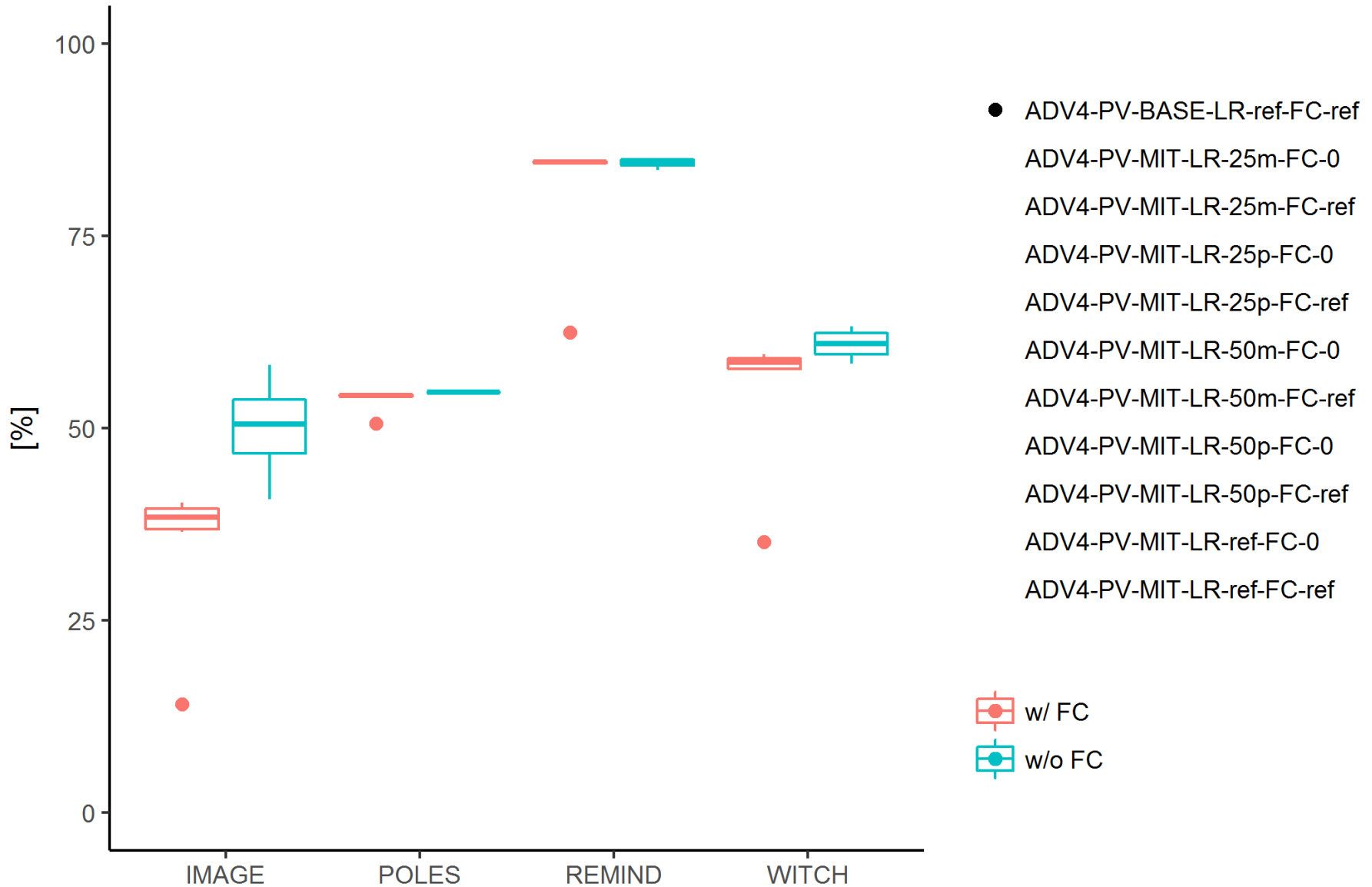
Solar (PV and CSP) + wind share in the electricity mix - World - 2030



Solar (PV and CSP) + wind share in the electricity mix - World - 2050

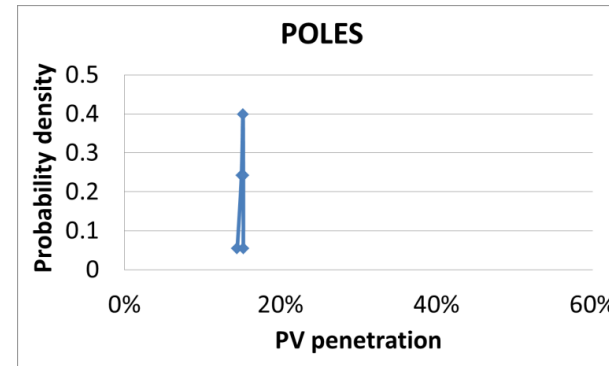
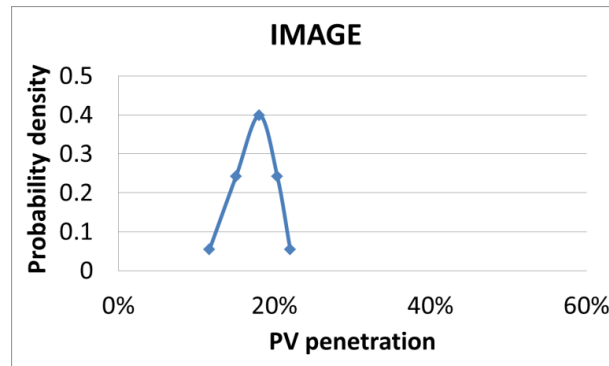
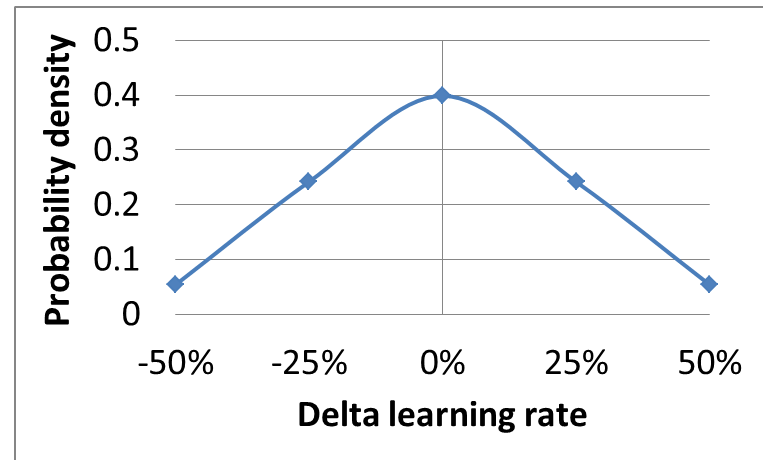
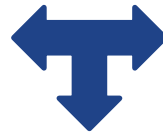
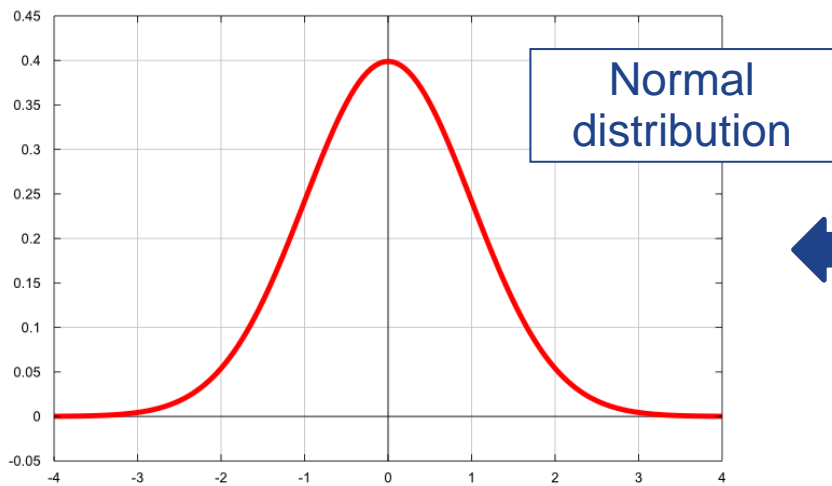


Solar (PV and CSP) + wind share in the electricity mix - World - 2100

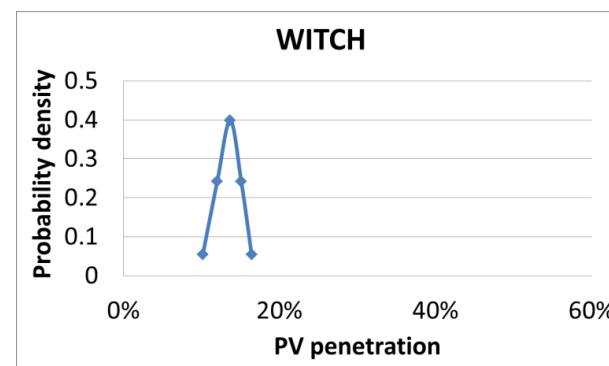
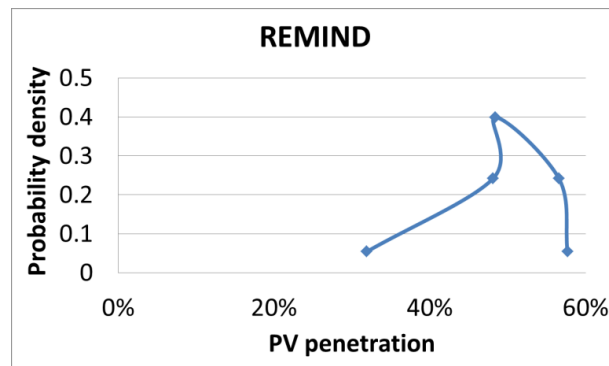


PV + CSP + wind share – Comments

- 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%).



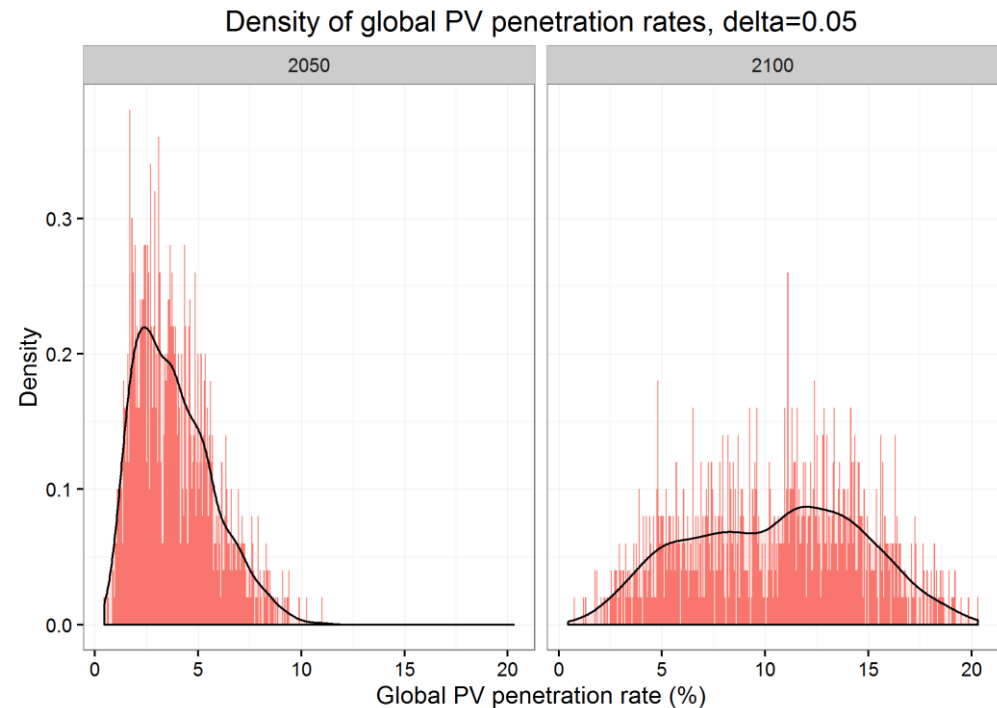
PV share in the ref. case World 2100



Statistical analysis

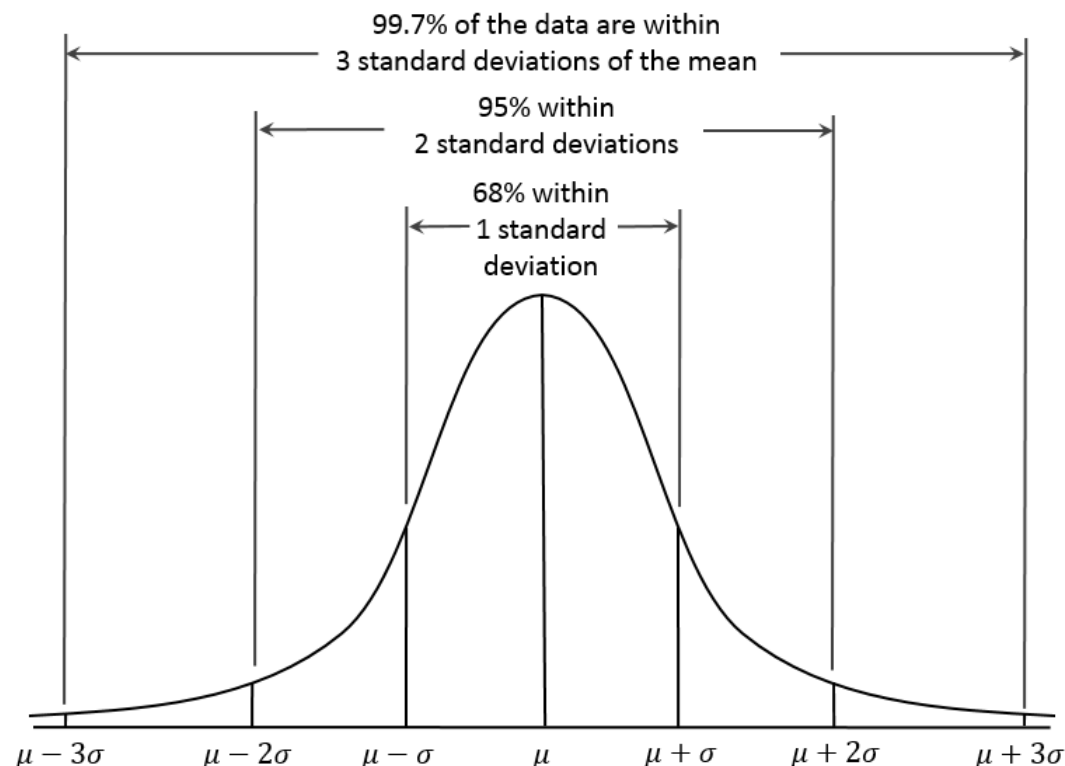
- The previous slide is a draft of what I would like to develop after the next submission.
- The objective is to derive statistical information in order to obtain the “real” penetration, weighting the different PV shares on the probability density of the corresponding learning rate (basing on the assumption 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 $\mu \pm 3\sigma$ (thus $\pm 75\%$) 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**

www.mercury-energy.eu



The MERCURY project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 706330.
The dissemination of results it reflects only the author's view, the Agency is not responsible for any use that may be made of the information it contains.