



**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

**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

Associazione Italiana Economisti dell'Energia (AIEE) – 3<sup>rd</sup> Energy Symposium  
Bocconi University, Milan, Italy – December 10-12, 2018



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.<sup>1,2</sup>, Bevione M.<sup>1,3</sup>, de Boer H.S.<sup>4</sup>, Gernaat D.<sup>4</sup>, Mima S.<sup>5</sup>, Pietzcker R.C.<sup>6</sup>, and Tavoni M.<sup>1,7,8</sup>**

<sup>1</sup> Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

<sup>2</sup> Renewable and Appropriate Energy Laboratory (RAEL) and Energy and Resources Group (ERG), University of California, Berkeley, USA

<sup>3</sup> INRIA, Grenoble, France

<sup>4</sup> PBL Netherlands Environmental Assessment Agency, Den Haag, the Netherlands

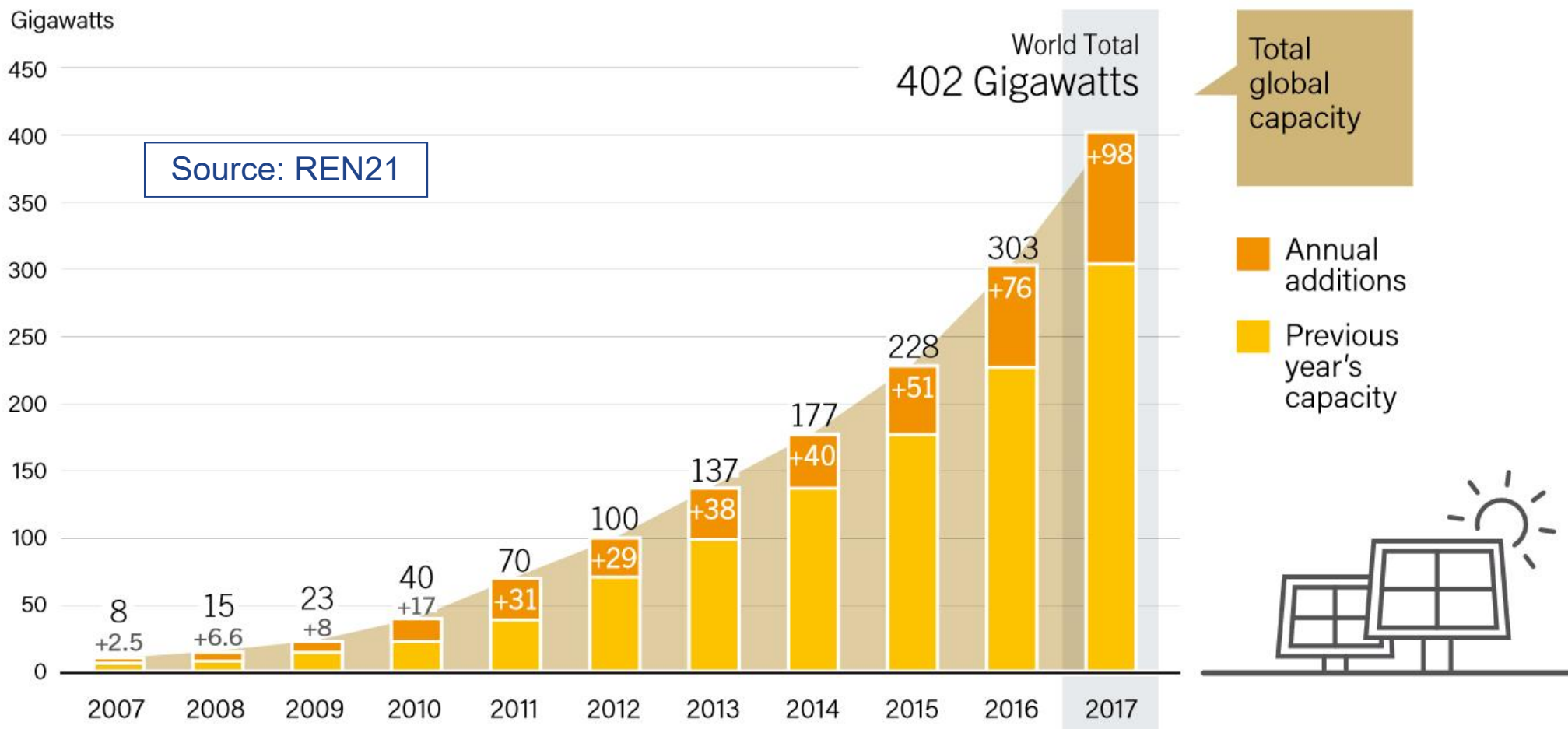
<sup>5</sup> Univ. Grenoble Alpes, CNRS, Grenoble INP, INRA, GAEL, Grenoble, France

<sup>6</sup> PIK Potsdam Institute for Climate Impact Research, Potsdam, Germany

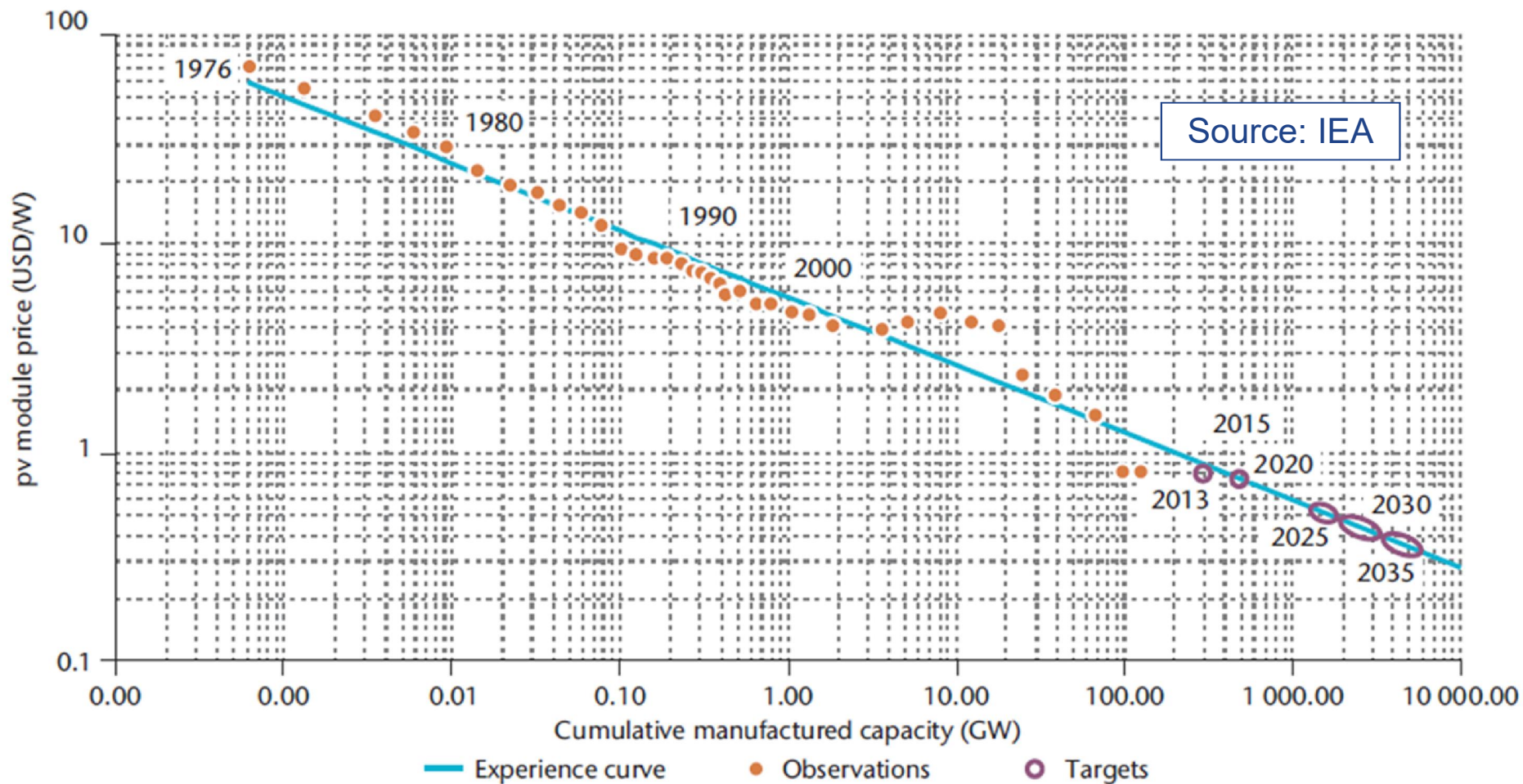
<sup>7</sup> Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy

<sup>8</sup> 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-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**
  - **REMIND**
  - **WITCH**
- } Recursive dynamic partial equilibrium models
- } 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



# 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

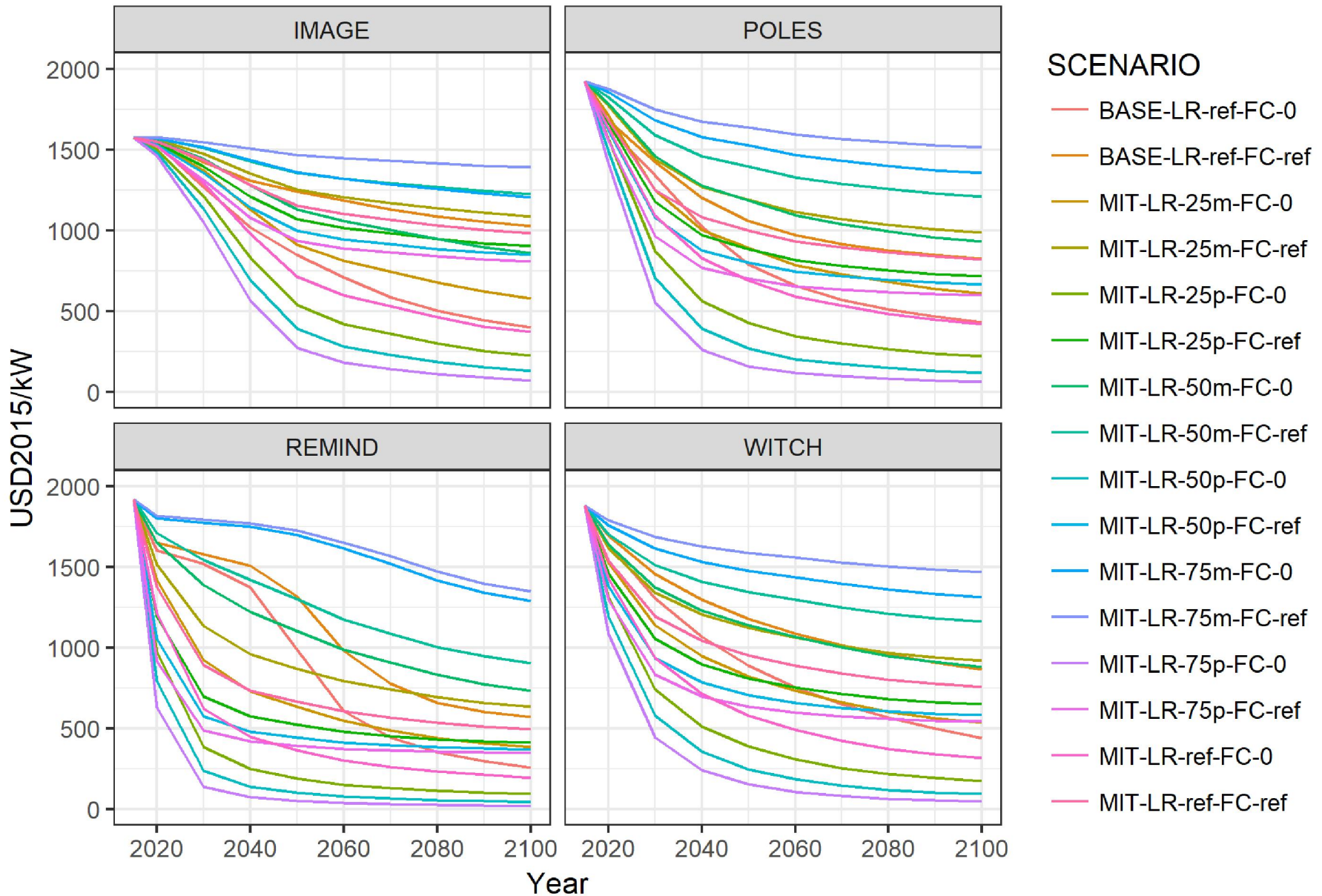
Mitigation → ctax | cumulative 1000 GtCO<sub>2</sub> in 2011-2100 in the Ref-Ref scenario → +2°C in 2100

# Modeling assumptions (stocktaking)

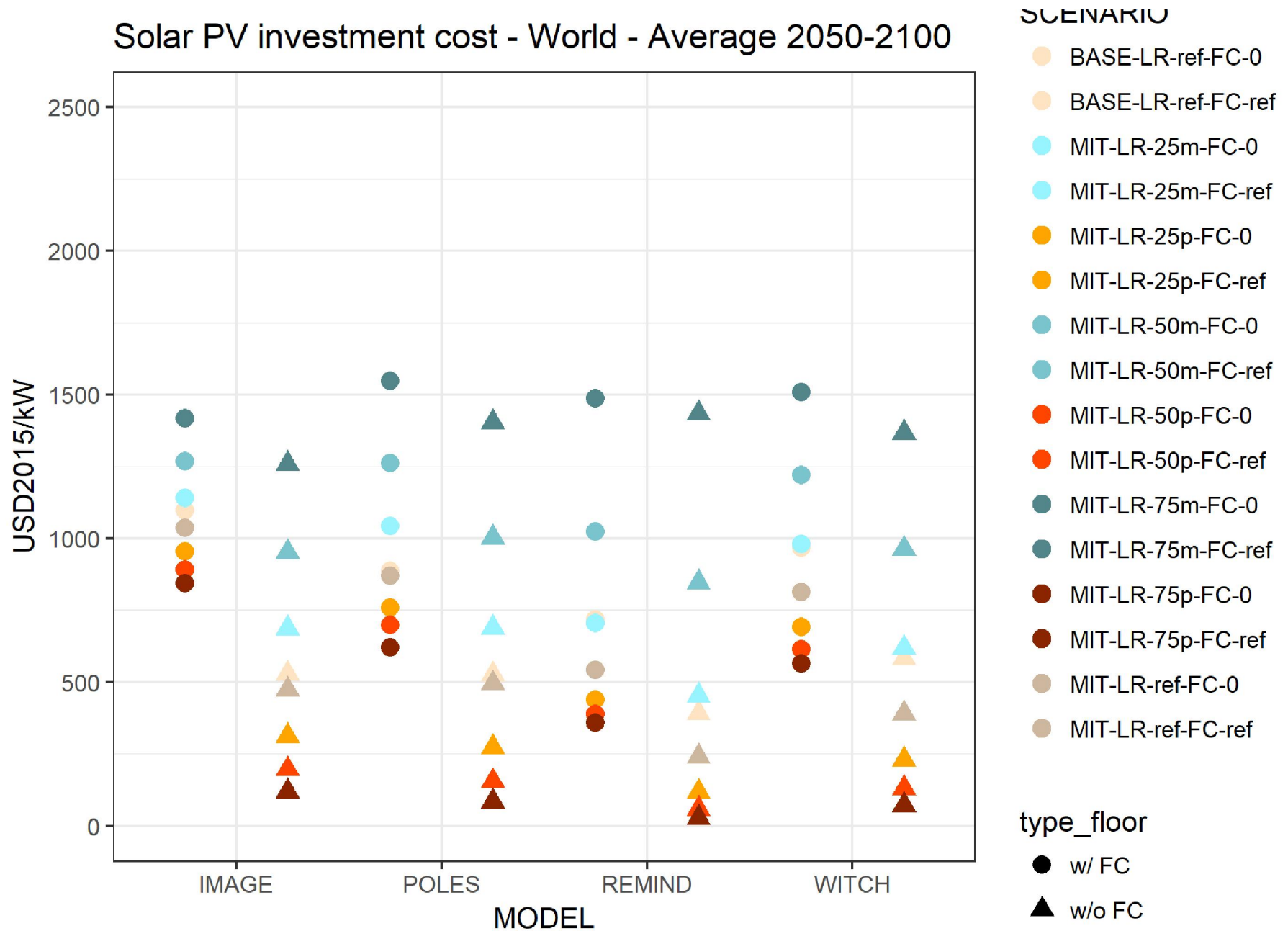
	IMAGE	POLES	REMIND	WITCH
Cost calculation	Endogenous			
Type of endogenous modeling	One-factor learning curve (LbD)			
Regional differentiation	Yes, with (limited) spillover effects	No, only one global cost		
Type of floor cost	Soft bound (asymptotic)			
Plant depreciation	Linear	Linear	Concave	Exponential
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



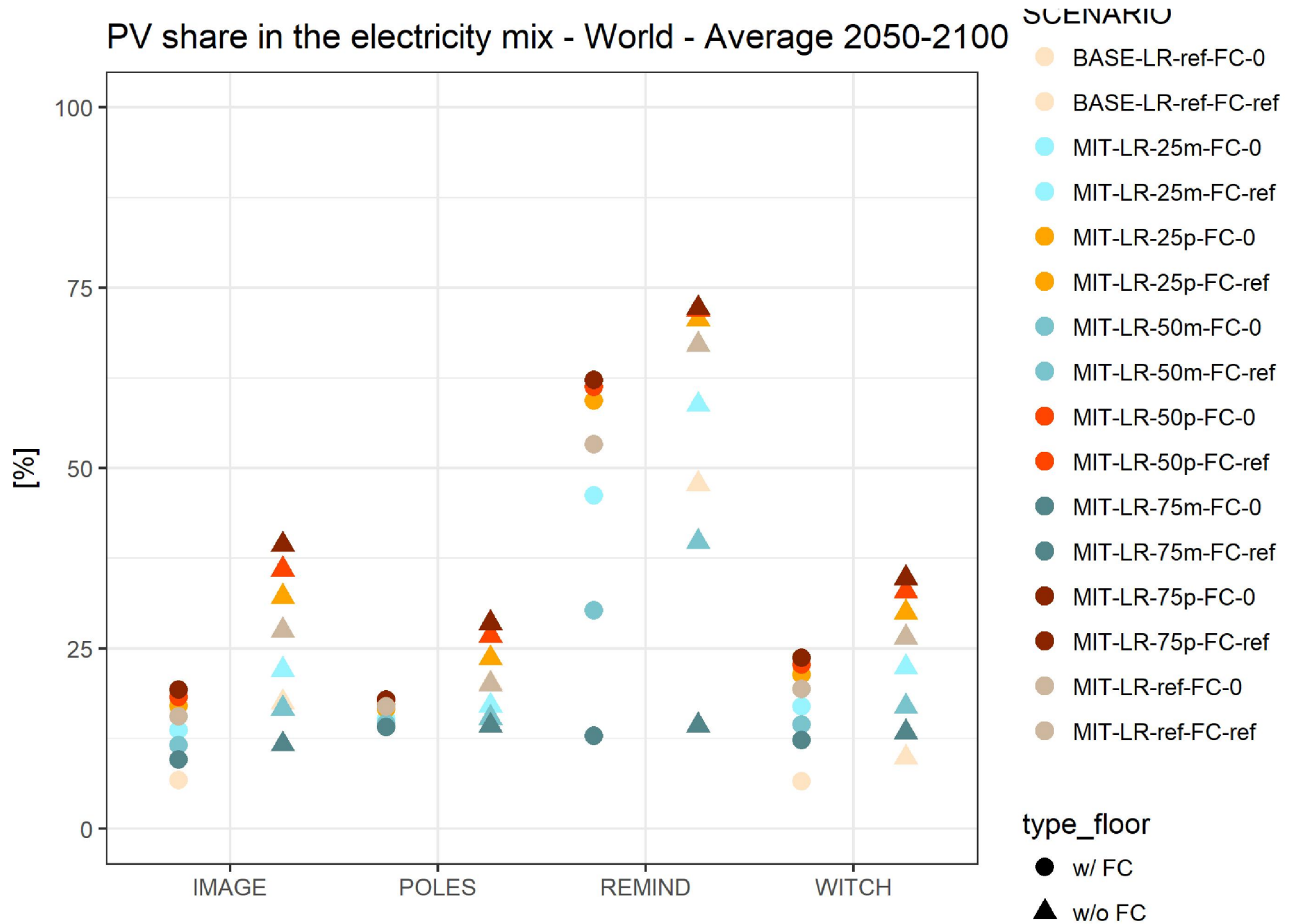
# Solar PV investment cost over time - World - All scenarios



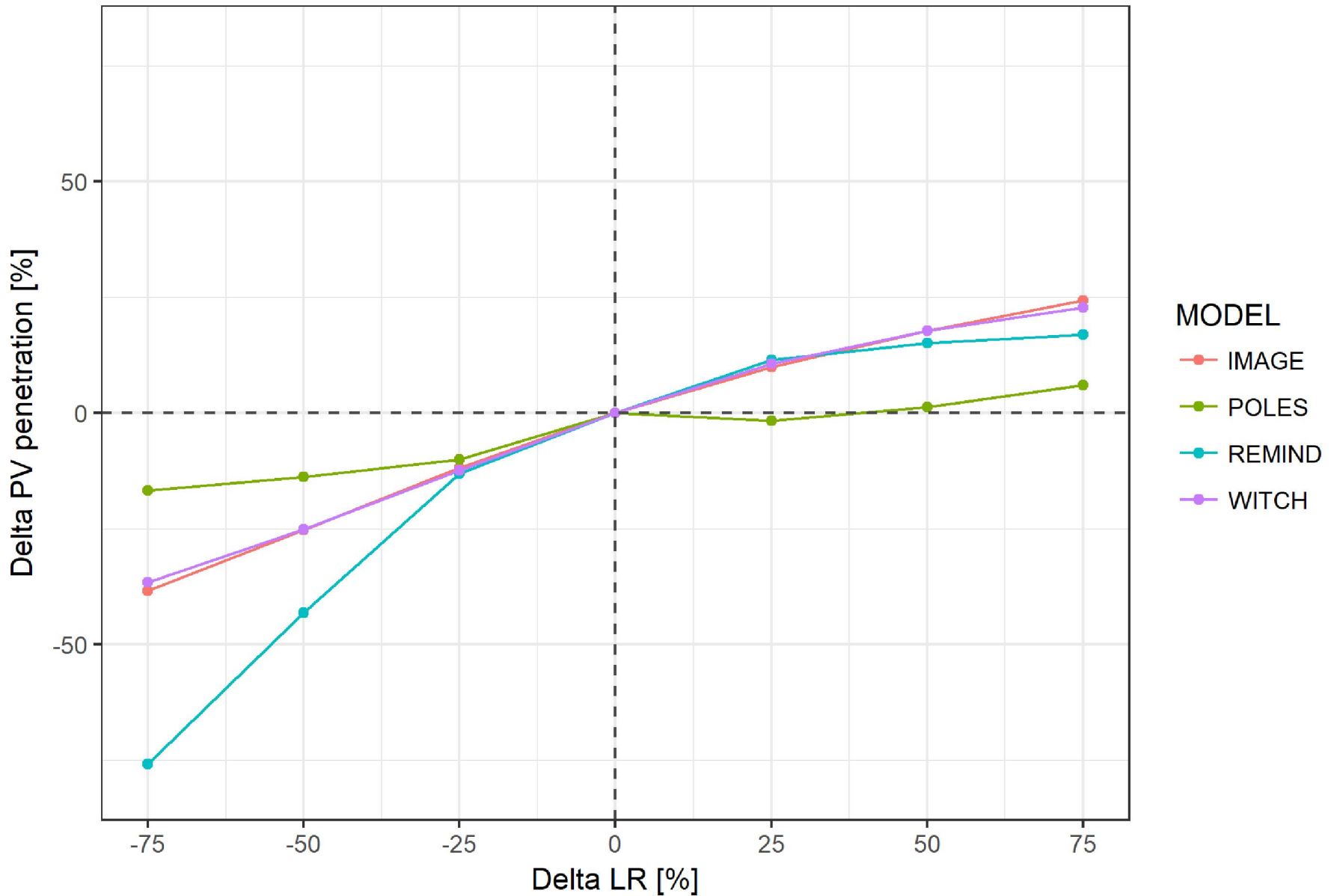
# Solar PV investment cost - World - Average 2050-2100



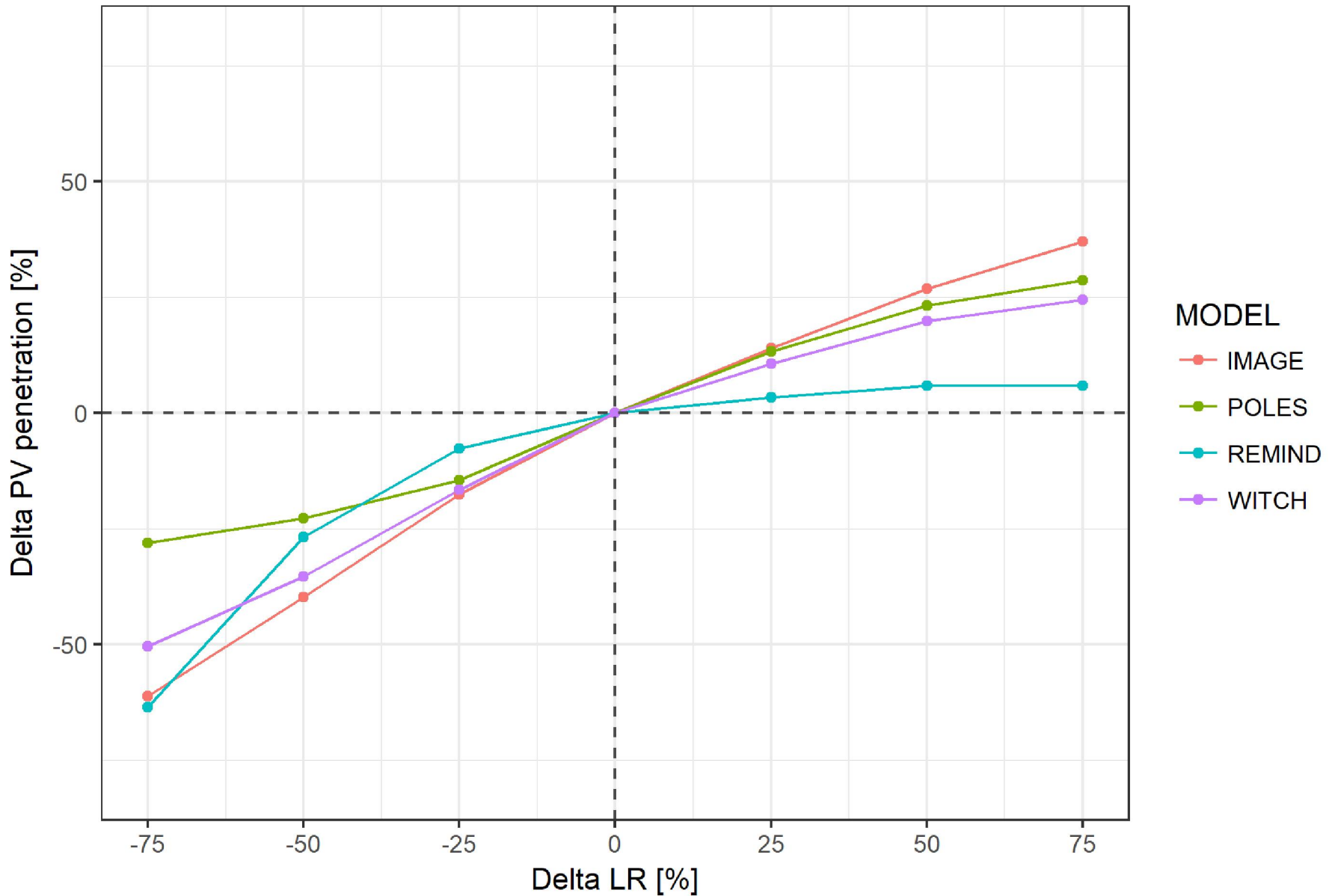
# PV share in the electricity mix - World - Average 2050-2100



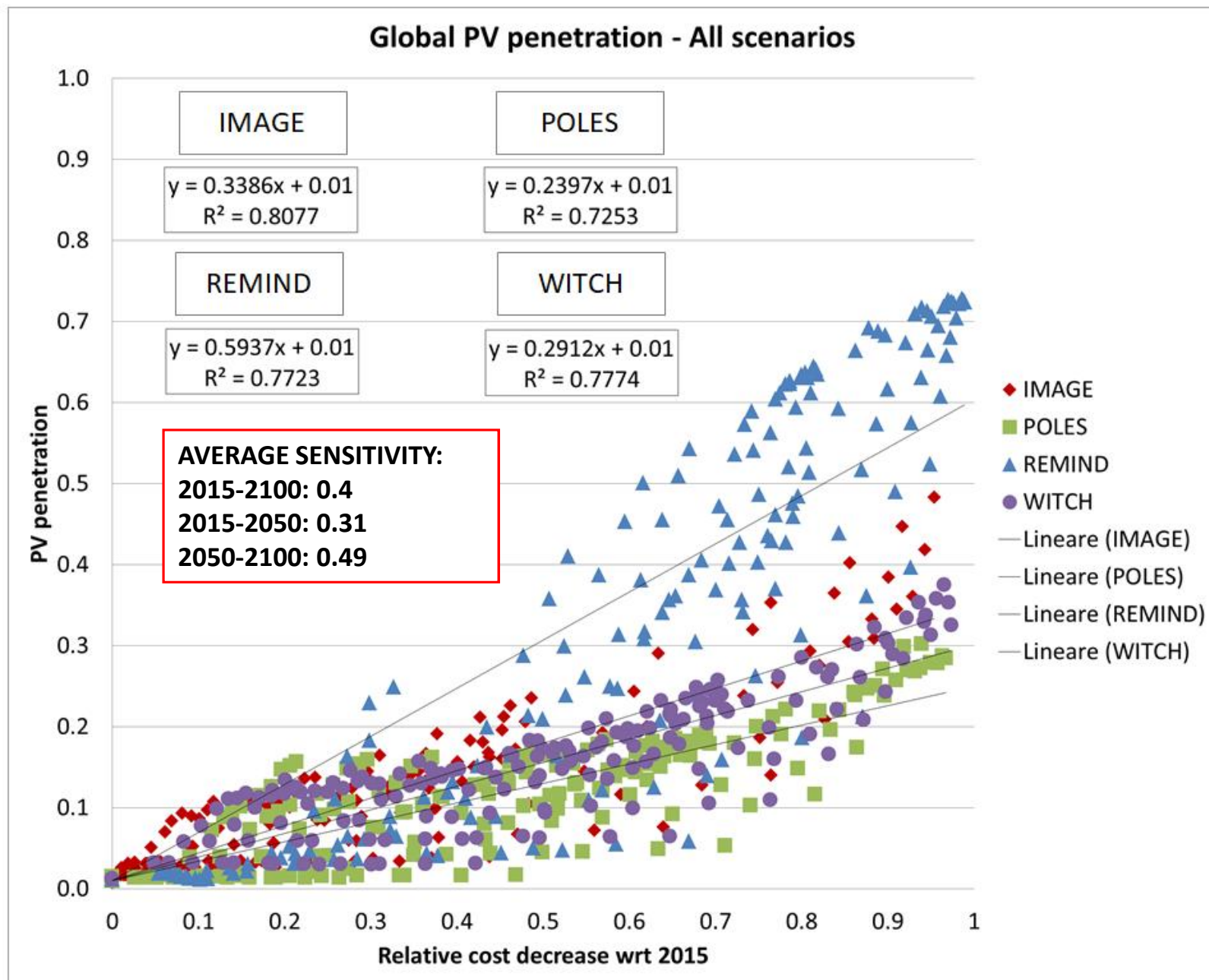
# PV share variation wrt reference case (with FC) - World - Av. 2050-2100



# PV share variation wrt reference case (without FC) - World - Av. 2050-2100

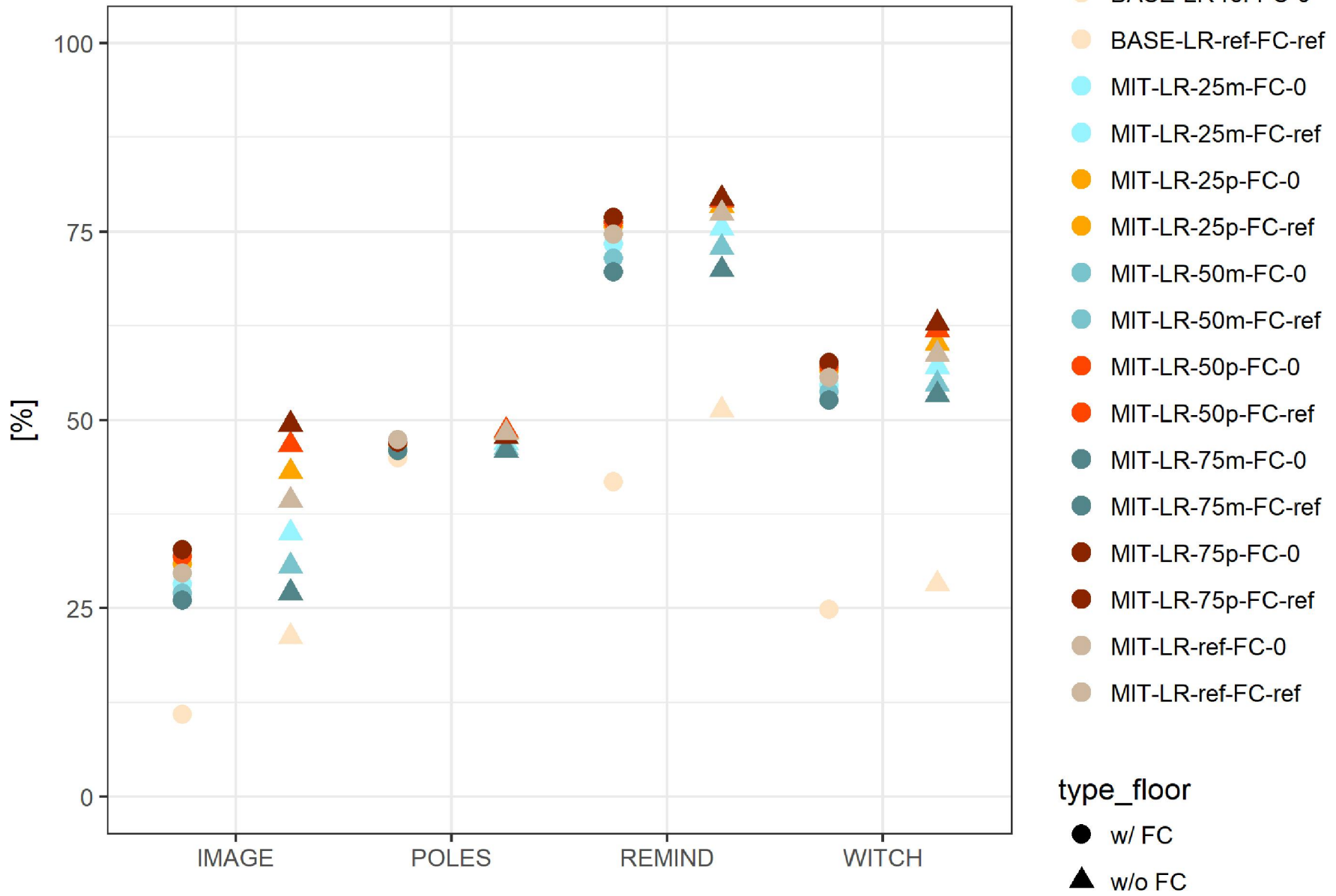








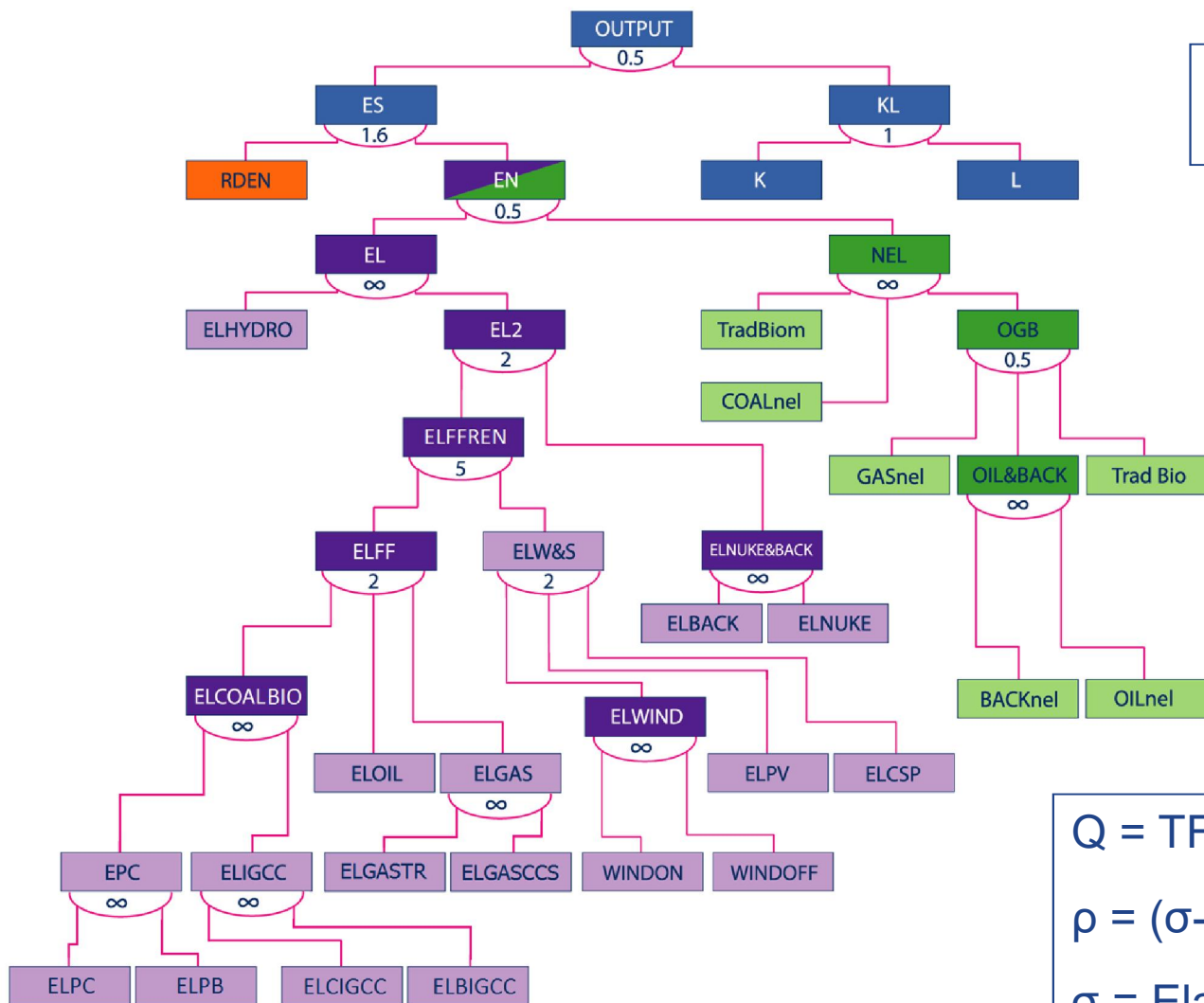
# PV + CSP + wind share - World - Av. 2050-2100



# 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.

# WITCH: The CES structure



CES = Constant Elasticity of Substitution

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

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

$\sigma$  = Elasticity of Substitution





**THANK YOU  
FOR YOUR ATTENTION**

[www.mercury-energy.eu](http://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.