37th International Energy Workshop (IEW)
June 19-21, 2018 – Chalmers University of Technology, Gothenburg, Sweden

# Modeling system integration of variable renewable energies for long-term climate objectives: the role of electric grid and storage

**Samuel Carrara[1,2], Marco Marni[1,3], Simone Prato[1,3], and Massimo Tavoni[1,3,4]**

[1] Fondazione Eni Enrico Mattei (FEEM), Milan, Italy
[2] Renewable & Appropriate Energy Laboratory (RAEL), UC Berkeley, USA
[3] Politecnico di Milano, Milan, Italy
[4] Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy

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.

# VRE penetration and modeling in IAMs

- **Decarbonization of the energy system →**

  - Energy efficiency
  - Nuclear
  - Carbon Capture and Storage (CCS)
  - Renewables (especially Variable Renewable Energies, VREs, i.e. wind and solar PV)

- **VREs**

  → variability and non-dispatchability, in contrast with the requirement that the load be instantaneously equalized by the generation
  → problems in terms of management of the electrical grids

- **Integrated Assessment Models (IAMs)**

  → objective: simulate the evolution of electricity demand and mix over the next decades
  → mandatory to properly model VRE system integration, although inevitably in a simplified / aggregated form (different spatial and temporal scales)

# 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: VRE integration (old version) – Summary

The limitation to VRE penetration into the electrical grid was (mainly) modeled in WITCH through:

- a constraint on the **flexibility** of the power generation fleet
- a constraint on the installed **capacity** of the power generation fleet

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: Flexibility constraint (old version)

| Power technology | Flexibility coefficient (f) |
|---|---|
| Load | -0.1 |
| Wind | -0.08 |
| PV | -0.05 |
| CSP | 0 |
| Nuclear | 0 |
| Coal | 0.15 |
| Oil | 0.3 |
| Biomass | 0.3 |
| Gas | 0.5 |
| Hydro | 0.5 |
| Storage | 1 |

→ 2000 h/yr eq.

$$\sum_i Q\_EL(t,n)_i \cdot f_i + Q\_EL\_TOT(t,n) \cdot f_{LOAD} \geq 0$$

# WITCH: Capacity constraint (old version)

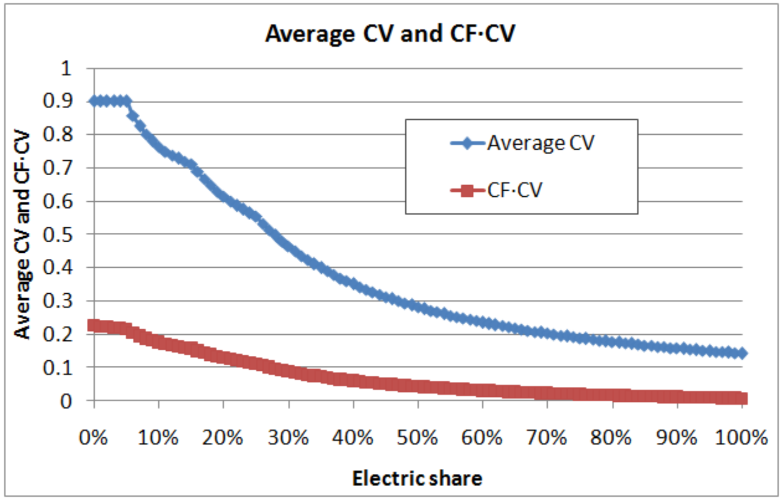
Firm generation capacity ≥ (1.5-2) · Annual average load

Non-variable capacity + “weighted” variable capacity (wind and PV)

$$\sum_i K\_EL(t,n)_{i,non\_VRE} + \sum_i K\_EL(t,n)_{i,VRE} \cdot CF_i \cdot CV_i\,(share) + K\_EL_{stor} \cdot CV_{stor} \geq$$

$$\geq c(n) \cdot Q\_EL\_TOT(t,n)/yearly\_hours$$

- $CV_{stor} = 0.85$
- $CF_i \cdot CV_i$ (share)



# WITCH: Grid (old version)

Grid requirement (depending on power capacity)

$$K\_EL\_GRID(t,n) = \sum_{jel|non\_VRE} K\_EL(jel,t,n)$$

$$+ \sum_{jel|VRE} \sum_{distance} K\_EL\_D(jel,t,n,distance) \times \frac{transm\_cost(jel,distance)}{grid\_cost}$$

$$+ \sum_{jel|VRE} K\_EL(jel,t,n) \times \left(1 + SHARE\_EL(jel,t,n)^{b}\right)$$



MERCURY

# WITCH: VRE integration (old version) – Main 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 (but: regional variability)
  - the flexibility coefficients might change with VRE penetration

- No curtailment of VRE electricity generation is considered.

- Storage and grid are modeled quite rudimentarily.

→ These issues have been addressed in the new model version.

# WITCH: New VRE integration – Reference

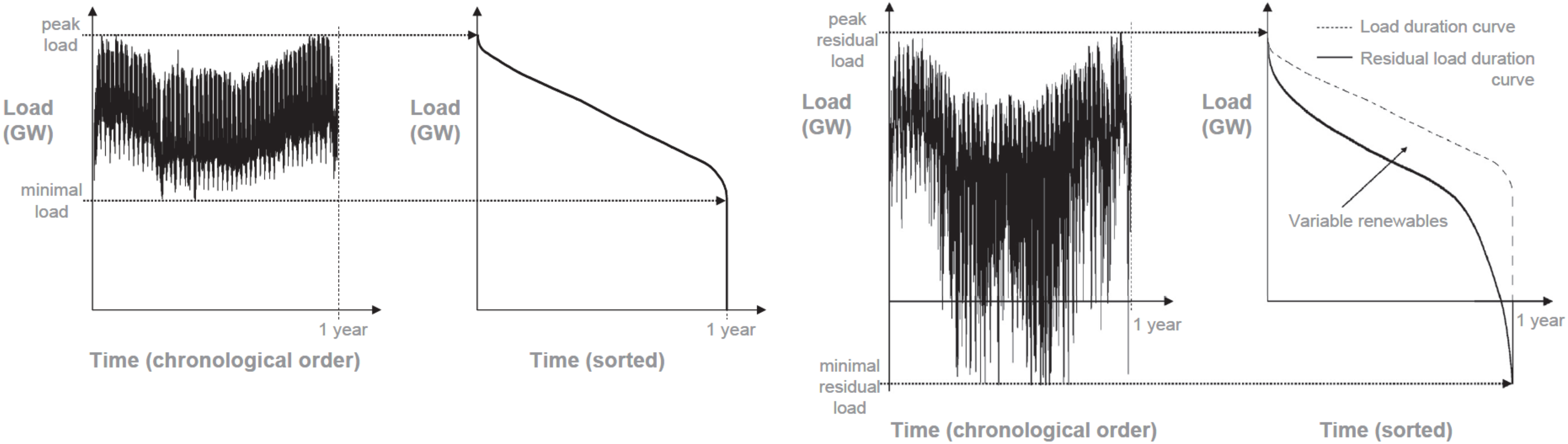
Johnson, N., Strubegger, M., McPherson, M., Parkinson, S.C., Krey, V., Sullivan, P. (2017). A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system, Energy Economics, Vol. 64, pp. 651-664

→

Indirect implementation of the Residual Load Duration Curves (RLDC) to the MESSAGE model, i.e. to a framework based on the following main points:

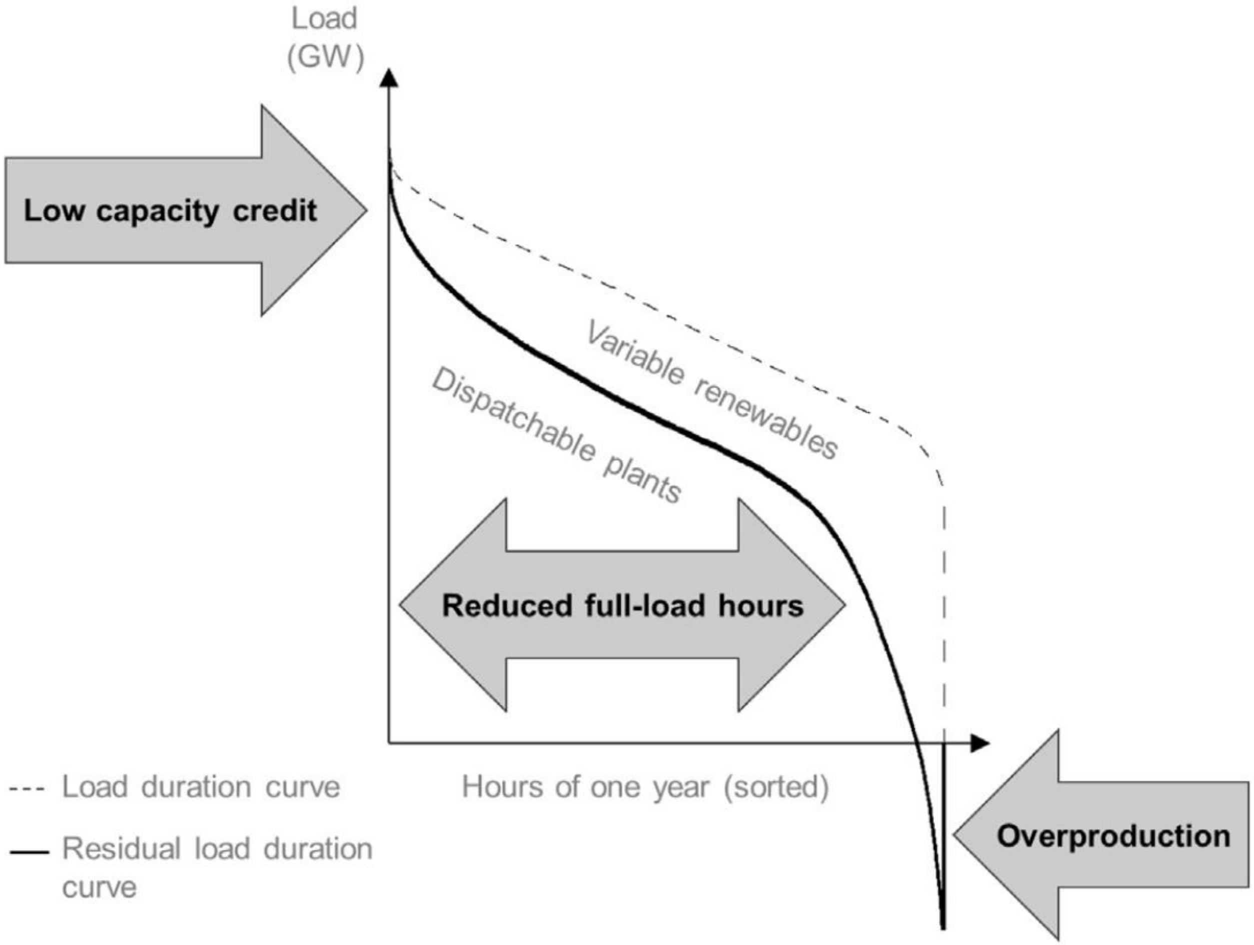
- Electricity treated as a homogeneous good
- Flexibility constraint
- Capacity constraint

# Residual Load Duration Curves (RLDC)




Ueckerdt, F., Brecha, R. and Luderer, G. (2015). Analyzing major challenges of wind and solar variability in power systems, Renewable Energy, Vol. 81, pp. 1-10

# Residual Load Duration Curves (RLDC) – VRE effects




Ueckerdt, F., Brecha, R. and Luderer, G. (2015). Analyzing major challenges of wind and solar variability in power systems, Renewable Energy, Vol. 81, pp. 1-10

# MESSAGE – Data/parameters derived from the RLDCs

**CURTAILMENT**

- Introduction of short-term and seasonal curtailment

**FLEXIBILITY CONSTRAINT**

- Load flexibility coefficients (differentiated by region)
- VRE flexibility coefficients (variable with VRE share)

**CAPACITY CONSTRAINT**

- Firm capacity requirement variable over time (already differentiated by region)
- Capacity values (variable with VRE share differentiating by region)

# WITCH: New grid modeling

- Differentiation between transmission and distribution

  → Same linear proportion with generation capacity, but grid capacity expressed in [km] instead of [GW]

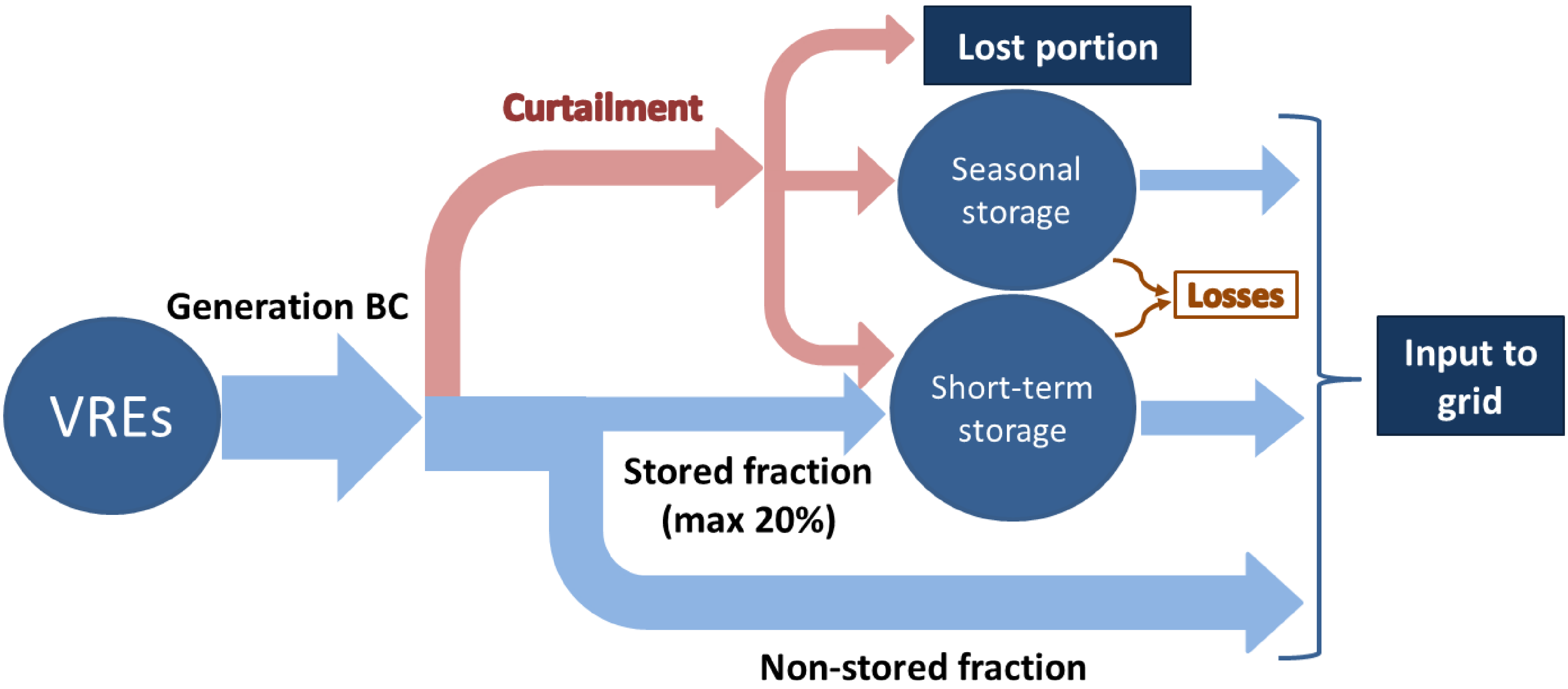
- Introduction of grid losses
- Regional grid requirement
- Introduction of grid pooling and smartening effects

  → Integration of grid into the flexibility constraint

# WITCH: New storage modeling – Technologies

| Type of storage | Technology | FlexC | CapC |
|---|---|---|---|
| Short-term | Pumped Hydroelectric Storage (PHES) | 0.75 | 1 |
| | Compressed Air Energy Storage (CAES) | 0.75 | 1 |
| | Lithium-ion batteries (LiB) | 1 | 0.8 |
| Seasonal | Alkaline electrolyzer → hydrogen → Polymer Electrolyte Membrane Fuel Cells (PEMFC) | 0.9 | 1 |

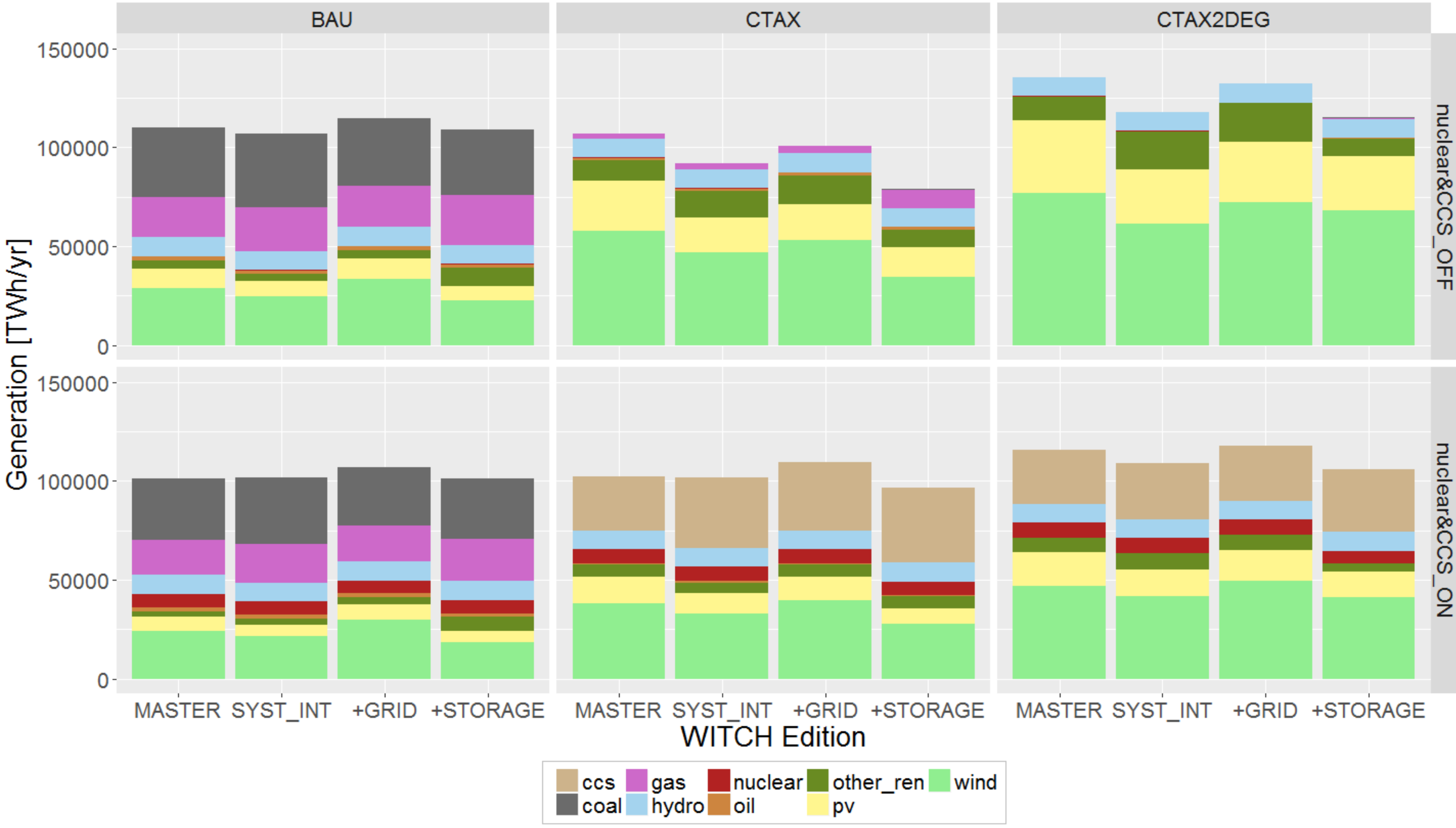
# WITCH: New storage modeling – Energy flows






MERCURY

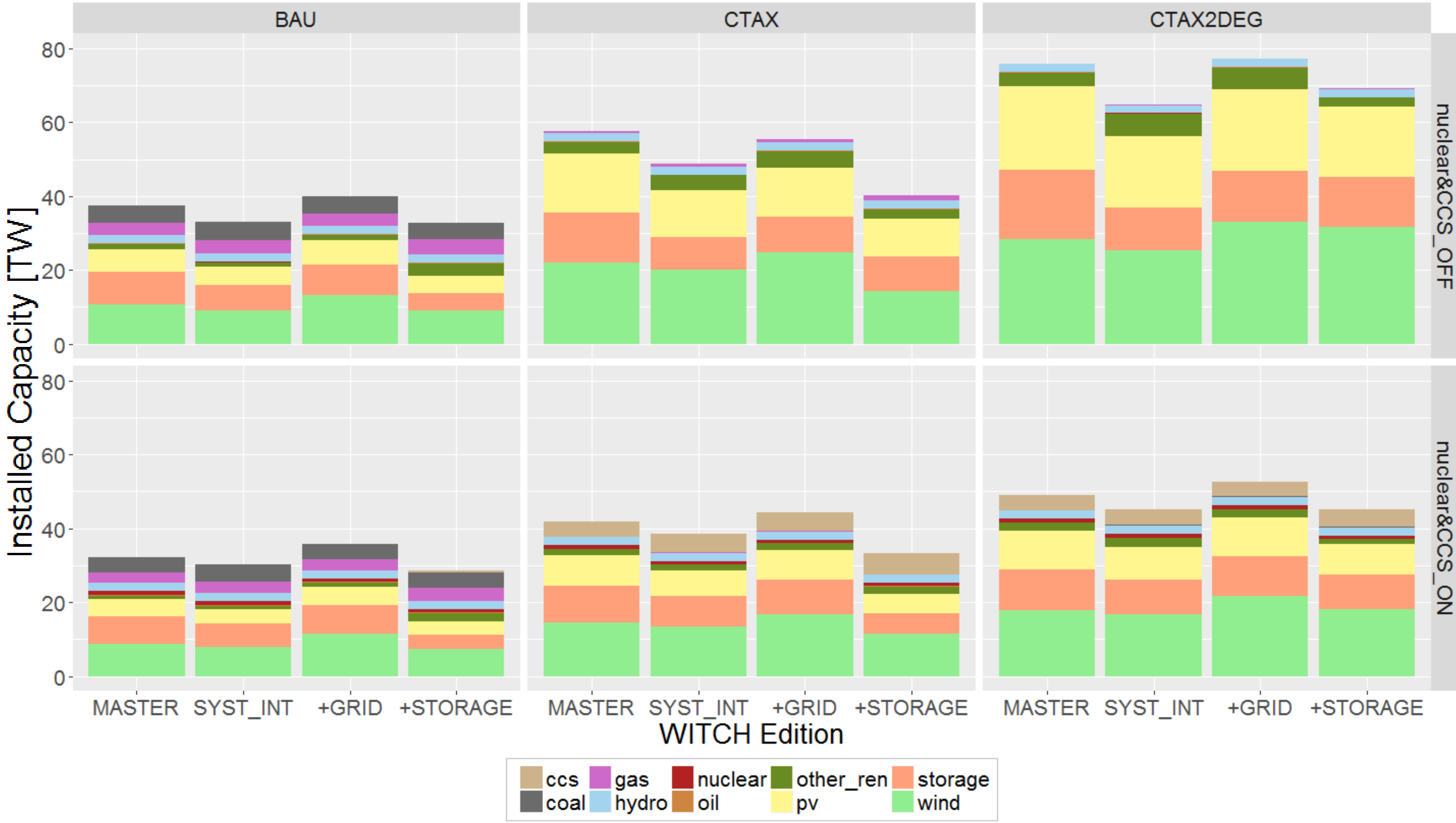
# WITCH: Results – Electricity mix (after storage) in 2100






MERCURY

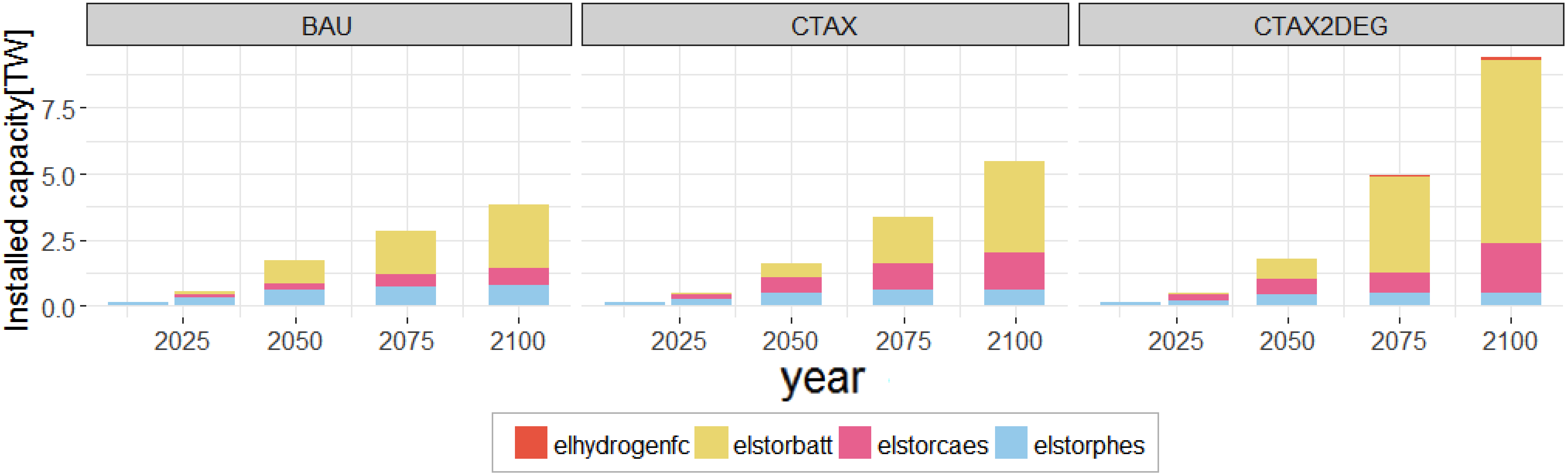
# WITCH: Results – Capacity mix in 2100



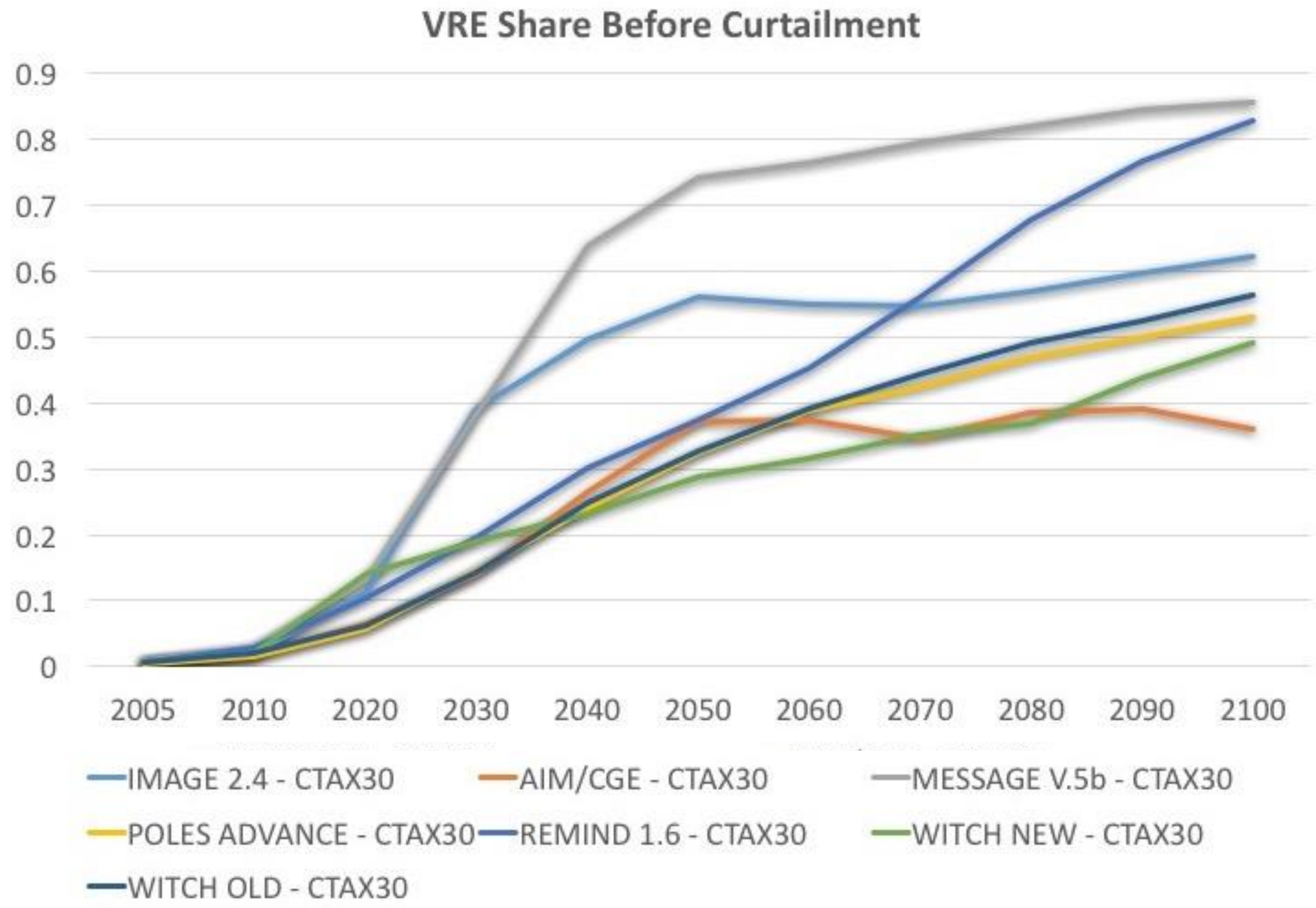

 **Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy**

MERCURY

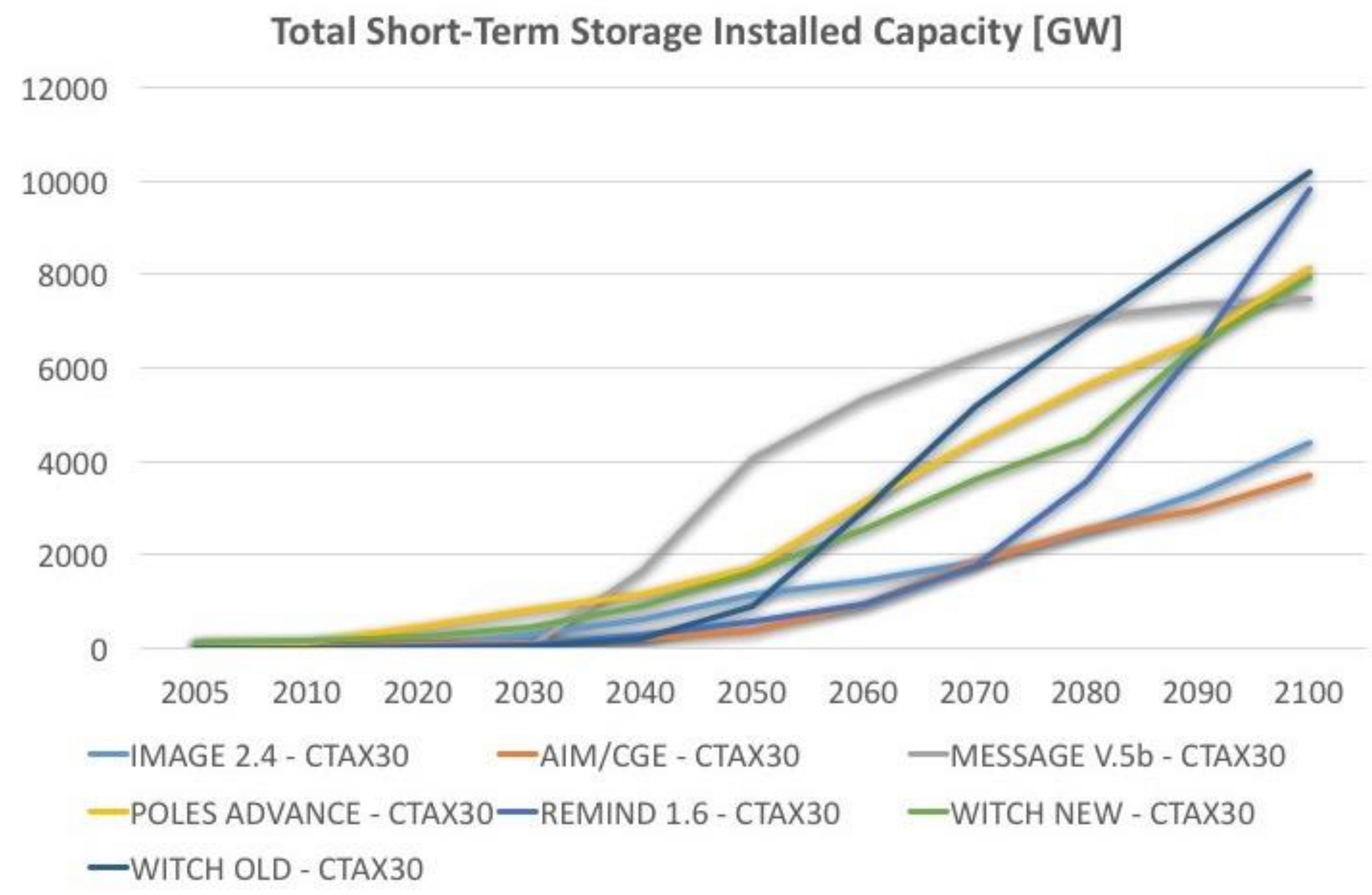
# WITCH: Results – Storage capacity



# WITCH: Results – Comparison with IAMs (VRE share)



# WITCH: Results – Comparison with IAMs (storage)



# THANK YOU
# FOR YOUR ATTENTION

www.mercury-energy.eu

**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**

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 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.