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Including system integration of Variable Renewable Energies (VRE) in a constant elasticity of substitution framework: the case of the WITCH model

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Introduction – VRE penetration

- According to the International Energy Agency (IEA), the decarbonization of the energy system will rely on four great pillars: energy efficiency, renewables, nuclear and Carbon Capture and Storage (CCS). In particular, Variable Renewable Energies (VREs), i.e. wind and solar PV, will play a major role among renewables.

- The penetration of VREs in the electricity mix poses serious problems in terms of management of the electrical grids, as the associated intermittency and non-dispatchability are in contrast with the requirement that the load be instantaneously equalized by the generation.

- One of the goals of Integrated Assessment Models (IAM) is to simulate the evolution of electricity demand and mix over the next decades, therefore a proper modeling of VRE system integration is mandatory, though inevitably in a simplified / aggregated form (→ different temporal scales).

VRE integration – Overview

Different mechanisms to describe the integration of VREs into the electrical grid may be adopted. The main solutions, at increasing levels of complexity, are (Pietzcker, 2013):

- Hard upper bound on the VRE share in the electricity mix
- Direct LCOE (Levelized Cost Of Electricity)
- Implicit cost markups (e.g. deriving from a CES structure)
- Explicit cost markups (e.g. a cost function depending on the VRE share, grid expansion, etc.)
- Constraints on the flexibility/reliability of the power generation fleet
- Constraints on the installed capacity of the power generation fleet
- Time slices/load curves
- Residual load duration curves

VRE integration – WITCH

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

- *The CES structure*

OLD FORMULATION

- An external explicit cost markup → Hoogwijk et al., 2007

NEW FORMULATION

- 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

Objectives

The main objectives of this work are:

- analyze and discuss the effects of the flexibility and capacity constraints on the electricity mix and the economic performance;
- provide an in-depth analysis of the role of the CES structure, by analyzing different structures of the tree and/or different elasticities of substitution.

The WITCH model: introduction

WITCH – World Induced Technical Change Hybrid

- Climate-energy-economic IAM → 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)

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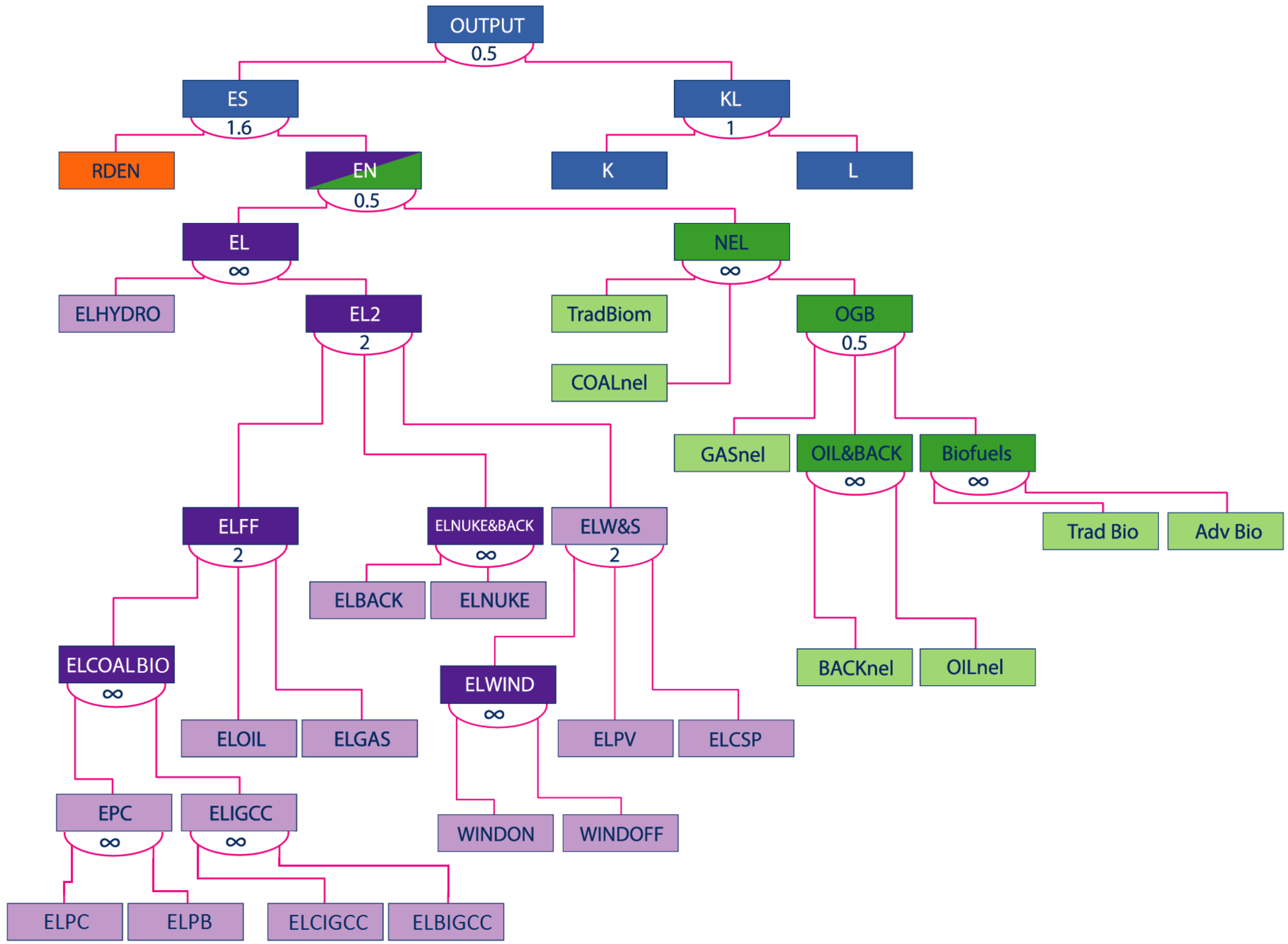
The WITCH model: CES structure (beginning)



Flexibility constraint

Table 2
Flexibility coefficients by technology.

Technology	Flexibility parameter
Load	−0.1
Wind	−0.08
Solar PV	−0.05
Geothermal	0
Nuclear	0
Coal	0.15
Biopower	0.3
Gas-CC	0.5
Hydropower	0.5
H_2 Electrolysis	0.5
Oil/gas steam	1
Gas-CT	1
Electricity storage	1

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

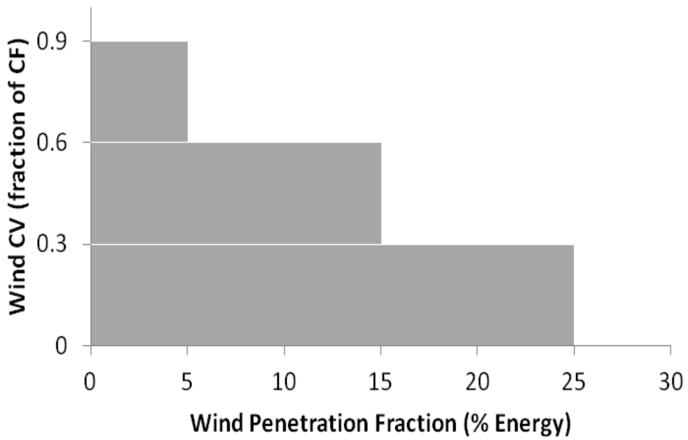
$$\sum_i Q\_EL(t,n)_i \cdot f_i + Q\_EL\_TOT(t,n) \cdot f_{LOAD} \geq 0$$

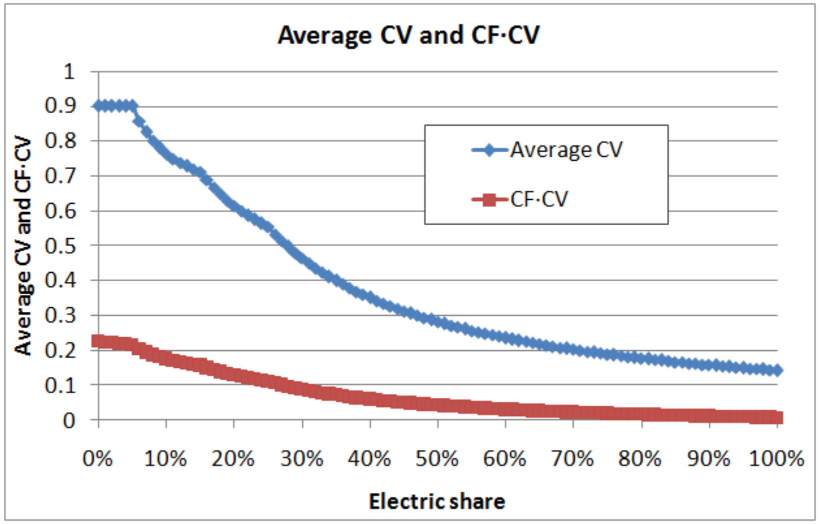
Capacity constraint

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

Non-intermittent capacity + "weighted" intermittent capacity (wind and PV)

$$\sum_i K\_EL(t,n)_{i,non\text{-}int} + \sum_i K\_EL(t,n)_{i,int} \cdot CF_i \cdot CV_i\,(share) \geq c(n) \cdot Q\_EL\_TOT(t,n)/8760$$

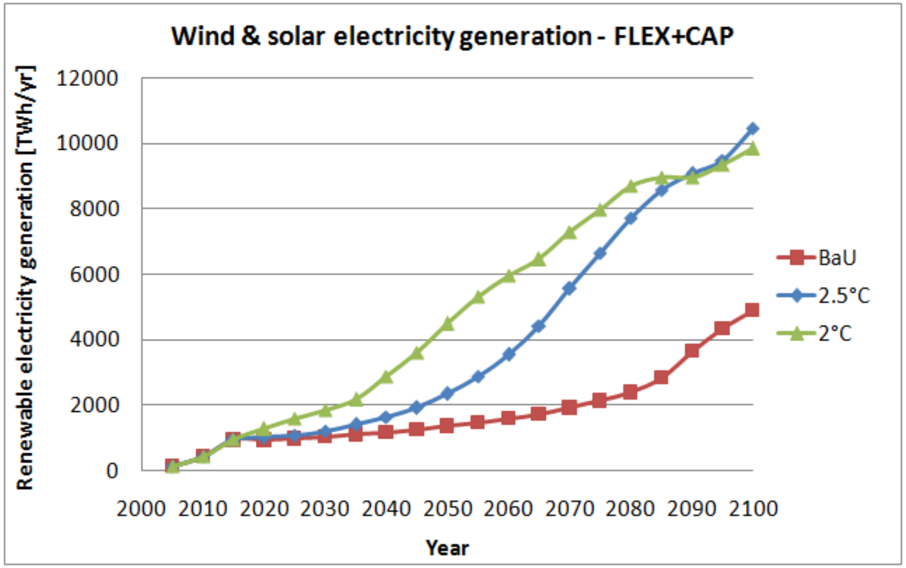


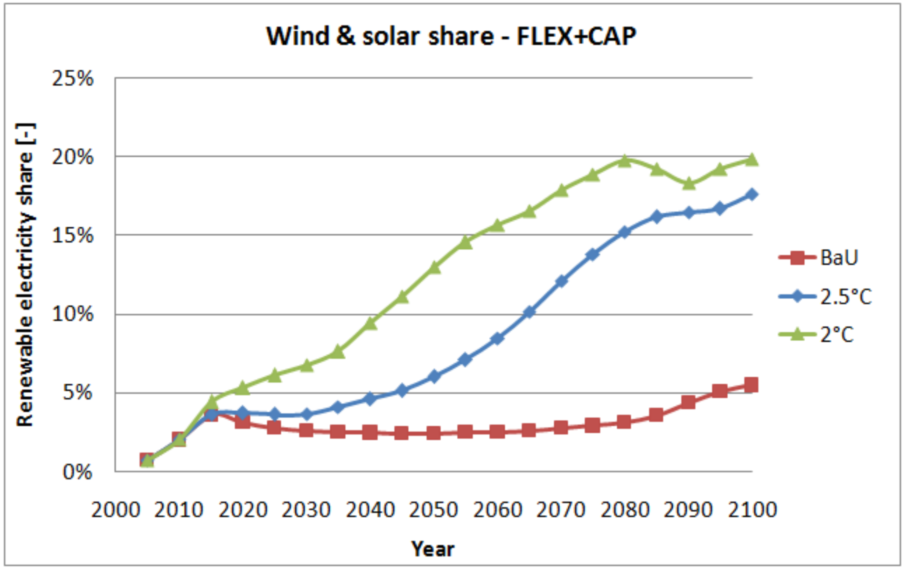


Flexibility and capacity constraints: results

- The flexibility constraint is binding in policy cases only and for a limited set of time periods and regions (in particular those which would base their carbon mitigation on VREs + nuclear), causing not only a rearrangement of the electricity mix if the nuclear-VRE transition is too deep, but also a reduction of the energy demand.
- The capacity constraint leads to the installation of backup capacity to meet the peak demand and is penalizing for VREs. The constraint is practically binding across all regions and time periods, even if the associated shadow price is much lower than the flexibility one, when relevant.

Flexibility and capacity constraints: results





The flexibility and capacity constraints, coupled with the present CES configuration, lead to a low renewable penetration → A reconsideration of the CES is needed.

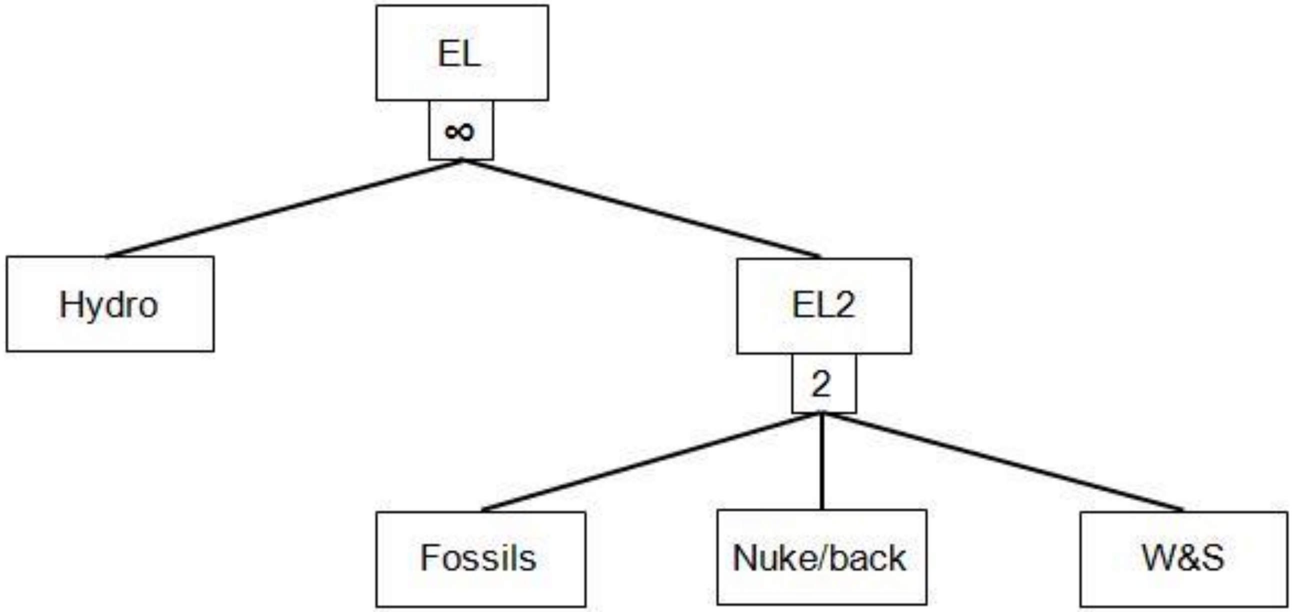
The CES structure

CES functions are the preferred way in WITCH to enforce in the energy system what in reality is observed as a preference for heterogeneity. Without these constraints, the system would reasonably, yet unrealistically, be monopolized by the cheapest available technology. With respect to VRE integration, CES functions are able to implicitly capture the increase in costs due to increasing share of VRE technologies to the detriment of dispatchable power sources by adding inflexibility to the system.

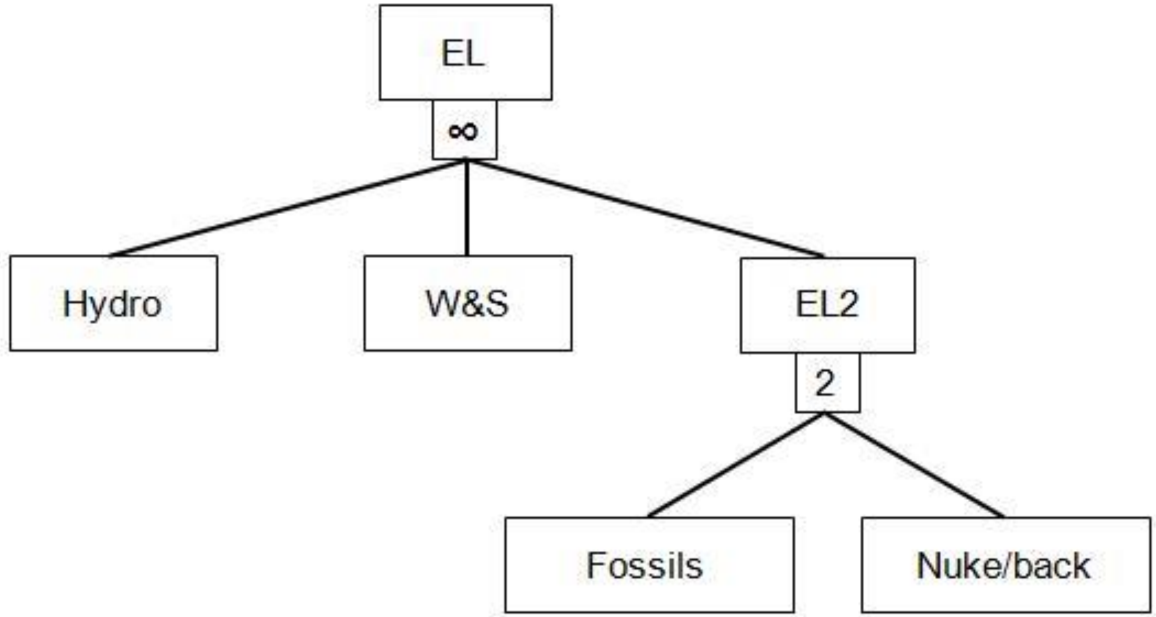
Nonetheless, this approach has several limitations:

- it is very coarse, as it lacks of a clear engineering interpretation of its mathematical formulation or parameterization;
- outcomes are highly dependent on the particular CES structure and values adopted;
- the calibration in the base year (2005 for WITCH) leads to a deployment of VREs in the first decade discernibly different from the one observed in reality, especially with low substitution elasticities.

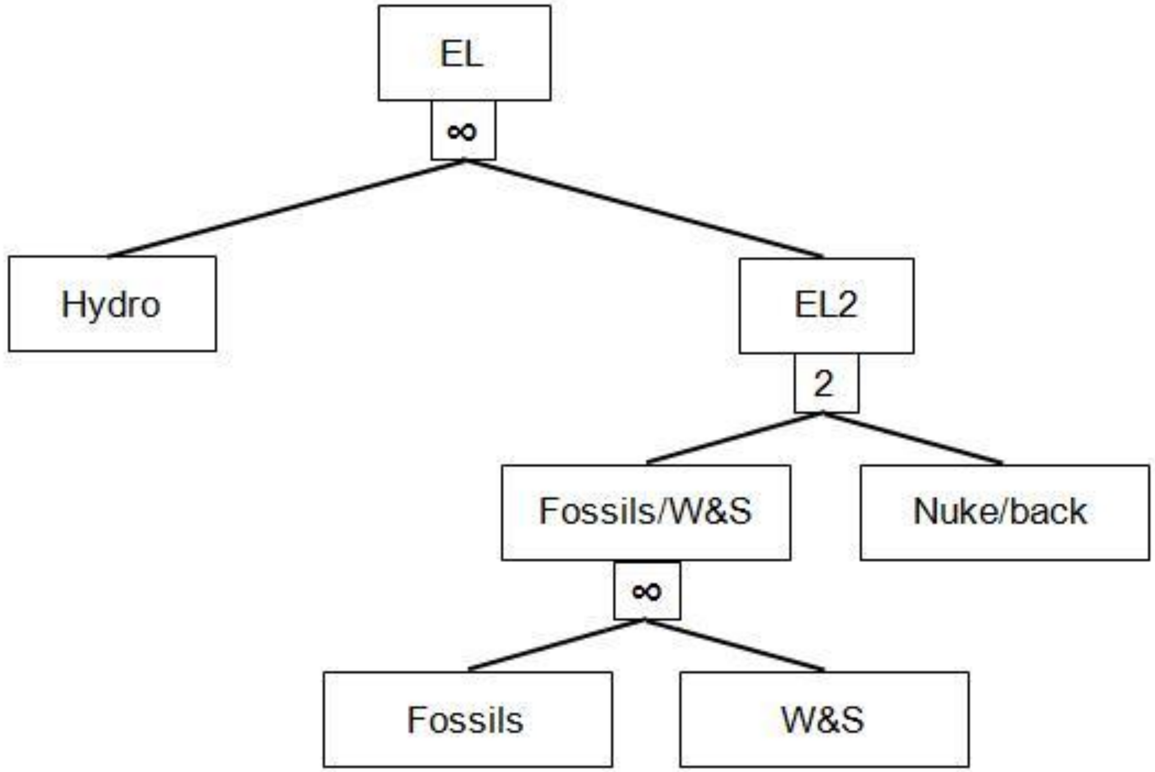
Tested CES solutions: EL2 (current)



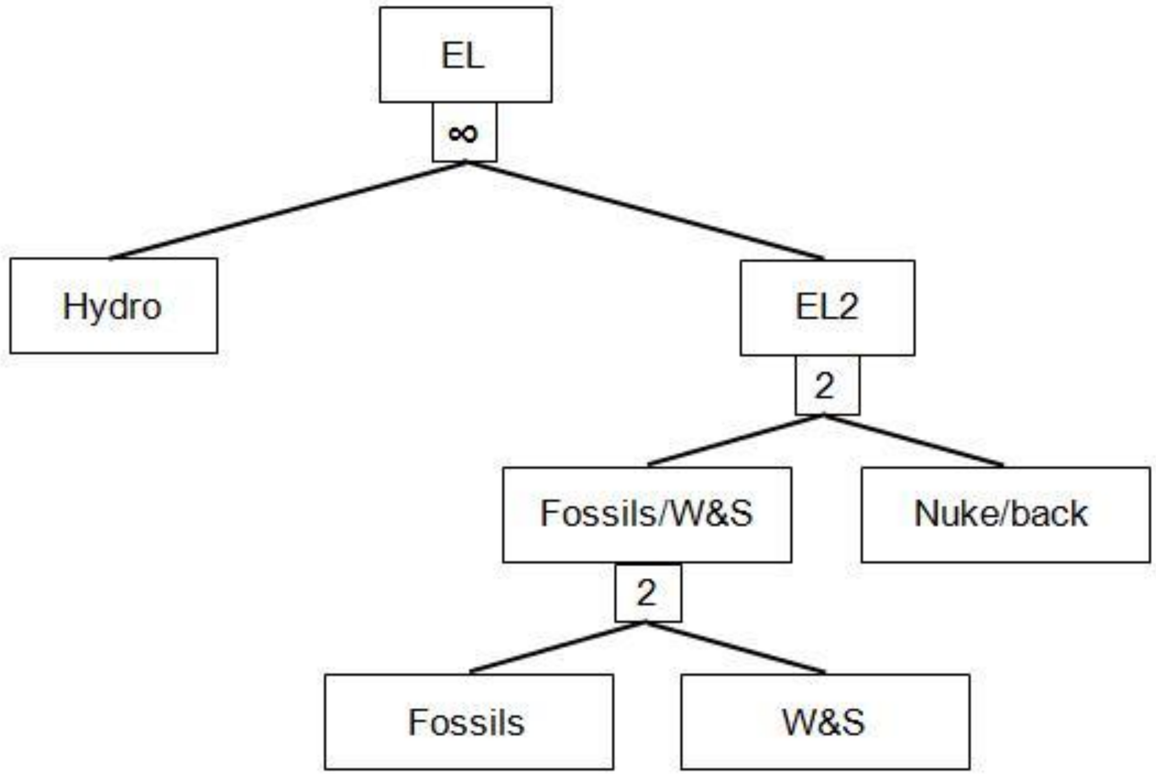
Tested CES solutions: EL



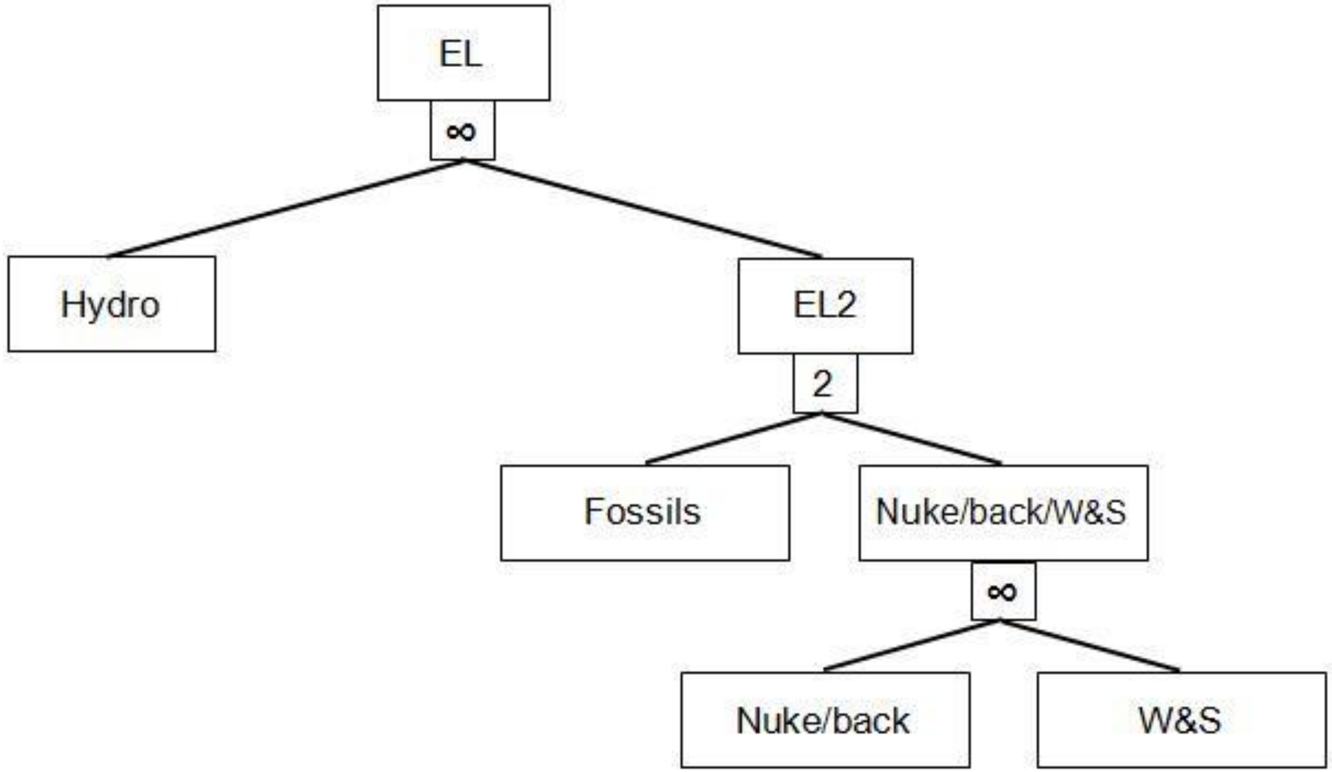
Tested CES solutions: ELFF_LIN



Tested CES solutions: ELFF_CES2



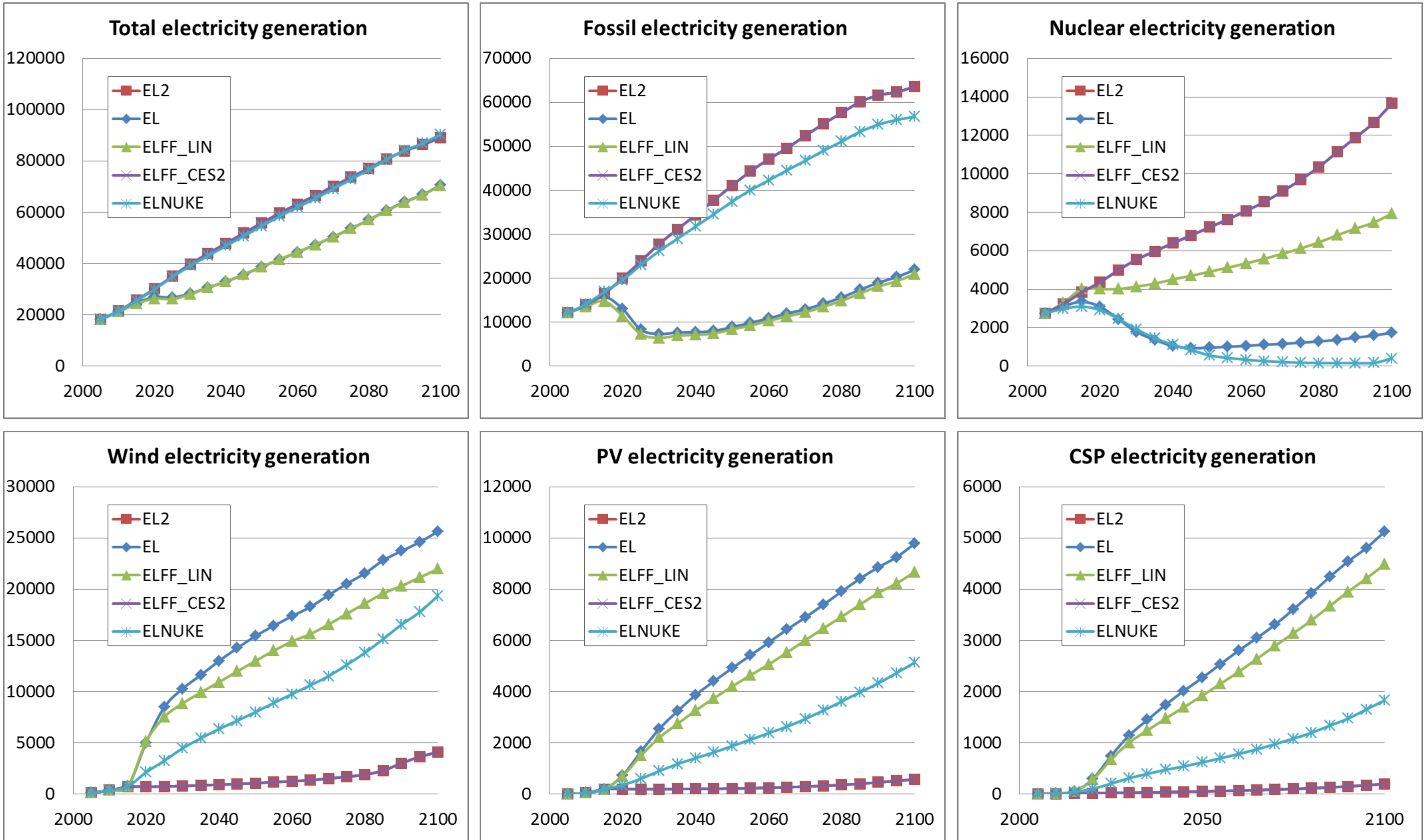
Tested CES solutions: ELNUKE



CES structure: sensitivity analysis – Electricity Generation

BaU

[TWh/yr]



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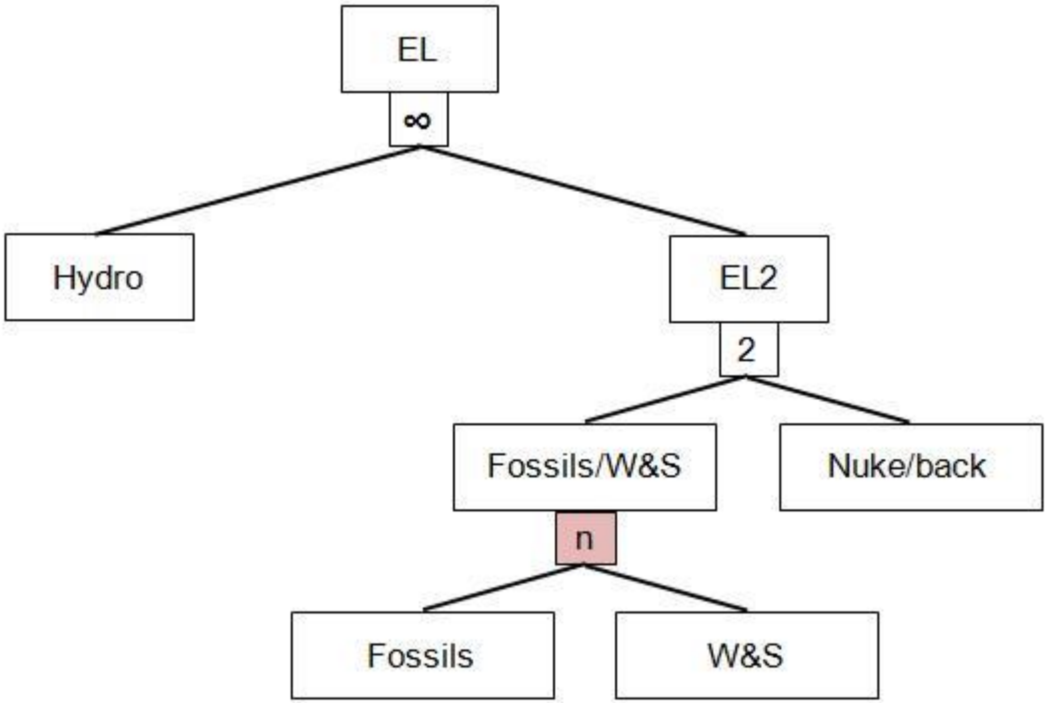
CES structure: sensitivity analysis – Electricity Generation

- If renewables are constrained in a highly nested structure and/or with low elasticities (as happens in the EL2 and ELFF_CES2 cases), their growth over time is extremely penalized.
- If they are let more freely compete with the other technologies (EL, ELFF_LIN, ELNUKE), their growth over time is impressive. This growth is naturally performed to the detriment of fossils (ELFF_LIN), nuclear (ELNUKE) or both of them (EL). In the ELNUKE case, nuclear is completely phased out over time.
- The overall electricity production mainly reflect the fossil behavior.
- These are baseline cases: in policy scenarios, the growth of VREs would be even more dramatic.

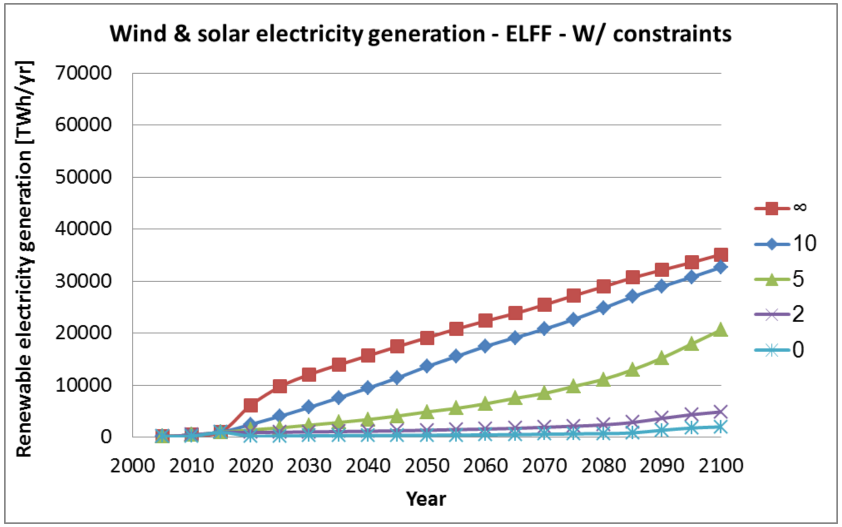
Elasticity values

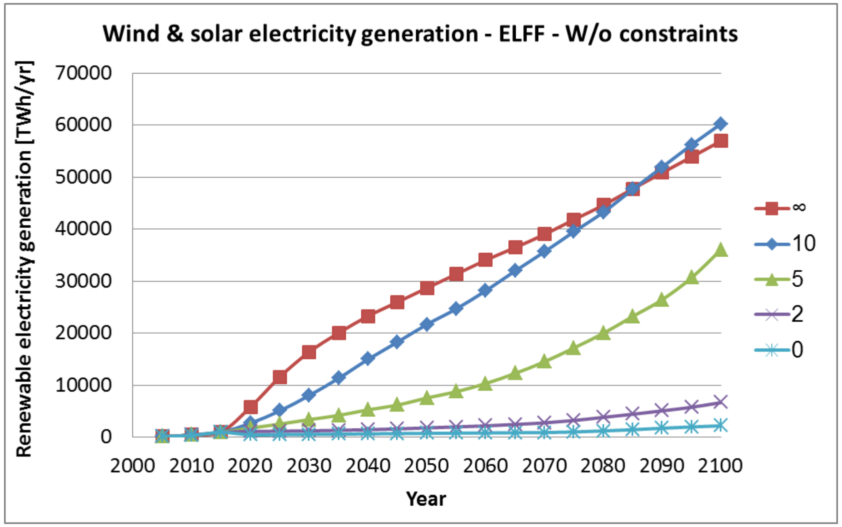
The actual CES configuration should be chosen basing on technical considerations. Renewables substantially compete with fossils, while nuclear (and even more hydro) are normally less subject to this competition → The final scheme adopted is to nest renewables with fossils, as done in the ELFF configuration.

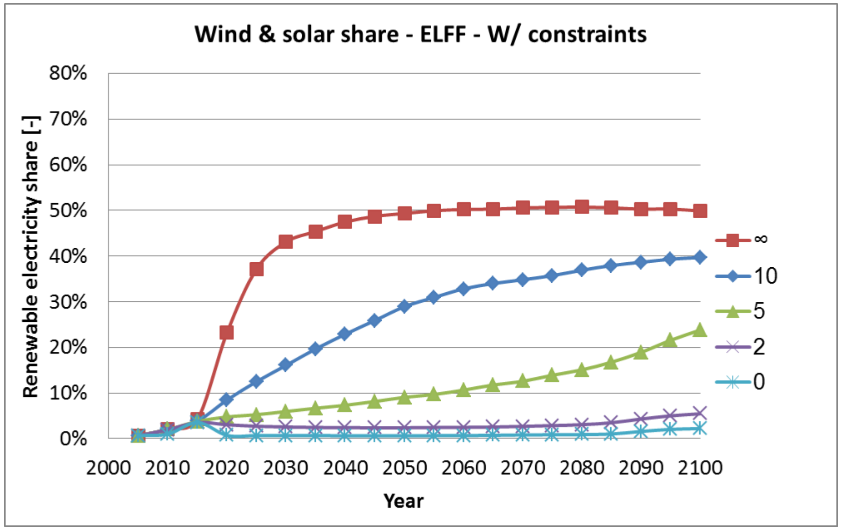


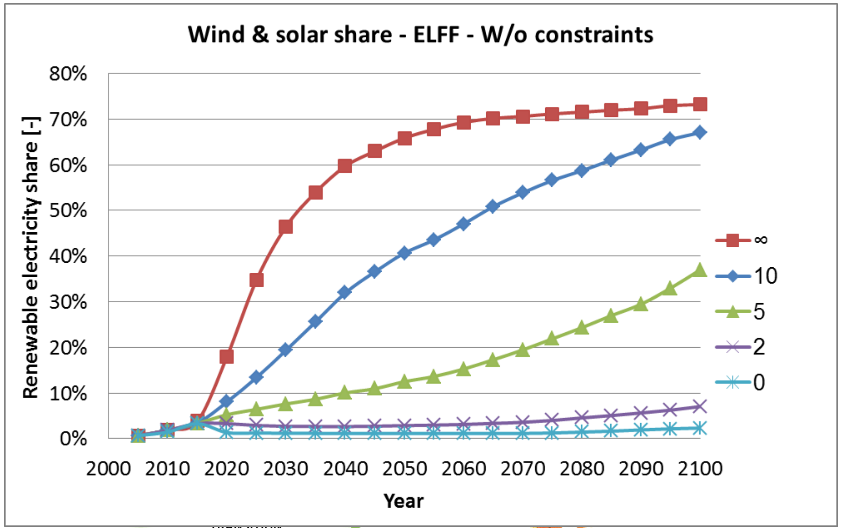
Sensitivity analysis on the elasticity value

Elasticity values: sensitivity analysis – Gen. and share









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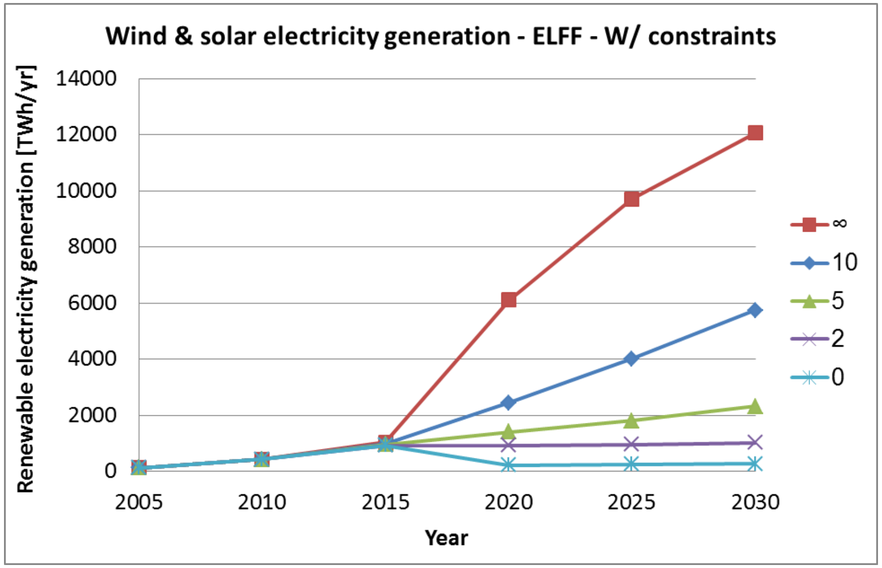
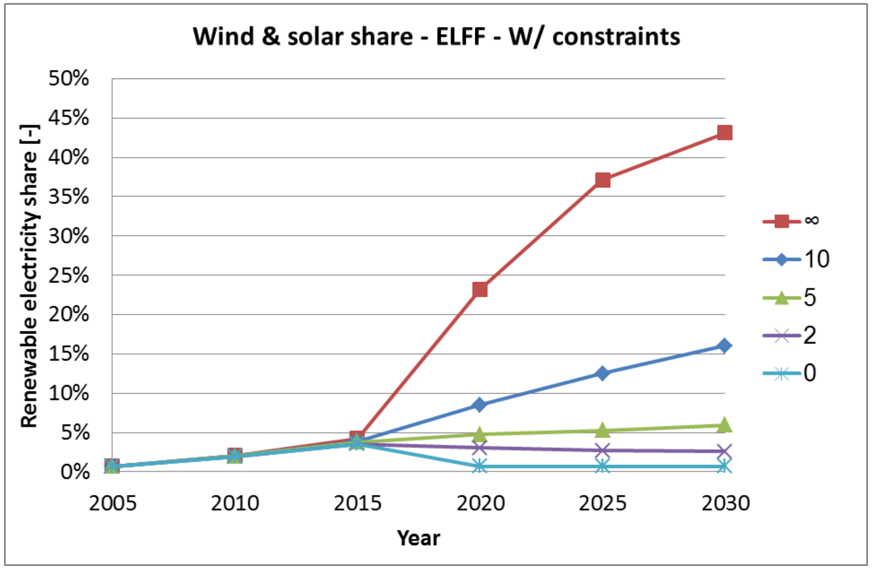
Elasticity values: sensitivity analysis – Gen. and share

- The value assigned to the elasticity of substitution is of paramount importance.
- Very low levels of elasticity imply no or low VRE penetration in the electricity mix over time.
- If higher and higher elasticities are applied, renewable penetration becomes more and more marked. With the application of an infinite elasticity, VREs are characterized by a tremendous growth immediately after 2015 (VREs capacity is fixed up to 2015).
- Elasticities of substitution are the key driver of VRE penetration, but the two explicit constraints play a role, too, especially at high levels of VRE penetration, i.e. at high levels of elasticities.
- A saturation effect takes place in the linear case (due to the flexibility constraint in the w/ constraints case).

Elasticity values: sensitivity analysis – Gen. and share





- An intermediate level of elasticity of substitution determines the most likely behavior, in general terms and also in the light of last years' evolution.
- Only the BaU cases have been taken into account in this analysis: the implementation of mitigation policies would inevitably lead to a higher deployment of renewable technologies.

→ An elasticity of substitution equal to 5 has been chosen for the final version of the model.

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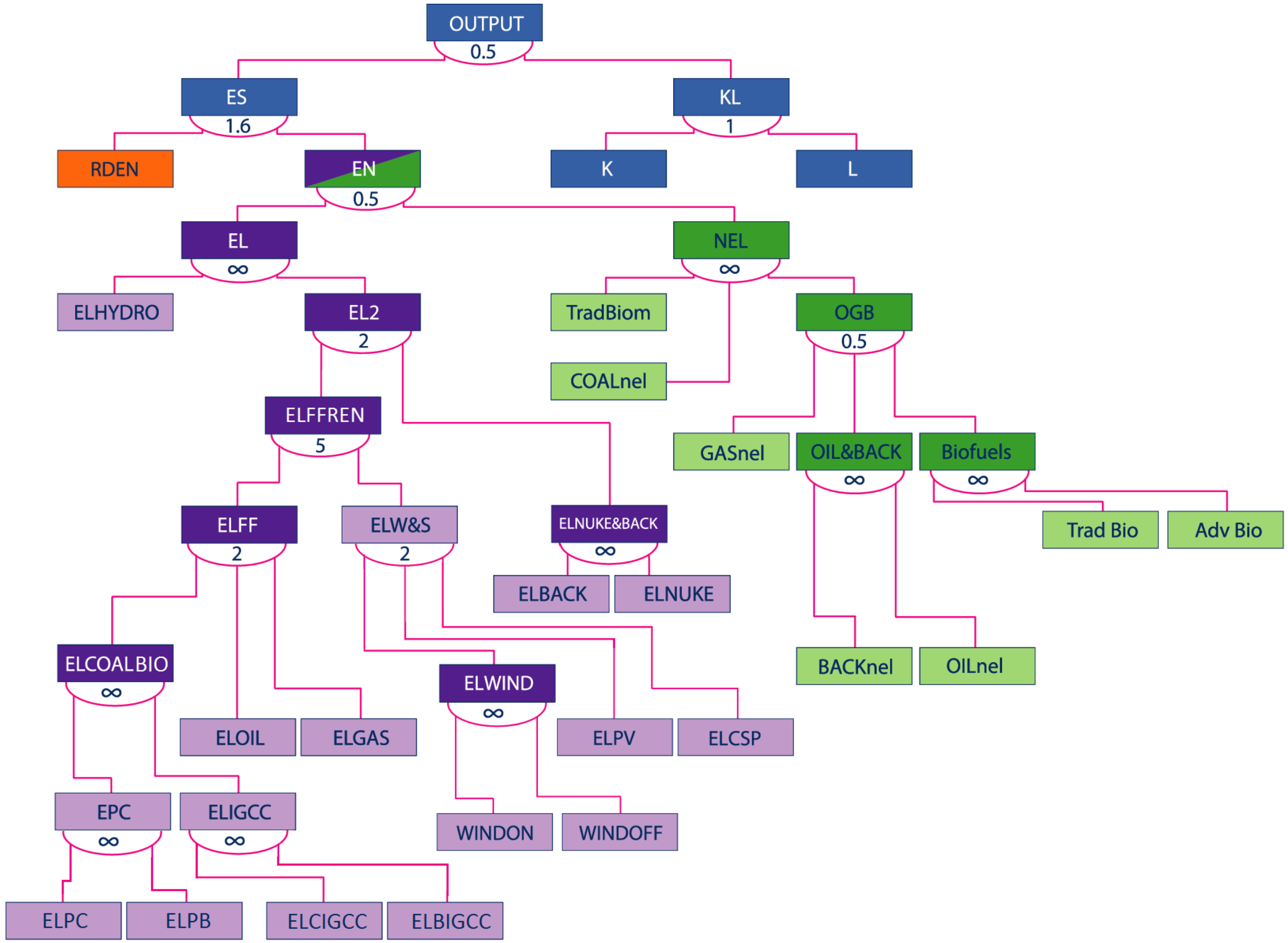
The WITCH model: CES structure (final)



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Conclusions

- The CES structure and the elasticity values are fundamental in determining VRE penetration.
- The most proper solution has been identified in a CES structure where wind and solar technologies are nested in a node with fossils according to an intermediate elasticity of substitution (equal to 5). This intends to take into account that:

  i) renewables mainly compete with fossils;

  ii) this competition is rather elastic, which means that an elasticity equal to 2 is not sufficient to capture the real dynamics of the electricity sector.
- In general, the explicit flexibility and capacity constraints are necessary to describe specific technical aspects related to VRE penetration (e.g. the need for a flexible fleet and for the installation of a backup capacity), but the CES configuration is the main driver of VRE penetration.

Caveats (… and implied future work)

- WITCH does not feature many power technologies which might lead to different electricity mixes (storage, combustion turbines, etc.).
- No curtailment of VRE electricity generation is considered.
- Flexibility parameters have been calibrated basing on the US power system.
- The flexibility parameters of CCS plants have been assumed equal to the corresponding non-CCS ones, while a higher inflexibility might be envisioned.

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http://www.pathways-project.eu/ email: pathways@pbl.nl

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