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Including System Integration of Variable Renewable Energies in a Constant Elasticity of Substitution Framework: the Case of the WITCH Model

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Summary

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Keywords: Variable Renewable Energies, System Integration, Electrical Grid, Constant Elasticity of Substitution, Integrated Assessment Models

JEL Classification: Q4, Q41, Q42

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Including System Integration of Variable Renewable Energies in a Constant Elasticity of Substitution Framework: the Case of the WITCH Model

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Abstract

The penetration of Variable Renewable Energies (VREs) in the electricity mix poses serious challenges in terms of management of the electrical grids, as the associated variability 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 (IAMs) is to simulate the evolution of electricity demand and generation mix over time, therefore a proper modeling of VRE system integration is crucial.

In this paper we discuss how different modeling mechanisms can profoundly impact the evolution of the electricity mix, and specifically renewable penetration. In particular, we focus on the effects of introducing a set of explicit system integration constraints in a model, WITCH, characterized by a Constant Elasticity of Substitution (CES) framework.

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1. Introduction

Climate mitigation, and especially the reduction of greenhouse gas emissions, is necessary for preventing detrimental climate change during the 21st century. Power generation is the largest contributor to anthropogenic CO_2 emissions (IPCC, 2014) and therefore great mitigation efforts will be required in this area. In the next decades, a general electrification of the energy sector (Wei et al., 2013) and a simultaneous decarbonization of the electric sector (Capros et al., 2012) are expected to take place. According to the International Energy Agency (IEA), the decarbonization of the energy system will rely on four pillars: energy efficiency, renewables, nuclear and Carbon Capture and Storage (CCS) (IEA, 2012).

Since the beginning of the 21st century, renewable energies have been characterized by a great expansion and have been gaining market share, even if many of them have not yet reached a complete techno-economic maturity: in most cases, their diffusion was possible only thanks to generous public incentives. Focusing on the power sector, renewable energies can be classified into dispatchable and non-dispatchable, depending on the nature of the power output. Dispatchable technologies are fed by a controllable or relatively constant energy source (e.g. biomass, hydroelectric, geothermal), and thus guarantee a constant power output. Non-dispatchable technologies rely on sources which are variable (thus the name, Variable Renewable Energies, VREs) and cannot be fully controlled (e.g. wind and solar). Indeed, only PhotoVoltaics (PV) is usually considered a VRE among solar technologies, since Concentrated Solar Power (CSP) is normally coupled with a thermal energy storage, which guarantees dispatchability. Most renewables are likely to play a role in the future power scenario, and this particularly applies to wind and solar (Krey et al., 2014 and Luderer et al., 2014), especially in Europe (Knopf et al., 2013) .

The integration of high levels of variable renewable energies into the electrical grid is an awkward problem, however. Electrical grids require that the load be equalized instantaneously with the generation. This does not represent a major issue as far as traditional dispatchable technologies are concerned, since power plant operators can adjust the power output by regulating the fuel input in a thermoelectric plant, or the water flow through a dam, and so on. But wind and solar sources are intermittent by nature and the associated electric production, in the absence of storage devices which may compensate punctual fluctuations, may change markedly depending upon the prevailing weather conditions and time of day. Therefore, as storage technologies are not available at large scale at least in the short term, grid management with increasing levels of renewable penetration becomes a potential non-trivial issue. Finding an adequate level of detail to tackle this aspect within Integrated Assessment Models (IAMs) is not an easy task: high spatial and temporal resolution is needed for model accuracy, but IAMs inevitably feature some level of aggregation and long-time periods can also be needed to examine how the system will evolve to meet changing energy demands and climate change. As a result, different modeling mechanisms, characterized by different levels of detail, can be implemented to describe this issue.

A strong research effort to improve the description of VRE system integration in climate-energy-economic models has been carried out in the context of the Task 5.1 of the European ADVANCE project ("Report documenting methodological approaches for representing VRE in Energy System Models"). The WITCH model has been developed by introducing a set of explicit constraints aiming at properly describing VRE system integration; however, the WITCH model is also characterized by a Constant Elasticity of Substitution (CES) framework, which represents an implicit constraint to renewable penetration. The main aim of this work is to provide a quantitative evaluation of the impacts that the CES structure and the explicit system integration constraints have on the evolution of the electricity demand and mix, and the interaction of these two modeling mechanisms, highlighting also the important role played by storage.

The paper is structured as follows. Section 2 is dedicated to the presentation of the WITCH model, and in particular to the modeling of wind and solar technologies. Section 3 is dedicated to the mechanisms adopted to describe VRE integration in the grid, firstly presenting the different solutions proposed in the literature and then focusing on those adopted in WITCH. Section 4 describes the impacts of modifying the CES tree. The effects of the implementation of the explicit VRE modeling constraints are discussed in Section 5, also analyzing the impacts of the introduction of storage. Finally, Section 6 concludes.

2. The WITCH model

WITCH (World Induced Technical Change Hybrid) is a climate-energy-economic IAM, written in the GAMS (General Algebraic Modeling System) language, aimed at studying the socio-economic impacts of climate change throughout the 21st century (starting from 2005 with time steps of five years). It is defined as a hybrid model as it combines an aggregated, top-down inter-temporal optimal growth Ramsey-type model with a detailed description of the energy sector, nested in a CES structure (see Figure 1 in the next pages for more details). The model is defined on a global scale: countries are grouped into thirteen aggregated regions, which behave independently with respect to all major economic decision variables, including investments and fossil fuel use, by playing a non-cooperative Nash game. The thirteen economic regions are USA (United States), WEURO (Western EU and EFTA countries), EEURO (Eastern EU countries), KOSAU (South Korea, South Africa and Australia), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states and non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa except South Africa), SASIA (South Asian countries except India), EASIA (South-East Asian countries), CHINA (People’s Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India). Technological change in energy efficiency and specific clean technologies is endogenous and reacts to price and policy signals. Technological innovation and diffusion processes are also subject to international and intertemporal spillovers. A more detailed description of the model can be found in Bosetti et al. (2006, 2007 and 2009) and in the web http://witchdoc.like-spinning-plates.com/.

Supply curves for the wind module are provided by the National Renewable Energy Laboratory (NREL), see Eurek et al. (2016). These curves provide the installable capacity as a function of wind class, which corresponds to a specific level of full load hours[1], and of distance from load centers (onshore wind) or from shore (offshore wind). For offshore wind, an additional disaggregation is performed as a function of sea depth.

Resource supply curves are implemented also for solar technologies. These have been provided by the German Aerospace Center (DLR, Deutsches Zentrum für Luft- Raumfahrt), see Pietzcker et al. (2014). Similarly to wind curves, they provide capacity as a function of solar class (i.e. full load hours) and of distance from load centers. However, there is an important difference between solar and wind curves: differently from onshore and offshore wind, solar PV and solar CSP compete for the same resource, although CSP requires flatter grounds and thus the area where it can be installed is lower than the suitable one for PV. An additional constraint thus takes into account this competition.

Table 1 summarizes the main economic and technical assumptions for wind and solar technologies. As already discussed, CSP is not strictly an intermittent energy technology, but it is presented for

[1] Full load hours indicate the yearly hours in which the plant would be supposed to operate at the nameplate capacity to equivalently generate the same amount of energy produced in the year. The so-called capacity factor expresses the same concept in normalized terms.

completeness. In particular, a solar multiple 2 (SM2) configuration has been considered, which entails a 6h-storage capacity. Although the base year for the simulations is 2005, the installed capacity is fixed up to 2015, in order to capture the massive expansion that has been taking place in recent years and that would not be otherwise shown by the model due to the economic performances and the CES structure. Capacity data are taken from IEA (2012), which reports the real 2010 data and the projected 2015 data. Initial cost assumptions are taken from IEA (2005) and Kaltschmitt et al. (2007). For offshore wind, a specific investment cost is assigned to each depth category: the cost increase with respect to onshore wind is equal to 80% for the shallow offshore (0-30 m), 100% for the transitional offshore (30-60 m) and 120% for the deep offshore (60-1000 m), respectively (Carbon Trust, 2008). O&M costs are fixed: no variable O&M costs are considered. The model accounts for technical change, and in particular features a progressive cost reduction related to the cumulative capacity installed over time (learning-by-doing). The learning rate indicates the cost reduction associated to a doubling of the global installed capacity. Learning rates have been calibrated to replicate the cost reduction experienced in the past years and the projected evolution in the near future. Learning rates are taken from Kaltschmitt et al. (2007), Carbon Trust (2008), and Neij (2008). Considering the strict relationship existing between onshore and offshore wind, the installed capacity of the former is accounted for in the learning process of the latter to an extent of 80%, and vice versa (cross learning) (Carbon Trust, 2008). Floor costs are implemented, too.

Parameter	Onshore wind	Offshore wind	PV	CSP
Global capacity	63 GW (2005) 195 GW (2010) 379 GW (2015)	0 GW (2005) 3 GW (2010) 10 GW (2015)	3 GW (2005) 38 GW (2010) 153 GW (2015)	0.4 GW (2005) 1 GW (2010) 6 GW (2015)
Investment cost (2005)	1467 $/kW	Shall.: 2641 $/kW Trans.: 2861 $/kW Deep: 3081 $/kW	4650 $/kW	6123 $/kW
Lifetime	30 years		25 years	
O&M cost	25-30 $/kW	2 · onshore	43 $/kW	120 $/kW
Learning rate	10%	13%	17.5%	10%
Cross learning	80%		-	-
Floor cost	500 $/kW	900 $/kW	400 $/kW	1500 $/kW

Table 1 – Design parameters for renewable energies in WITCH.

The electrical grid is explicitly modeled as well. The main objective of this module is to calculate the investments needed to install the transmission lines sufficient to comply with the projected future capacity expansion. The description is quite simplified and it is summarized in two equations. The first one (1) is the capital equation which, for every region (n) and time step (t), accounts for the ageing and the consequent retirement of the existing capacity (K_EL_GRID), and the capacity addition due to the investments (I_EL_GRID), analogously to all the other energy technologies. Lifetime is supposed to be 60 years, which corresponds to a depreciation rate (δ) of 0.038 in WITCH. An equivalent investment cost of 400 $/kW (grid_cost) is adopted, averaging costs over lengths and capacities of the transmission lines (see Bauer et al., 2008, and Massetti and Ricci, 2013):

$$K\_EL\_GRID(t+1,n) = K\_EL\_GRID(t,n) \cdot (1-\delta) + \frac{I\_EL\_GRID(t,n)}{grid\_cost} \qquad (1)$$

In the second equation (2) the grid capital stock is adjusted to power capacity (K_EL), taking into account a linear relationship between grid capacity and power capacity for the non-VRE traditional power technologies, and an additional grid stock requirement for wind and solar technologies for i) connecting wind and solar plants located far from load centers or shore (transm_cost), and ii) building a wider interconnection for the integration of VREs (curtailment reduction, dispatchability increase, etc.), the latter exponentially increasing with VRE penetration (share_el), with an exponent (b) equal to 1.55 (Luderer et al., 2013). In formula (jel indicates the generic power technology):

$$K\_EL\_GRID(t,n) = \sum_{jel|non\_VRE} K\_EL(jel,t,n) + \sum_{jel|VRE} \sum_{distance} K\_EL\_D(jel,t,n,distance) \cdot \frac{transm\_cost(jel,distance)}{grid\_cost} + \sum_{jel|VRE} K\_EL(jel,t,n) \cdot \left(1 + share\_el(jel,t,n)^{b}\right) \qquad (2)$$

where $K\_EL(jel,t,n) = \sum_{distance} K\_EL\_D(jel,t,n,distance) \quad \forall jel|VRE$.

The actual result is that the grid requirement increases by averagely 5%, 10% and 20% with a 20%, 40%, and 60% VRE penetration, respectively.

The last version of the model adopted for the ADVANCE project also features a simple modeling of a generic storage technology. The investment cost decreases over time following an exogenously fixed path based on Viswanathan et al. (2014). This cost is equal to about 2000 $/kW in 2020, 1000 $/kW in 2050 and 550 $/kW in 2100. No O&M costs are assumed for simplicity, while plant lifetime is 22 years. Other modeling details are relevant in relationship with the constraints implemented to model the VRE penetration, thus they will be discussed in Section 3.

3. Modeling VRE integration

3.1 VRE integration mechanisms in IAMs

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 at al., 2016):

- 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 VRE share);
- 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.

These eight mechanisms can conceptually be grouped into four categories of two items each:

- The first two constraints are very basic solutions and can just be applied as provisionary solutions for first-attempt models.
- Implicit cost markups may derive from a set of non-linear production functions (e.g. CES), which model the resistance to changes in the technology mix from a calibrated status quo that is commonly experienced in reality. As a consequence, such constraints alone may not satisfy all the physical restrictions related to VRE integration. Explicit cost markups are exogenous functions which can be shaped to actually represent an aggregated system integration constraint, summarizing all the relevant costs (backup capacity, curtailment of peak production, etc.). Typically, they depend monotonically on the VRE penetration in the electricity mix. Their main limit is that they are applied directly and only to VREs, while indirect implications on the other technologies and on the power generation fleet are not considered.
- The constraints on the flexibility/reliability and the installed capacity of the power generation fleet account not only for VREs, but also for the interaction between them and the dispatchable share of the generation fleet, as they pose requirements for the whole electric system. As it will be described further on, they represent a balanced solution between accuracy and manageability for models which describe electricity consumption and production in average terms over the year, like WITCH (Sullivan et al., 2013).
- The last two mechanisms are available in models with higher time accuracy which explicitly describe different segments of the electric demand (peak, intermediate, base load, etc.), which is not the case for WITCH. For this reason, they are not considered in this work. These techniques allow capturing the temporal heterogeneity of electricity, but naturally imply a higher modeling complexity (Ueckerdt et al., 2011).

In general the different methods do not necessarily exclude each other, and may be jointly implemented, even though particular care must be adopted to avoid double counting. WITCH features a set of explicit constraints regarding the flexibility/reliability and the installed capacity of the power generation fleet (Section 3.3), but the underlying CES structure used to model energy supply across technologies also plays a role in limiting VREs (Section 3.2).

3.2 Implicit VRE integration in WITCH: 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 shares 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 parameterization adopted, where different nesting of production functions across dispatchable and non-dispatchable technologies may be envisioned;
- 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, as the economic forces of government policies of the last years are inevitably not accounted for in this setting; this may penalize VREs more than what would be reasonable to expect, especially with low substitution elasticities, which tend to maintain the starting share of factors and thus penalize the technologies starting from low penetration levels.

Despite all these limitations, the CES will still be retained in the final design of the model as a way to capture the residual costs left out from the other more specific modeling devices described below. Nonetheless, the calibration of its parameters concerning VREs is done consistently with the most recent estimates of VRE prices and quantities, and not with those of the base year, to better reflect the economic forces of the status quo.

Figure 1 shows the CES structure of the WITCH model. Energy (ES) on the one hand, and capital and labor (KL) invested in the production of final good on the other hand, are combined to produce the economic output of the aggregated model. Energy is firstly divided into the capital of energy R&D and the actual energy generation, which is described by a production function which aggregates the different technologies with different elasticities of substitution. The first distinction is between the electric and non-electric sector, with a progressive disaggregation down to the single technologies. The road passenger transport sector (Light-Duty Vehicles) is also explicitly modeled (not shown in the scheme).

Focusing on the electric sector, the hydroelectric technology is found first, which is substantially exogenous in the model. The remaining technologies are grouped in the EL2 nest, being divided into two nodes: EFLFFREN, which is the combination of fossils and renewables, and ELNUKE&BACK, which is the combination of nuclear and backstop. Fossils feature coal&biomass (further divided into pulverized coal without CCS, pulverized biomass without CCS, integrated gasification coal with CCS and integrated gasification biomass with CCS), oil (only without CCS) and gas (with and without CCS)[2]; variable renewables feature wind (further divided between onshore and offshore), solar PV and solar CSP; nuclear and backstop feature traditional fission nuclear and a backstop technology, which represents a hypothetical future technology which will allow electricity generation with no fuel costs and no carbon emissions (it can be interpreted as an advanced nuclear technology: nuclear fusion or advanced fast breeder fission reactors).

Elasticities of substitution are either infinite or 2, which indeed is a quite consolidated value in the literature (Papageorgiou et al., 2013), apart from the 5 between the fossils and the renewables node (see Section 4.2). The elasticity value is a fundamental parameter in a CES structure. A null elasticity means no substitutability between the production factors. Independently of costs, the production contributions are summed in fixed shares. An infinite elasticity entails a complete interchangeability of the factors, which are linearly combined and whose choice has no structural constraints and depends on cost considerations only. Intermediate elasticities determine an intermediate behavior.

[2] The capture rate for the CCS technologies is assumed equal to 90%.

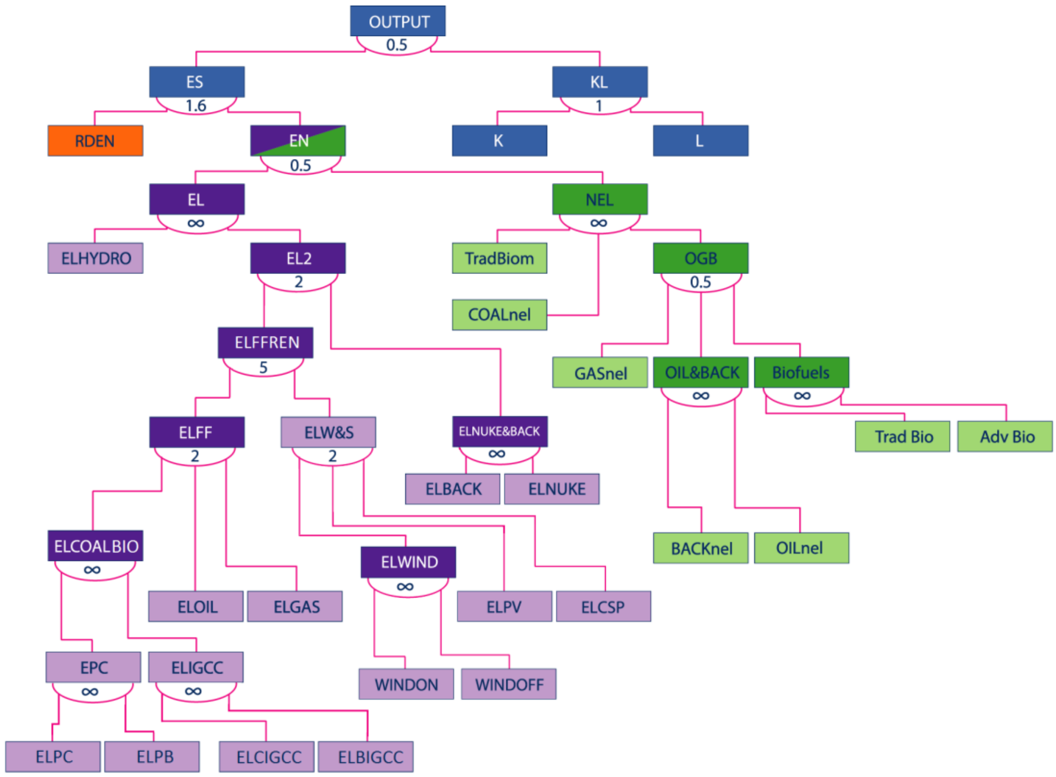

Figure 1 – The CES structure in WITCH.

3.3 Explicit VRE integration in WITCH: flexibility and capacity constraints

The first explicit solution for modeling VRE system integration in WITCH was the implementation of an external cost curve, based on Hoogwijk et al. (2007), which simulated an economic penalty increasing with the VRE penetration in the electric mix. The curve was almost flat up to a 25%-penetration (remaining lower than 1 c$/kWh), then increasing exponentially at higher penetration rates.

Afterwards, a deep revision of the modeling of renewable energies has taken place. Not only were offshore wind and solar technologies added to the renewable node (the original version of the model included onshore wind only), but the abovementioned external cost curve was substituted with the solution described in Sullivan et al. (2013)[3], which is based on two constraints: (1) a flexibility constraint imposed on annual generation and (2) a capacity constraint that ensures that peak capacity can be met.

The first constraint requires that the electricity system maintain a minimum level of flexibility to ensure that it can handle load fluctuations. All energy technologies are assigned a value from -1 to 1 accounting for their grade of flexibility. Negative values are assigned to inflexible, intermittent technologies, such as wind and solar PV. Wind is given a value of -0.08 while PV is assigned -0.05, since the solar source is generally less intermittent than wind. Zero is assigned to those technologies which, due to technical constraints, cannot assure flexibility to follow load (e.g. nuclear and CSP[4]). Positive coefficients are assigned to flexible

[3] This approach has been developed for the MESSAGE model, which features similar characteristics as WITCH.

[4] The CSP value is not specified in Sullivan et al. It has been fixed to 0 because this technology is not inflexible, thanks to the already described SM2 configuration, but it cannot be considered fully able to provide flexibility when required. In this sense it must be underlined that real plants always feature a complementary gas feeding (to prevent the working fluids from freezing, to provide a backup thermal source, etc.), which in reality allows some flexibility, but this aspect is not modeled in WITCH.

technologies. For example, 0.5 is assigned to gas combined cycles[5] and hydropower, whereas 0.3 is assigned to technologies with less flexibility, such as biomass and oil power plants, and 0.15 to coal. Finally, 1 is assigned to storage, which provides full flexibility. CCS plants are assumed to have the same flexibility coefficient as the corresponding traditional ones, even though further research may unveil lower flexibility levels. A negative value (-0.1) is also assigned to the overall demand, in order to account for the fact that some flexibility is required even in a grid with no VRE due to the variability of the load. Table 2 summarizes the flexibility coefficients for the technologies considered in WITCH.

Power technology	Flexibility coefficient
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

Table 2 – Design flexibility parameters for power technologies in WITCH.

The constraint is then formulated so that the sum of the electricity generated by the different technologies jel (Q_EL) weighted on the corresponding flexibility coefficients (f) – considering also the load contribution – is larger than or equal to 0. The resulting quantity can be called flexible residue. In formula:

$$\sum_{jel} Q\_EL(jel,t,n) \cdot f(jel) + Q\_EL\_TOT(t,n) \cdot f_{load} \geq 0 \quad (3)$$

This constraint, for instance, prevents the electricity mix from converging to a 50% nuclear + 50% VRE scheme, as the electric system would not be sufficiently flexible.

In our modeling, storage is not supposed to actually generate useful electricity, being essentially adopted for flexibility purposes. Within this constraint, the equivalent electricity contribution from storage is obtained by multiplying its capacity by a fixed value of 2000 h/yr.

The abovementioned constraint guarantees an average flexibility of the grid, but does not guarantee the fulfillment of the instantaneous peak capacity demand. Thus Sullivan et al. introduced a constraint that requires that firm capacity is at least twice as the yearly average load, the latter being simply calculated as the yearly energy demand divided by the yearly hours. The factor 2 is estimated on an empirical analysis in the USA where peak load is normally about 1.7 times higher than average load, and adding a 15-20% reserve margin, one obtains roughly this value. In WITCH this factor is determined by calibrating it with the

[5] WITCH does not feature gas combustion turbines.

real characteristics of each region's grid, basing on the real 2005 data for installed capacity and average load. For some regions it can be significantly lower, i.e. 1.5.

The firm capacity represents the guaranteed, dispatchable capacity. For flexible, non-intermittent technologies, it is simply the nameplate capacity. For intermittent technologies, the firm capacity is the installed capacity multiplied by two reducing factors. The first one is the capacity factor (CF), which indicates the fraction of the year that the plant needs to generate, running at the nameplate capacity, the amount of electricity really produced during the year; it accounts for the fact that renewable plants indeed do not always run at nameplate capacity for all hours of the year. The second factor is the capacity value (CV): it is a coefficient that decreases with VRE penetration and it is generally related to the ability of a generator to produce during hours with peak load; it is a measure of the reliability of generators when they are really needed and practically accounts for the fact that not only does the wind not always blow at nominal velocity or the sun shine at nominal radiation, but that this is statistically more and more critical with increasing penetrations, as the share of the guaranteed dispatchable capacity is accordingly lower. Sullivan et al. estimate this parameter as equal, in marginal terms, to 90% for a penetration up to 5% in the electricity mix, 60% from 5% to 15%, 30% from 15% to 25%, and 0% above 25%. This expression is applied to wind (summing onshore and offshore) and PV separately. Figure 2 shows the resulting average form of the capacity value and an example of resulting curve given by the multiplication of the two factors, assuming a 25%-capacity factor progressively declining over time. Finally, storage capacity is multiplied by a capacity value, fixed to 0.85, which takes into account the reduction of its contribution at high shares of VRE penetration.

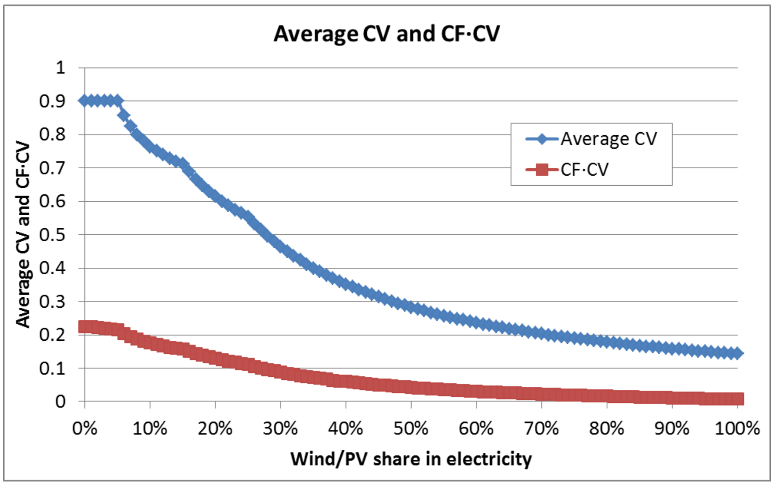

Figure 2 – Capacity value and capacity reduction function.

In mathematical terms the constraint requires that:

$$\sum_{jel|non\_VRE} K\_EL(jel,t,n) + \sum_{jel|VRE} K\_EL(jel,t,n) \cdot CF(jel,t,n) \cdot CV(SHARE(t,n)) + \\ + K\_EL_{storage}(t,n) \cdot CV_{storage} \geq c(n) \cdot Q\_EL\_TOT(t,n)/yearly\_hours \quad (4)$$

where c stands for the multiplicative factor (1.5-2) of the average load.

This constraint requires the installation of backup capacity to guarantee that the power generation system can meet peak load and contingencies when the renewable penetration is large. It should be added that other similar modeling mechanisms involving backup capacity have been proposed (e.g. Bollen, 2013, and Arent et al., 2012), but they are quite rigid, as they all establish a direct correlation between VRE capacity/penetration and backup capacity, which does not capture the rearrangement effects on the entire electric system as occurs with the described method.

4. Effects of the CES structure

4.1 Different tree structures

The first analysis is concentrated on the different positions in the CES tree where the renewable node can be located. Figure 3 reports the several configurations explored.

Taking Figure 1 as a reference, in the first configuration (called EL in the following graphs) the renewable node (W&S, wind and solar) is put in parallel with hydro and the EL2 node[6]. In the second configuration (EL2) the wind and solar node is nested together with fossils and nuclear&backstop. In the third (ELFF_LIN) and fourth (ELFF_CES5) configurations, VREs are nested with fossils, with an elasticity of substitution set to infinite or 5, respectively. The latter is the final configuration adopted in WITCH and described in Figure 1: the reasons which led to this choice are discussed later in this section. Symmetrically, the fifth (ELNUKE_CES0) and sixth (ELNUKE_CES5) configurations have wind and solar nested with nuclear and backstop, again with an elasticity of substitution equal to either infinite or 5.

Figure 4 reports the electricity production per technology in the different CES configurations. For this analysis, the Business-as-Usual (BaU) or baseline scenario has been adopted, which means that no constraints or costs are imposed to carbon emissions.

The impacts of the different positions of the renewable node are remarkable. In general, if renewables are constrained in a structure with low elasticities (as it happens in the EL2 case), their growth over time is extremely penalized. As already discussed, low elasticities tend to preserve the initial shares, thus renewables, which start practically from a zero penetration in 2005, barely manage to enter the electricity mix. Similar or even more marked results would be obtained with lower elasticities: cases like ELFF_CES2 and ELNUKE_CES2 (i.e. similar to ELFF_CES5 and ELNUKE_CES5 but with an elasticity of substitution equal to 2 instead of 5) would give the very same results as the EL2 case (the same elasticity would simply be applied in two different steps), while in the more extreme cases of ELFF_CES0 and ELNUKE_CES0 (with no substitutability between renewables and fossils or nuclear&backstop), VRE penetration would practically be zero all over the century.

On the other hand, if renewables are let more free to compete with the other technologies (linearly in the EL, ELFF_LIN and ELNUKE_LIN cases, with an intermediate elasticity in the ELFF_CES5 and ELNUKE_CES5 cases), they markedly grow over time. This growth occurs to the complete or partial detriment of fossils (ELFF cases), nuclear (ELNUKE cases) or both of them (EL). With the same elasticity, however, renewable penetration is higher if the competition is with fossils rather than with nuclear. Additionally, in the former case wind has the lion's share among renewables, while CSP has more success in the latter. Finally, the overall electricity production mainly reflects the fossil behavior. It is useful to remind that these are

[6] The names indicate the position of the wind&solar node in the CES tree according to the acronyms of Figure 1.

baseline cases (in policy scenarios, the VRE growth would be even more dramatic) and that both storage and the flexibility and capacity constraints are active.

This analysis clearly shows the capital importance of the CES structure. However, the preferred configuration (ELFF_CES5) was chosen basing on the technical consideration that renewables substantially compete with fossils (while nuclear, and even more hydro, are normally less subject to this competition) and basing on the sensitivity to elasticity discussed in the next section.

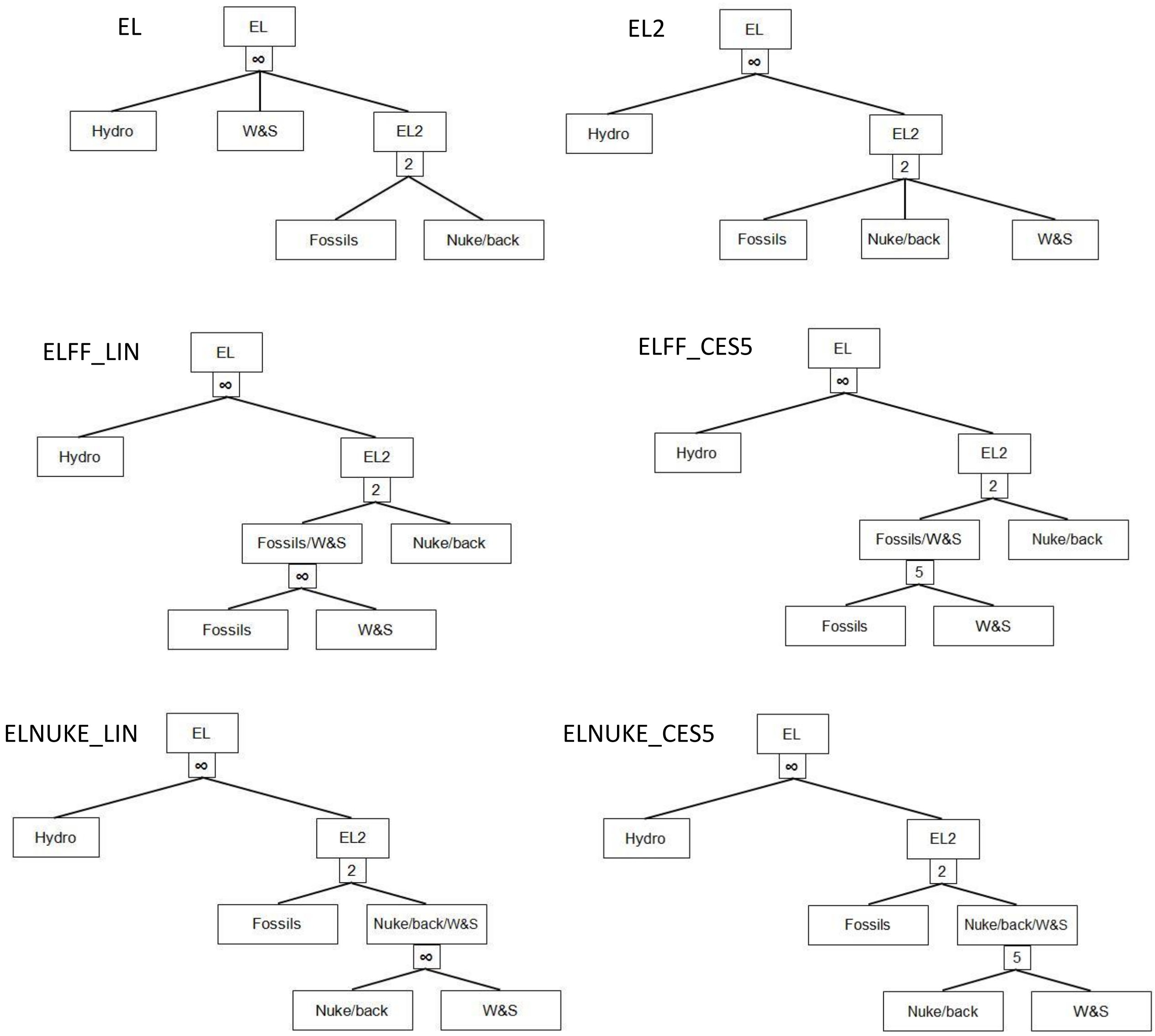

Figure 3 – Explored CES configurations.

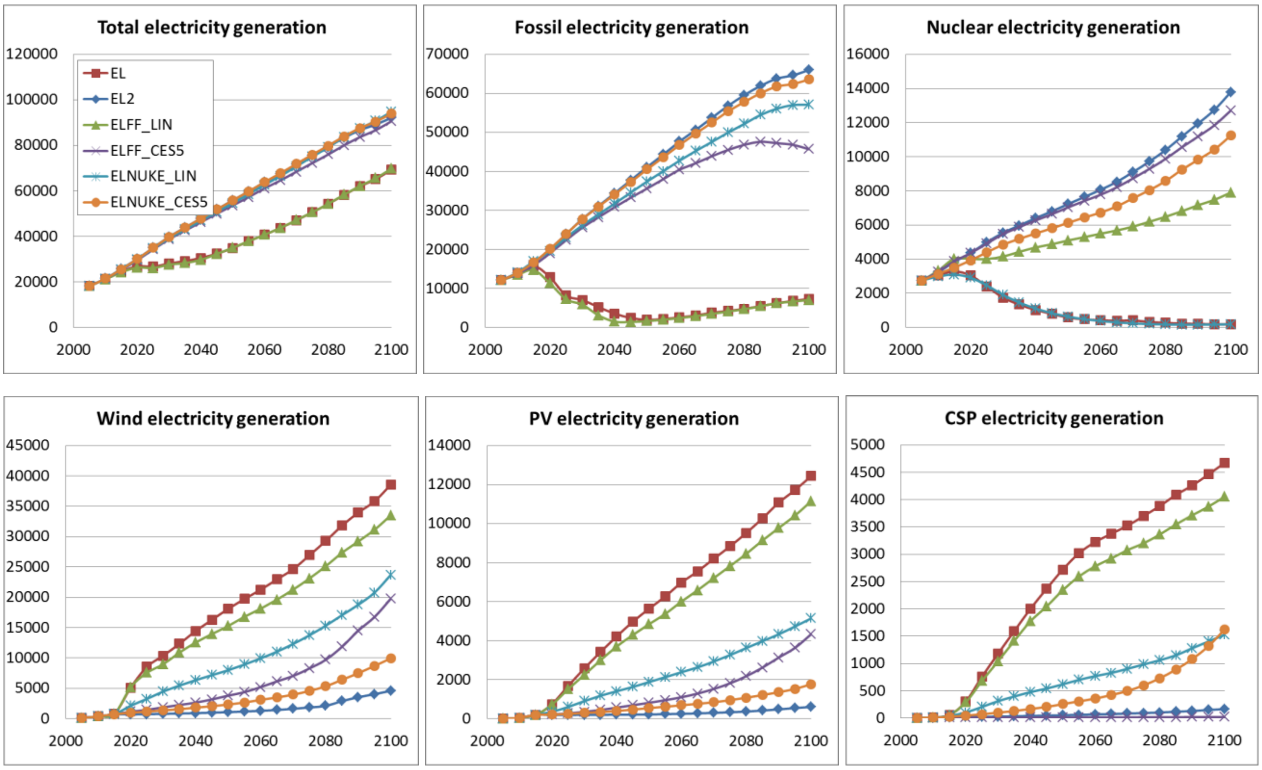

Figure 4 – Electricity generation in TWh/yr per technology over the century in the different CES configurations for the baseline case.

4.2 Elasticity values

In this section we analyze the effects of considering five elasticity values in the structure reported again in Figure 5: 0, 2, 5, 10 and infinite. Figure 6 shows the results for the baseline case, in terms of wind and solar electricity production and share in the electricity mix.

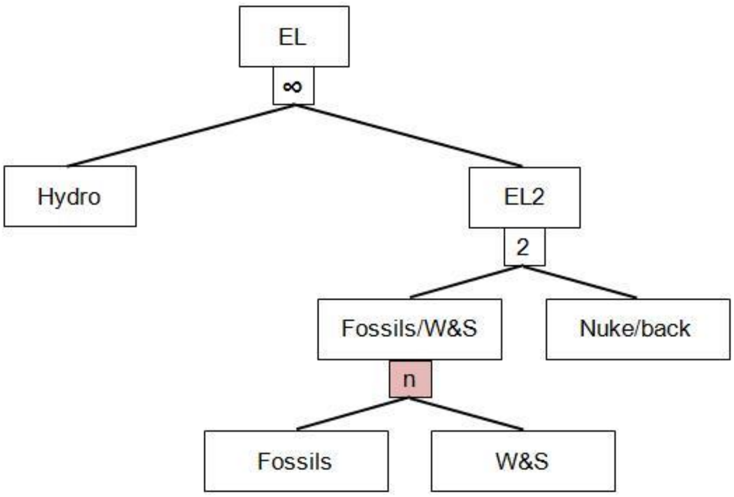

Figure 5 – Fossils-nested CES configuration.

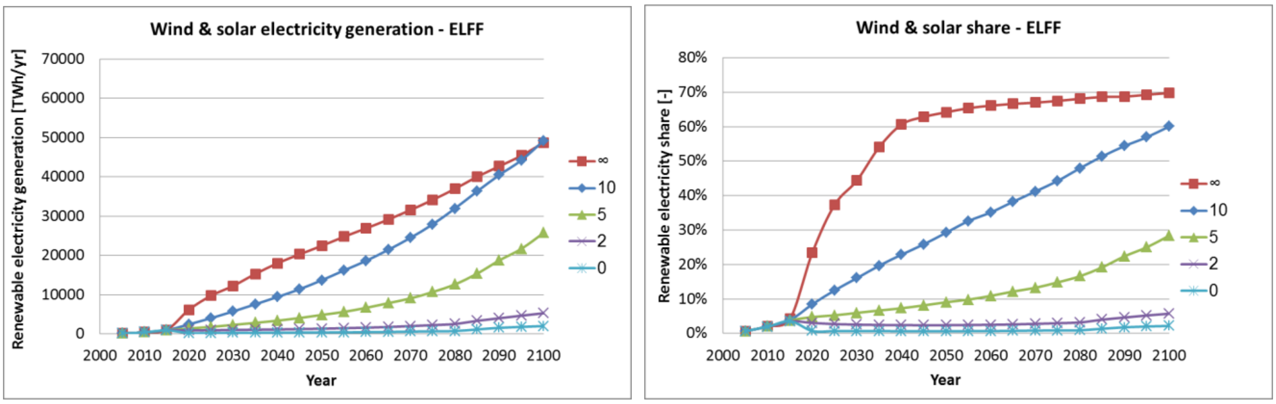

Figure 6 – Wind and solar electricity generation (left) and share (right) at different elasticities of substitution.

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. Indeed, this result is inevitable, since the initial renewable share against the fossil one is very low and low elasticites entail a substantial conservation of the energy shares over time, as already discussed. However, 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 (VRE capacity is fixed until that year). This case shows that the penetration in the electricity mix is not unbounded, however. The wind and solar share, in fact, rapidly reaches 60%, but then it saturates at about 70%, as a combined effect of a series of factors, such as the remaining CES structure (hydro and nuclear are outside the linear competition), the presence of the flexibility and capacity constraints, and the attainment of the floor costs for VREs.

If attention is focused on the evolution of wind and solar production in the first periods after 2015 (Figure 7), it can immediately be understood how an intermediate level of elasticity of substitution such as 5 determines the most likely behavior, in general terms and also in the light of last years' evolution. It should also be considered that only the baseline cases have been taken into account in this analysis and that the implementation of mitigation policies would inevitably lead to a higher deployment of renewable technologies.

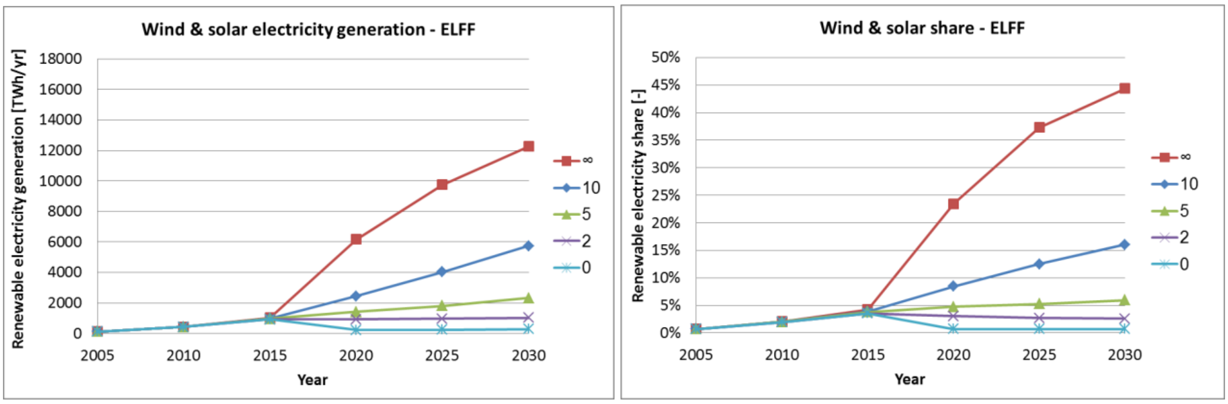

Figure 7 – VRE electricity generation and share with different elasticities of substitution (detail to 2030).

5. Effects of the flexibility and capacity constraints and storage

Having defined the CES structure adopted in the work, the effects of the implementation of the flexibility and the capacity constraints are discussed in this section. The constraints must be jointly applied in order to have a proper modeling of VRE penetration, but their effects will be analyzed separately.

Two scenarios have been taken into account here: a policy scenario where emissions are constrained in order to achieve a temperature increase in 2100 with respect to the pre-industrial level of 2°C has been considered in addition to the baseline scenario adopted above.

5.1 Flexibility constraint

In general, the introduction of the flexibility constraint could potentially have a limited impact. In fact this constraint requires that the electricity mix be sufficiently flexible, but this condition might already be observed in the regions' electricity mixes. In particular, it is instructive to plot the evolution of the flexibility share over the century comparing what happens with or without the application of the constraints, the latter meaning without any constraints with the exception of the CES structure[7] (Figure 8). Results are presented for the two policy scenarios. An additional variable is also considered, i.e. the activation or not of storage, which is of fundamental importance, as will be discussed shortly.

The graphs suggest that there is a quite clear distinction between two groups of regions in 2005, and that this distinction is generally kept or even sharpened over the decades in the baseline cases (left column), while the policy scenario is less neat in this sense (right column).

Let us start analyzing the situation in the base year. Given that wind and solar shares in 2005 were negligible in almost all regions (apart from a 2% wind share in WEURO and 1% in INDIA), the base year situation naturally derives from the traditional technologies on which regions based their electric production, which can be either flexible (gas and hydropower), poorly flexible/inflexible (coal and nuclear), or substantially neutral (oil and biomass). Table 3 summarizes the electricity shares from these technologies in 2005, underlining the polarization shown in the figures. USA, WEURO, EEURO, KOSAU, CHINA and INDIA are characterized by a substantially inflexible power generation fleet (which leads to a flexibility share of about 10%), while the opposite applies to MENA, SSA, SASIA, EASIA and LACA (whose flexibility share is in the order of 30%). TE and CAJAZ are instead intermediate regions.

Considering the evolution over time of the flexibility residue, and starting from the unconstrained scenarios (the top two), one can notice that in the baseline scenario, the flexibility share remains almost constant over time for most regions. More in detail, the regions with low and intermediate flexibility in 2005 feature a slow but constant decrease over time, while the regions with high flexibility in 2005 tend to keep a high level of flexibility over time, apart from MENA and partly LACA, which show a strong decrease in the second part of the century. Indeed, no climate policy is applied and thus regions tend to proceed with their current energy policies, or however with the most convenient ones for them. This leads to a moderate deployment of VREs, which in turn leads to (low) negative levels of the flexibility share only in few regions and towards the end of the century.

[7] It is easy to figure the effects of the external cost curve based on Hoogwijk et al. (2007) which was implemented in the old version of WITCH: i) the reduction in the deployment of the penalized technology, due to the higher costs, and ii) a general threshold of 25-30% as a penetration share in the electricity mix.

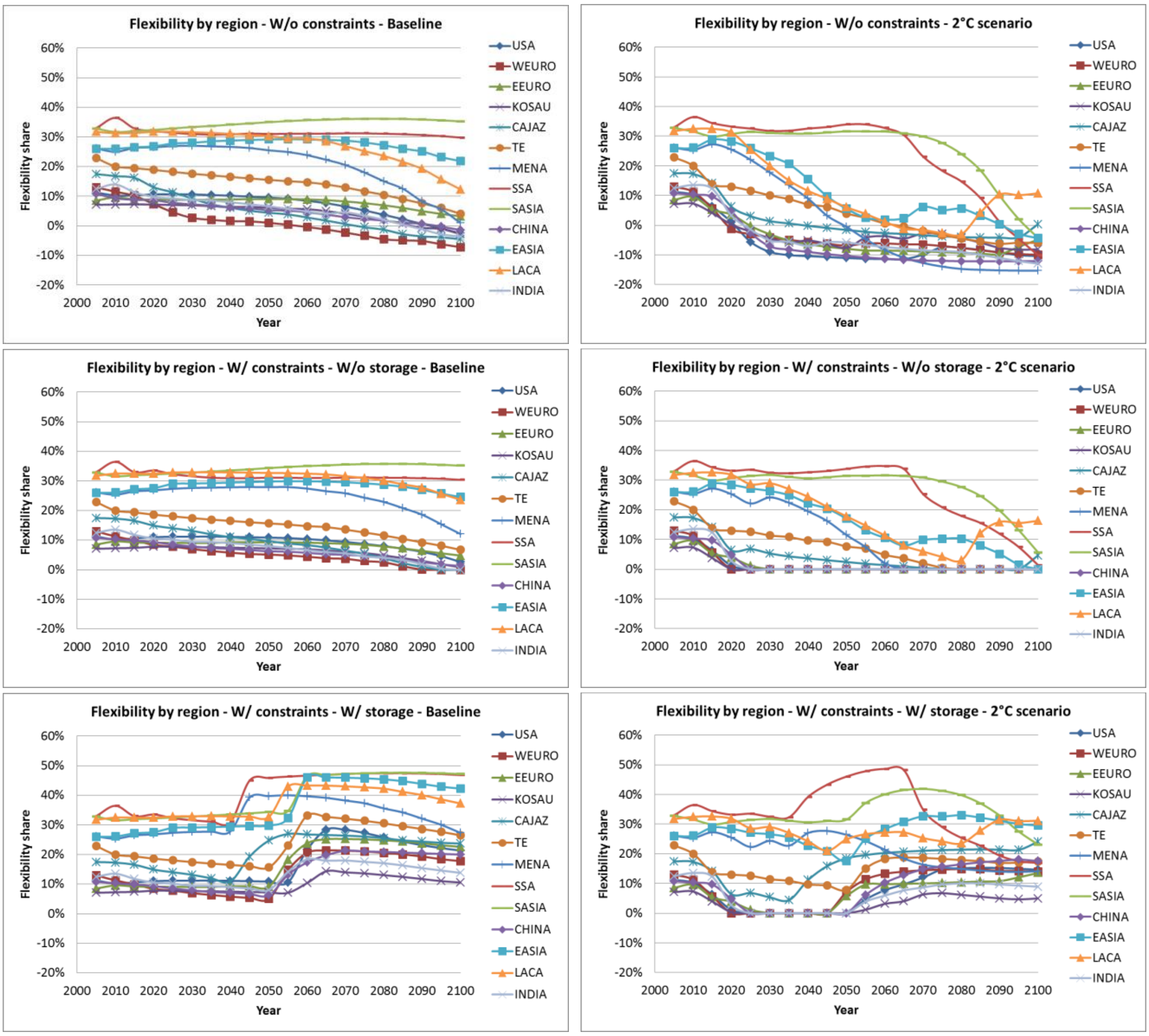

Figure 8 – Flexibility by region: effects of the flexibility and capacity constraints and of storage.

	Coal	Nuclear	Inflexible	Gas	Hydro	Flexible	Oil	Biomass	Neutral
USA	50%	19%	**69%**	18%	7%	**25%**	3%	2%	**5%**
WEURO	24%	30%	**54%**	20%	15%	**35%**	4%	4%	**8%**
EEURO	59%	19%	**78%**	6%	12%	**18%**	2%	2%	**4%**
KOSAU	65%	18%	**83%**	11%	3%	**14%**	3%	1%	**4%**
CAJAZ	24%	23%	**47%**	17%	28%	**45%**	6%	1%	**7%**
TE	23%	16%	**39%**	39%	19%	**58%**	4%	0%	**4%**
MENA	6%	0%	**6%**	56%	4%	**60%**	34%	0%	**34%**
SSA	5%	0%	**5%**	17%	64%	**81%**	14%	0%	**14%**
SASIA	0%	2%	**2%**	49%	31%	**80%**	17%	0%	**17%**
CHINA	74%	3%	**77%**	3%	15%	**18%**	3%	1%	**4%**
EASIA	25%	0%	**25%**	46%	14%	**60%**	14%	0%	**14%**
LACA	5%	2%	**7%**	20%	55%	**75%**	13%	4%	**17%**
INDIA	68%	3%	**71%**	9%	14%	**23%**	5%	1%	**6%**

Table 3 – Flexible vs. inflexible electricity generation in 2005.

In the 2°C scenario, instead, the need for decarbonizing the economy leads to a much higher installation of renewable plants, with the flexibility share which becomes negative already around 2020 for the regions with low flexibility in 2005 and in the second part of the century for the other regions. SSA and SASIA tend to keep a high and constant level of flexibility until about 2070 because they abate by deploying CCS, mainly based on gas and/or biomass, which guarantees a fair level of flexibility (always under the assumption that CCS does not entail a significant loss of flexibility). After that date, they too begin installing VRE plants, and thus flexibility drops.

The application of the flexibility constraint prevents the flexible share from becoming negative, and looking at the unconstrained graphs it is immediate to forecast that its impact will be higher in the policy case.

Some interesting results are visible in the baseline case as well, though. In the unconstrained baseline case, the flexible share for WEURO becomes negative after 2050. If we neglect storage (mid left graph), we could expect the constraint to lead to the same evolution of the flexible share until that date, becoming zero afterwards. Instead the flexible share results constrained only after 2090. This is because WITCH is a model with perfect foresight, where the optimization of the decision variables in each period is performed considering the aggregate welfare over the entire time horizon. Practically, the model redirects part of the investments to fossils, compatibly with the absence of climate policies. In the policy case, instead, the effect of the constraint is much more marked (mid right graph): in many regions the model cannot find an optimal flexible generation fleet, and the constraint becomes binding.

The introduction of storage results in a huge change. Indeed, the storage technology is applied precisely to tackle the issues described by the flexibility and the capacity constraints, i.e. i) to make the generation fleet more flexible and ii) to provide backup capacity (see the next section for this point). This is also the reason why in the absence of these constraints, storage is not installed anyways. The baseline graph (bottom left) clearly shows when the installation of storage starts in the different regions: about from 2040 to 2050 almost all the regions' flexible share has a sudden increase, which stops in 2060-2070, when the additional flexibility of storage starts being compensated by the progressive installation of VRE plants. In the 2°C scenario something similar happens, even if, since the installation of storage becomes competitive in the second part of the century, nothing prevents the low flexible regions from reaching the flexibility bound in 2020-2025, as happens in the case without storage. When storage begins being installed, the flexible residue of all regions becomes again strictly positive.

The effects of the application of the flexibility constraint on power generation are very strong, when relevant. In particular, sometimes the model cannot find a less costly solution than reducing significantly the demand. Figure 9 shows how the electricity production in 2100 in India (a region where the described phenomenon is particularly clear) changes when the flexibility constraint is applied, with or without storage. Under a 2°C policy scenario and with no constraints, one can see how the electricity mix in 2100 is dominated by wind and PV. If the constraints are applied, and storage is not active, the model rearranges the electricity mix (the combined share of wind and PV decreases from 78% to 37%, while CSP grows and gas with CCS appears), but also hugely reduces electricity demand (about 50%). In economic terms this translates in a GDP decrease of 5% in the year 2100. On the other hand, if storage is available, the electricity generation and the mix are barely affected by the application of the flexibility and capacity constraints, even if a slight change can still be found, essentially as a consequence of the constrained period from 2025 to 2050.

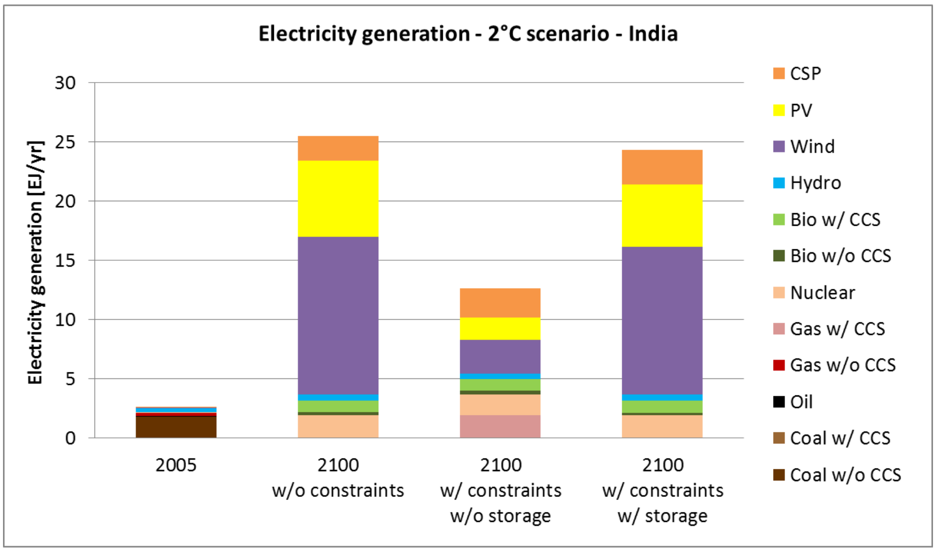

Figure 9 – Electricity generation in India in 2100 with or without the flexibility and capacity constraints, and with or without storage.

5.2 Capacity constraint

The introduction of the capacity constraint has obvious and inevitable impacts on the installed capacity, while the generation side is basically unaffected. In WITCH, the electricity demand is evaluated in average terms over the year. The calibration for the base year, being based on real data, overcomes this problem, as the excess capacity is automatically guaranteed by the description of the existing electric system. Nevertheless, the existing plants are replaced by new ones over time, and the optimization carried out by the model is such that every plant is normally only required to operate at its nameplate capacity. It might happen that part of the installed capacity at some point is no longer used (e.g. because a high carbon price makes a coal plant not profitable), but no excess capacity is installed on purpose, neither for reserve margin scopes, nor to simulate the fact that excess capacity exists and competes for access to the market, nor to take into account that only the average annual load is considered in the model.

The formulation of the constraint is such that renewables become strongly penalized. In calculating the firm capacity, in fact, not only is the renewable capacity cut by the capacity factor (which provides a statistical average of the available capacity), but it is additionally penalized by the capacity value. In the example shown in Figure 2, the VRE firm capacity is accounted for 13% of the nameplate value with a 20%-penetration. Wind and solar PV almost do not concur in meeting the constraint, so the model re-addresses investments to other technologies. This is a policy relevant result: renewable penetration will require significant backup capacity in order to ensure adequate reliability for meeting peak demand. The application of the constraint precisely leads to the installation of backup capacity. If storage is available, this is the technology adopted for this purpose. If it is not available, this role is played by gas (w/o CCS), i.e. the cheapest and most flexible among the traditional technologies[8]. In any case, this need for extra investment in backup capacity would not be captured without the imposition of such a constraint, which represents an extra cost related to high VRE penetration.

[8] Hydroelectric has limitations in terms of resource availability.

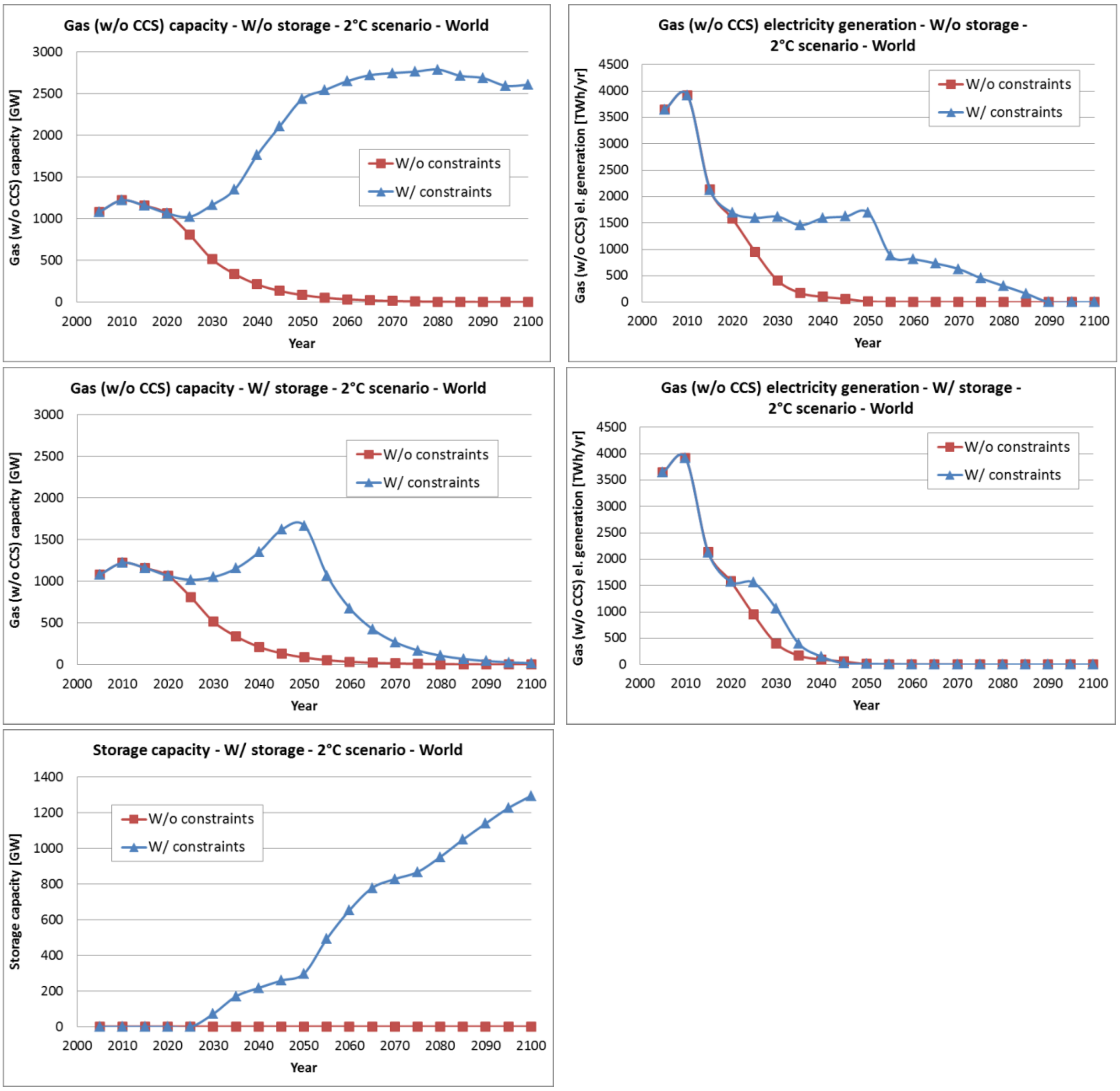

Figure 10 – Global gas (w/o CCS) electricity generation and capacity, and storage capacity in the 2°C scenario with and without the flexibility and the capacity constraints.

Referring to the 2°C scenario, Figure 10 shows the evolution of the global electricity generation and installed capacity of gas w/o CCS and of the storage capacity (when provided), with or without the flexibility and the capacity constraints. In the former case, thousands of gigawatts are required to meet the capacity constraint, either of gas or of storage. With no storage, the fact that gas is (mostly) used for backup purposes is shown by the evolution of the actual electricity generation, which practically phases out over time both with and without the constraints. With storage, when the need for backup capacity arises in 2025, both gas and storage technologies are deployed; in 2050, storage penetration bends upwards, clearly becoming more convenient to the detriment of gas.

5.3 Impacts on the LCOE

Having analyzed the technical implications on energy supply and demand of the flexibility and capacity constraints, in this section we discuss the economic impacts, and in particular it is shown how the LCOE is affected. Results are shown in Figure 11. The analysis has been conducted on wind, but similar results would apply to solar PV. The 2°C policy scenario – with or without storage – has again been considered to better illustrate the dynamics at play.

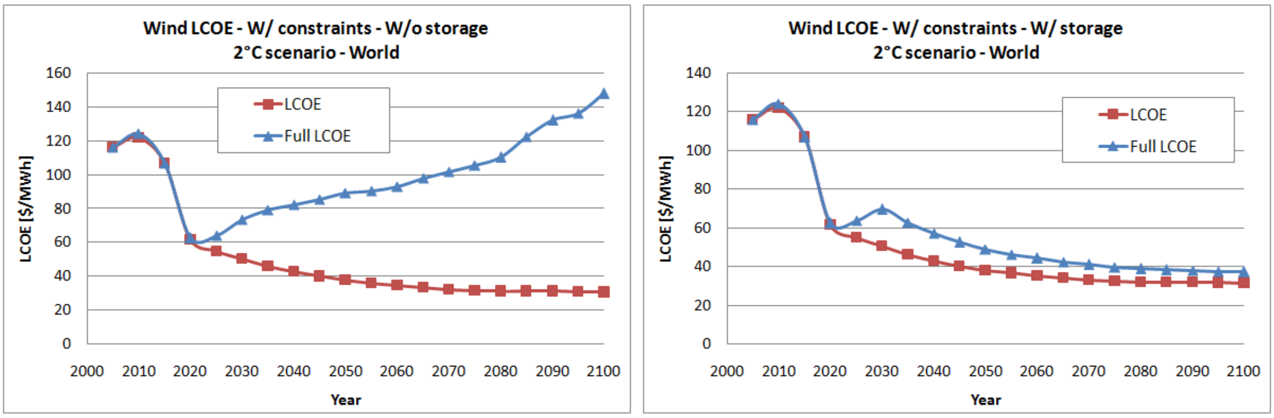

Figure 11 – Wind LCOE and Full LCOE with and without storage (2°C scenario, World).

The figures report both the LCOE and the Full LCOE. The LCOE comprises the costs related to investment and O&M. The Full LCOE also includes the contribution from the flexibility and the capacity constraints[9]. The difference thus gives an immediate quantification of the impacts of these constraints. Without the application of the constraints, by definition there would not be any difference between the LCOE and the Full LCOE. The LCOE contributions from the flexibility and the capacity constraints are calculated as the ratio between the marginal of the constraint equation and the marginal of the production function, multiplied by the relevant flexibility coefficient for the flexibility constraint, and by the complementary of the relevant capacity value and by the yearly hours (in order to obtain values in dollars per watt-hour) for the capacity constraint.

Wind LCOE starts at about 120 $/MWh in 2005/2010 and progressively declines over time, thanks to the learning-by-doing process, achieving about 31 $/MWh in 2100, both with and without storage. The Full LCOE instead has a markedly different behavior if storage is available or not. In the latter case, the constraints become binding in many regions in about 2020-2025 and their effect lasts all over the century. Precisely in 2025 the Full LCOE starts diverging from the LCOE and constantly increases, up to 147 $/MWh in 2100, i.e. about five times as the corresponding LCOE and higher than the 2005 value. If storage is available, a slight divergence is still noted starting from 2025, because in that year the technology is not yet convenient to enter the market, but when this happens, i.e. in the immediately following periods (see also Figure 8), the Full LCOE starts declining again, progressively approaching the LCOE, since the effects of the flexibility and the capacity constraints are “absorbed” by the installation of storage capacity. When comparing the individual contributions to the increase in LCOE of the two types of constraints, the flexibility one results to be averagely one order of magnitude greater than the capacity one, when binding.

[9] By definition, the LCOE would also include the fuel cost, while the Full LCOE would also include the CO_2 cost and the CCS contribution, but all these items are obviously irrelevant for wind, or VREs in general.

5.4 Impacts on VRE penetration

The implementation of the flexibility and capacity constraints, coupled with the CES structure, leads to a quite low penetration of VREs, if storage is not available. Figure 12 shows the evolution over time of the VRE share in the electricity mix in the two considered policy scenarios (in different colors), considering the four combinations given by the application or not of the flexibility and the capacity constraints (top vs. bottom) and of storage (left vs. right).

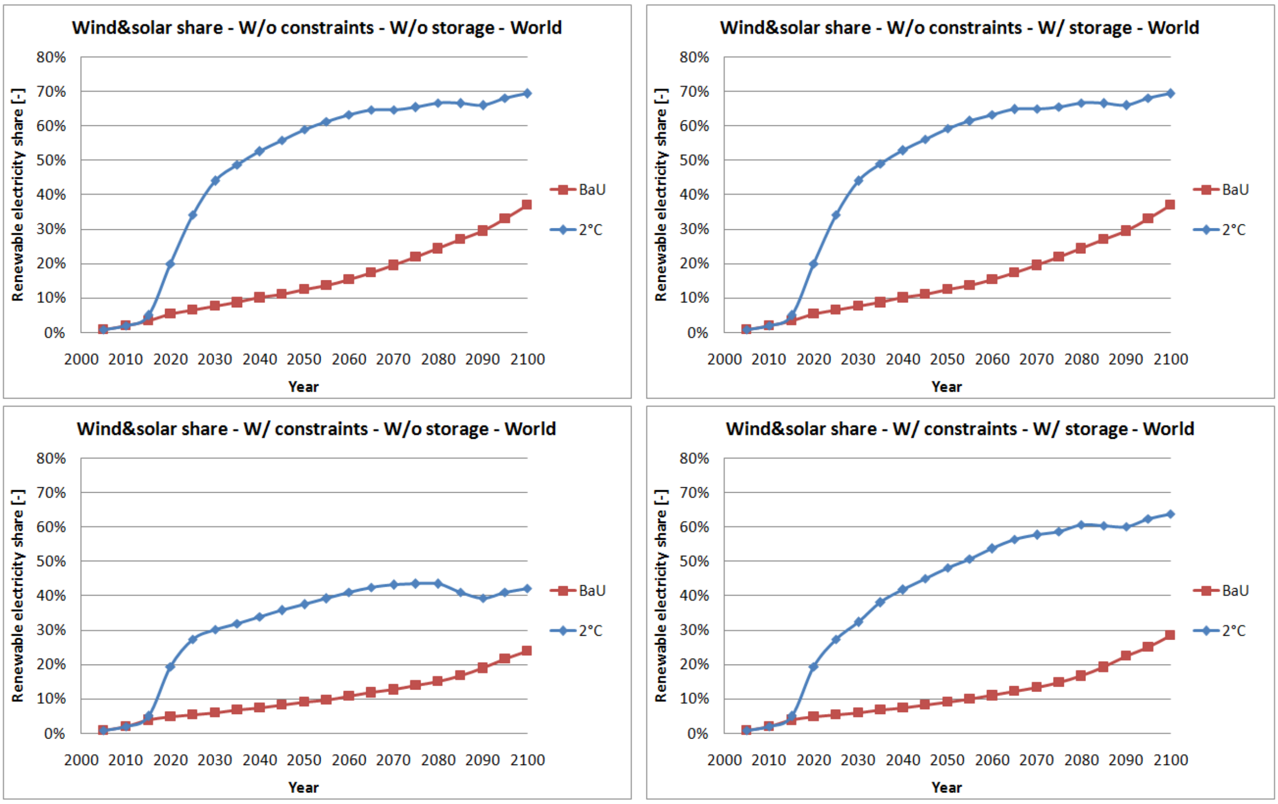

Figure 12 – VRE penetration in the electricity mix.

As already noted, if the flexibility and the capacity constraints are not applied, the implementation of storage has no effect. In the baseline scenario, the VRE penetration follows the trend of the last years (as discussed in Section 4.2), achieving a level equal to about 40% in 2100. In the policy scenario, the VRE penetration heavily accelerates after 2015, and in a couple of decades it reaches about 50%. Then the growth rate declines, and the shares become relatively stable in the second part of the century at about 70%.

If the flexibility and the capacity constraints are applied, the behavior is identical to the previous one until 2020, when the constraints become binding. If storage is available, VRE penetration is limitedly affected, however, and manages to reach 30% in the baseline scenario and 60% in the 2°C scenario. If storage is not available, the limitation is much more evident, especially in the policy scenario, where the VRE share in the electricity mix barely exceeds 40%. These graphs show once again how the flexibility and the capacity constraints heavily impact the VRE penetration, and how storage can substantially compensate for the imposed limitation. Naturally, it must be reminded that these constraints are not primarily imposed to limit

VRE penetration per se, but to represent a power generation fleet which is technically feasible, in terms of flexibility and backup capacity.

Finally, comparing the graphs of Figure 12 with those of Figures 4 and 6, it can be noted that the role of the CES in determining the electricity mix dominates with respect to the one of the flexibility constraint, the capacity constraint or the presence of storage.

6. Conclusions

The penetration of variable renewable energies in the electricity mix is technically limited by constraints related to the management of the electrical grid. Integrated assessment models have to take into account this issue when they model the future evolution of the power sector. Different modeling mechanisms can be implemented. A purely CES-based approach would naturally fit in the context of a model like WITCH, but would fail to capture crucial technical aspects. This paper explores alternative CES configurations, as well as the impacts of an additional and more explicit modeling scheme, based on a flexibility constraint, which requires that the annual average energy production be sufficiently flexible to meet demand fluctuations, and a capacity constraint, which requires that sufficient firm capacity be installed to meet peak load.

The evolution of the electricity mix primarily depends on the CES structure and on the chosen values for the elasticities of substitution. 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 is intended to take into account that i) renewables mainly compete with fossils, and ii) this competition is rather elastic, and an elasticity equal to 2, traditionally used across fossil fuel technologies and nuclear, is not sufficient to capture VRE dynamics in the electricity sector, either recently observed or expected.

The flexibility constraint is binding especially in the policy scenario, where the need for decarbonization leads to the installation of a considerable amount of VRE plants. If the model finds too costly to rearrange the electricity generation mix to yield a fleet which could be sufficiently flexible to accept higher and higher renewable shares, the natural response is a reduction in the overall electricity production, with inevitable economic impacts. The capacity constraint leads to the installation of more power capacity to meet the peak demand, i.e. of backup capacity. In fact, in the absence of such a constraint, IAMs like WITCH significantly underestimate the needed power capacity, since they evaluate the electricity demand in average terms on a yearly basis.

If storage is available, the technical and economic impacts of the flexibility and capacity constraints are substantially limited. In fact, both the renewable penetration and Full LCOEs almost reach the levels of the unconstrained scenarios. Indeed, storage is installed precisely to add flexibility to the system and to provide backup capacity. Naturally, this contribution is not for free, since the cost related to the installation of the technology must be considered.

In general, the explicit flexibility and capacity constraints are useful to describe specific technical aspects related to VRE penetration (e.g. the need for a flexible generation fleet and for the installation of a backup capacity). They make VRE penetration more costly, but still less than what a different CES structure or parameterization could imply.

There are some limitations in our approach, which would require future modeling developments. First, the flexibility and capacity constraints are quite aggregated tools to model the limits to VRE penetration in the electricity mix. The flexibility and capacity coefficients from Sullivan et al. are quite poorly parameterized and documented, and however they have been calibrated only on the US power system. In reality, power technologies in different regions could be characterized by different levels of flexibility (e.g. a dam plant is more flexible than run-of-the-river hydroelectric stations) and by different capacity values for VREs; the flexibility parameters might also change with VRE penetration, while they have been considered constant here. Second, WITCH does not feature, or poorly models, some power technologies which might lead to different electricity mixes, like combustion gas turbines, while storage modeling is still at an early stage. Third, no explicit curtailment of VRE electricity generation is considered. Fourth, the flexibility parameters of CCS plants have been assumed equal to the corresponding non-CCS ones, while a higher inflexibility might be envisioned. Finally, the costs associated with operating plants flexibly (like efficiency, load factor, and O&M penalties) should be considered, while they have been considered independent from flexibility in this work.

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