MODELING THE INTEGRATION OF VARIABLE RENEWABLE ENERGIES (VRE) INTO THE ELECTRICAL GRID IN THE WITCH MODEL: TECHNO-ECONOMIC IMPACTS OF DIFFERENT APPROACHES

Samuel Carrara,
Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
Corso Magenta 63, 20123 Milan, Italy. Tel: + 39-02-52036932, Fax: + 39-02-52036946,
E-mail: samuel.carrara@feem.it
Giacomo Marangoni,
Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
Corso Magenta 63, 20123 Milan, Italy. Tel: + 39-02-52036916, Fax: + 39-02-52036946,
E-mail: giacomo.marangoni@feem.it

Overview

Climate mitigation, and signally the reduction of greenhouse gas (GHG) emissions, is a vital target for the 21st century. In particular, power generation is the largest responsible of CO2 emissions, therefore great mitigation efforts will be required in this area. In the next decades a general electrification of the energy sector and a simultaneous decarbonization of the electric sector will take place. 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).

Over the last years, renewable energies have been characterized by a great expansion and have been gaining growing market shares, even if many of them have not reached a complete techno-economic maturity yet (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, while non-dispatchable technologies rely on sources which are variable (thus the name, Variable Renewable Energies, VRE) and cannot be fully controlled (e.g. wind and solar, signally PhotoVoltaics, PV, while Concentrated Solar Power, CSP, guarantees dispatchability if coupled with a thermal energy storage, as normally happens). Most renewables are likely to play a role in the future power scenario, especially wind and solar.

The integration of high levels of variable renewable energies into the electrical grid, however, is an awkward problem. Electrical grids require that the load be equalized instantaneously with the generation. As far as traditional dispatchable technologies are concerned, this does not represent a major issue, as power plant operators, in general, 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 fully mature, and cannot be deployed at large scales, grid management with increasing levels of renewable penetration becomes a non-trivial issue. One practical result is that VRE penetration in the electricity mix cannot be unlimited. Finding an adequate level of detail to tackle this aspect within Integrated Assessment Models (IAM) is not an easy task, though: 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 can be implemented.

After giving an overview of the main modeling solutions that have been recently proposed and that are currently under implementation in the different IAMs, the main aim of this work is to provide, adopting the WITCH model, a quantitative evaluation of the impacts that some of these different integration mechanisms have on the evolution of the electricity demand and mix.

Methods

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. 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. Energy 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.

In the first part of the work, attention is focused on three modeling solutions: i) an explicit cost markup (in particular an external cost function depending on the VRE share), ii) a constraint on the flexibility of the power generation fleet, and iii) a constraint on the installed capacity of the power generation fleet.

The second part of the work is dedicated to analyzing the role and the impacts of the CES (Constant Elasticity of Substitution) modeling structure.

Results

The external cost curve representing the explicit cost markup applied to wind and PV is almost flat up to a 25% penetration (remaining lower than 1 c$/kWh), then increasing exponentially at higher penetration rates, which indirectly limits VREs expansion to a maximum of about 25/30% each (thus 50 ÷ 60% overall). The curve slightly constrains VREs diffusion, but the model framework (CES) is such that normally the 25%-threshold would not be reached all the same in classic policy scenario, thus the impact is quite limited.

The flexibility constraint is binding for a limited set of regions and time periods. Many regions, in fact, would base their emission abatement on a complete switching to CCS of their electricity generation fleet (mainly basing on gas and/or biomass), which guarantees an adequate level of flexibility. Other regions instead would base their carbon mitigation on a transition from fossils to an inflexible nuclear-renewable mix: here the constraint would be relevant and would lead not only to a rearrangement of the electricity mix, but also, in some cases, to a reduction of the energy demand.

The capacity constraint leads to the installation of more power capacity to meet peak demand. In fact IAMs like WITCH, evaluating the electricity demand in average terms on a yearly basis, in the absence of such a constraint significantly underestimate the needed relevant power capacity. VREs are penalized by this constraint as they do not provide dispatchable capacity. Differently from the flexibility constraint, it is practically binding across all regions and time periods, even if the associated shadow price is lower that the flexibility one, when applied.

The CES structure represents by itself a constraint resulting in a limitation of VRE expansion, thus producing, combined with the abovementioned constraints, a double counting effect. A proper integration of the constraints in the model thus requires a reconsideration of the model framework.

Conclusions

The choice of the modelling mechanism for describing the integration of variable renewable energies in the electrical grid has great impacts. It is shown how electricity demand and mix, and thus the economic performance, may be strongly influenced by the imposed constraints. The paper shows how a quite refined modelling scheme is necessary for IAMs to produce a proper modelling of renewable diffusion in the next decades. In fact many IAMs do not rely on sufficiently detailed integration models, and thus simulation results may not be credible or coherent (e.g. the mentioned problem of the power capacity underestimation based on the average annual electricity generation).

WITCH does not feature a description of storage technologies yet. Indeed, the possibility of coupling VREs with storage devices would be certainly relevant in the system integration context. The next step of this research work will thus move towards this direction.

References

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006): “WITCH: A World Induced Technical Change Hybrid Model”, Energy Journal, Special issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38

Hoogwijk, M., D. van Vuuren, B. de Vries and W. Turkenburg (2007): “Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy”, Energy, 32, 1381-1402

Sullivan, P., V. Krey and K. Riahi (2013): “Impacts of considering electric sector variability and reliability in the MESSAGE model”, Energy Strategy Reviews, 1, 157-163