Fondazione Eni Enrico Mattei

NOTA DI LAVORO

71.2014

Integration of Power Generation Capacity Expansion in an Applied General Equilibrium Model

By **Gauthier de Maere d'Aertrycke**, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies, Fondazione Eni Enrico Mattei (FEEM) and Euro-Mediterranean Center on Climate Change (CMCC)
Olivier Durand-Lasserve, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies
Marco Schudel, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies

Energy: Resources and Markets

Series Editor: Giuseppe Sammarco

Integration of Power Generation Capacity Expansion in an Applied General Equilibrium Model

By Gauthier de Maere d'Aertrycke, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies, Fondazione Eni Enrico Mattei (FEEM) and Euro-Mediterranean Center on Climate Change (CMCC)
Olivier Durand-Lasserve, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies
Marco Schudel, GDF-SUEZ, Center of Expertise in Economic Modelling and Studies

Summary

This paper presents a version of a hybrid (top-down bottom-up), multi-region multi-period forward looking applied general equilibrium model, MERGE, that includes a capacity expansion submodel of the electricity sector with demand represented by various time segments. This model is solved numerically using the decomposition method proposed by Bohringer and Rutherford (2006). In the decomposition, the bottom-up (energy) submodel of MERGE is embedded in a quadratically constrained program (QCP) that maximizes a welfare function calibrated on a linear approximation, around a benchmark point, of aggregated energy and capital demand . This latter is provided by constraining energy supply in a nonlinear programming problem (NLP) that essentially contains the MERGE top-down (macro) submodel. The method is illustrated with a simulation that provides projections of load duration curves and hours of activity of various electricity technologies.

Address for correspondence:
Gauthier de Maere d'Aertrycke
Euro-Mediterranean Center on Climate Change (CMCC)
Corso Magenta 63
20123 Milan
Italy
E-mail: gauthier.demaere@cmcc.it

Integration of power generation capacity expansion in an applied general equilibrium model

Gauthier de Maere d'Aertrycke [1,2,3], Olivier Durand-Lasserve[1], and Marco Schudel[1]

[1]GDF-SUEZ, Center of Expertise in Economic Modelling and Studies
[2]Fondazione Eni Enrico Mattei (FEEM)
[3]Euro-Mediterranean Center on Climate Change (CMCC)

May 8, 2014

Abstract

This paper presents a version of a hybrid (top-down bottom-up), multi-region multi-period forward looking applied general equilibrium model, MERGE, that includes a capacity expansion submodel of the electricity sector with demand represented by various time segments. This model is solved numerically using the decomposition method proposed by Bohringer and Rutherford (2006). In the decomposition, the bottom-up (energy) submodel of MERGE is embedded in a quadratically constrained program (QCP) that maximizes a welfare function calibrated on a linear approximation, around a benchmark point, of aggregated energy and capital demand . This latter is provided by constraining energy supply in a nonlinear programming problem (NLP) that essentially contains the MERGE top-down (macro) submodel. The method is illustrated with a simulation that provides projections of load duration curves and hours of activity of various electricity technologies.

1 Introduction

Within the simulation models used to represent the economy energy interactions, one generally distinguish the bottom-up (BU) approach, narrowly tied to sectoral technological details and the the top-down (TD) approach, that embraces the entire economy, represented by means of macroeconomic functions.

The BU models represent, with explicit physical energy flows, how various energy commodities and transformation technologies compete to fulfill a given level of energy demand. Cost minimization over the full energy system is used to mimic the outcome of a competitive energy market equilibrium. The BU models are essentially dedicated to a specific sector and contain a detailed representation of the technologies. They are particularly fit for evaluating the impact of command and control policies and for sensitivity analysis on technology parameters. In general, these models are Linear Programs (LP). Since LP solution algorithms are very efficient, BU models can be easily computed with a very high degree of technological details.

The top down approach (TD), extends the modeling scope to the whole economy. Instead of physical flows, the TD models essentially rely on monetary transaction flows between various economic agents (firms, governments, households). The TD representation is fit for dealing with effects that are beyond the grasp of sectorial models. A specific class of TD is computational general equilibrium models (CGE). Their success is due to their microfounded theoretical structure based on Arrow and Debreu (1954). CGE models capture the price-induced substitution of non-energy to energy production factors, revenue effects (through recycling taxes or change in rents), or effects on capital accumulation and growth. In general, CGEs are based on a smooth representation of technologies, typically by means of CES functions. These models can be formulated and solved as constrained nonlinear systems (CNS), mixed complementarity problems (MCP) or as sequences of non-linear programming problems (NLP). For these classes of problems, solution algorithms are less efficient than for LP problems. Consequently, for TD models, dimensionality is an issue and one have to seriously limit the number of variables and equations.

There have been several efforts to build hybrid frameworks that combine the benefits of BU and CGE models Drouet et al. (2008). The methods used were characterized by the type of link between the two models. We distinguish three different types of methods: the soft link, the top down-oriented, and the hard-link approaches.

With the soft-link methods, the BU and the TD are solved iteratively, despite the behavioural and accounting inconsistencies between the two models. At each iteration the models exchange data, in the hope of converging to a fixed point. This approach was followed by Hoffman and Jorgenson (1977) for linking a CGE models and and technological description of energy supply, by Messner and Schrattenholzer (2000) for coupling the MACRO and the MESSAGE models or by Beltran et al. (2005) for coupling GEMINI-E3 and a Swiss MARKAL model.

In the top-down oriented methods, the macroeconomic production function calibration is refined in order to better reflect some technological conditions contained in the BU model. The functions are calibrated either on price and quantities points computed with a BU model (Schäfer and Jacoby, 2005; Pizer et al., 2003) or on enhanced Social Accounting Matrixes (SAM) that include additional energy specific information (Sue Wing, 2008).

In the hard-link approach, a TD and a BU submodel are fully integrated in a single "monolithic" mathematical problem [1]. Instances of such hard-link models are ETA-MACRO (Manne, 1977), MARKAL-MACRO (Manne and Wene, 1992), MERGE (Manne et al., 1995). The full integration guarantees the economic consistency of the modeling framework: competitive equilibrium conditions are respected for both the BU and the TD submodel. The overall mathematical formulation of such problems is well known and clearly formalized in Bohringer (1998). But they raise dimensionality issues that are difficult to overcome. The monolithic formulation of hybrid model corresponds to a "one shot" resolution of a NLP problem that combines linear and non-linear expression (in the BU and TD respectively). Therefore, the level of detail must be quite limited to keep the model numerically tractable. Finally, to be fully integrated with a TD a model, a large scale standalone BU models may need to be seriously simplified and become less fit for doing sensitivity analysis on policies or technologies.

This numerical issue is addressed by Bohringer and Rutherford (2006) who proposed

[1] Note that we include in the hard-link approach both the bottom-up oriented and integrated integrated approaches distinguished by Drouet et al. (2008)

a decomposition scheme. They obtain convergence to the solution of the integrated model by iterating between a MCP top down model and bottom up model formulated as a Quadratically Constrained Program (QCP). The QCP is a welfare maximization problem submitted to the constraints contained in the BU. The welfare function maximization aims at portraying a linear demand system. The energy supply computed from the QCP is set exogenously in the MCP model which computes energy prices. Price and demand are then used to recalibrate the objective of the QCP problem. Bohringer and Rutherford (2006) illustrate their method with a stylized integrated hybrid model.
To our knowledge, the US-REGEN model EPRI (2012) is the only instance of application of the method to a fully-fledged hybrid models [2].

In this paper, we use this decomposition approach in order to solve a version of the MERGE model whose BU submodel is augmented with load duration curves. The two main contribution w.r.t. EPRI (2012) are the adjustment of the method to the case of putty-clay technologies and to a NLP formulation of the general equilibrium model.

After a brief presentation of the integrated MERGE model in section 2, we explain how the method is adjusted to the specificities of this model, in particular to the with putty-clay technologies 3. in section 4, the method is used to solving a MERGE coupled with a more detailed representation of electricity markets and the simulation results obtained are commented, before concluding in section 5.

2 A general overview of the MERGE model

This section intends to summarize the most important features of the MERGE model and to show intuitively how the TD and and BU submodels portray respectively regional energy demand and supply systems. The technical description will be restricted to the most specific features of MERGE: (i) the intertemporal dynamic optimization setting, (ii) the putty-clay macroeconomic production functions and (iii) the Sequential Joint Optimization solution method used to deal with interregional trade in a NLP setting. The reader willing to see the detailed equations of the model can refer to Appendix A.

MERGE (Model for Estimating the Regional and Global Effects of greenhouse gas reductions) was originated by Manne et al. (1995). It is a hybrid multiperiod forward-looking multiregional applied general equilibrium model representing interactions between the economy, energy technologies and environmental policies. The model's horizon extends from 2010 (base year) to 2100, with 5-year time periods. The world is divided into 11 regions that can trade a composite good, oil, gas, two types of coal, and emissions permits.

The macro submodel is largely similar to Manne et al. (1995). In each regions, a representative household that has an exogenous labour supply trades off between investment and consumption to maximize an intertemporal logarithmic utility function U_r.

$$U_r = \sum_t \beta_{r,t} \overline{L}_{r,t} \log(\frac{C_{r,t}}{\overline{L}_{r,t}}) \quad (1)$$

[2] Note that a conceptually similar method is used for integrating separate household for survey data in CGE models (Rutherford and Shepotylo, 2006; Rausch and Rutherford, 2010)

Where C is consumption, $\overline{L}$ population in (efficiency units), and β a the social discount factors. Consumption increases instantaneous utility while investment increases the capital stock and therefore future production, consumption and utility.

Competitive firms provide a composite good that is used for investment and consumption. The final good (Y) is produced using a CES technology that combines labour, capital (K), electric and non-electric energy (E and N) combined in putty-clay nested CES production functions. Production is obtained from various vintages (generation) of equipments. The production function $F_{r,t}$ that represents the technologies in a new vintages of equipment at time t is:

$$\begin{aligned}
&\Delta Y_{r,t} = F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta E_{r,t}, \Delta N_{r,t}) \equiv \\
&\left[a_{KL,r,t} \left[\Delta K_{r,t}^{\alpha} \Delta \overline{L}_{r,t}^{1-\alpha} \right]^{\rho_{KL}} + \left[[a_{E,r,t} \Delta E_{r,t}^{\rho_{EN}} + a_{N,r,t} \Delta N_{r,t}^{\rho_{EN}}]^{\frac{1}{\rho_{EN}}} \right]^{\rho_{KL}} \right]^{\frac{1}{\rho_{KL}}} \\
&(\text{With} \quad \rho_{KL} = (\sigma_{KL} - 1)/\sigma_{KL} \quad \text{and} \quad \rho_{EN} = (\sigma_{EN} - 1)/\sigma_{EN})
\end{aligned} \tag{2}$$

The optimal value share of capital in the value added of the final sector is given by α. The elasticities of substitution σ_{KL} and σ_{EN} indicate respectively how easily non-energy input can be substituted for energy input and how easily electric energy can be substituted to non-electric energy. Parameters a, which represent exogenous technological change that shifts the unit productivity of the various inputs. For instance, a_E and a_N translates autonomous energy efficiency improvements (AEEI) for electric and non-electric energy. They represent how electric and non-electric energy are assumed to evolve across the model's time horizon if their prices remained constant.

The technologies are putty-clay, which implies that the dynamics of total input and total output is defined as:

$$\begin{aligned}
Y_{r,t+1} &= Y_{r,t}(1 - \delta_{\mathrm{y}}) + \Delta Y_{r,t} &&, Y_{r,0} = \overline{Y}_{r,0} \\
K_{r,t+1} &= K_{r,t}(1 - \delta_{\mathrm{y}}) + \Delta K_{r,t} &&, K_{r,0} = \overline{K}_{r,0} \\
E_{r,t+1} &= E_{r,t}(1 - \delta_{\mathrm{y}}) + \Delta E_{r,t} &&, E_{r,0} = \overline{E}_{r,0} \\
N_{r,t+1} &= N_{r,t}(1 - \delta_{\mathrm{y}}) + \Delta N_{r,t} &&, N_{r,0} = \overline{N}_{r,0}
\end{aligned} \tag{3}$$

Total output (input) is the sum of previous period (output) decayed at rate (δ_{y}) and new vintage output (input). The cost-minimizing firms adjust their capital demand to the interest rate and energy demand to aggregate electric and non-electric energy prices. In addition, in our perfect foresight setting, the putty clay technologies induce a response of current demand to expected future prices. The putty-clay specification of the technologies induces a difference between long-run and short-run price elasticities of demand.

From a decomposition perspective, the TD model represents the dynamics of energy demand from the non-energy sectors of the economy.
This system takes into account gross output growth (largely driven by the exogenous increase in efficient labour), AEEI, production factor substitution induced by energy price changes, and the inertia due to the stock of equipment previously installed.

The BU submodel is a system of linear constraints that relates costs payments to the various primary energy production and energy transformation activities that lead up to final energy consumption. These operations require technologies that are characterized in

terms of costs, efficiency and emissions. In the profit maximization, the cash flows are discounted with an interest rate equal to the households' net return on savings of the TD model.
Note that the BU submodel also includes regional energy portfolio constraints, i.e. constraints that limit the speed of penetration or the market share of some technologies. Consequently, the approach is rather descriptive than explicative: it aims at portraying plausible evolution of the the energy system, evolve, but with limited explanation of the mechanism and the key parameters at stake.
From a decomposition perspective, the BU submodel represents a dynamic system of energy supply and capital demand, from the energy sectors to the rest of the economy.

For the model numerical resolution, the competitive equilibrium is computed with a Sequential Joint Optimization method (SJO) (Rutherford, 1999) based on the iterative adjustment of Negishi weights (Negishi, 1972). This method, allows for computing the general equilibrium using NLP for which solution algorithms are very efficient. In the SJO method, NLP problems, where a weighted sum of regional welfare is maximized under technological constraints, are iteratively solved. At each iteration, the weights are recomputed so as to increase the relative weight of the regions which have a current account deficit. The iterations stop once the weights' values imply at optimum a balanced trade in each region.

3 The decomposition algorithms

This section presents how the decomposition method by Bohringer and Rutherford (2006) is applied to MERGE. After a brief presentation of their method we will put forward how it has been adjusted to MERGE, in particular to putty-clay technologies and international trade. Then the information flows between the BU and the TD model are described.

3.1 Principle of the TD BU decomposition

In the decomposition, the BU (energy) submodel of MERGE is embedded in a constrained quadratic problem (QCP) that portrays a partial competitive equilibrium with the technologies as described in the integrated MERGE model and a demand system consistent with the TD submodel. The QCP maximizes a welfare function calibrated on a linear approximation of aggregated energy and capital demand around a benchmark point. This benchmark point is provided by constraining energy and capital supply in a NLP problem that essentially contains the TD (macro) submodel. At each iteration of the decomposition algorithm, the QCP computes energy quantities. These quantities are used to constrain supply in the NLP that computes, as dual variables, their associated price on the aggregated demand curve. These prices and quantities benchmark are used at the next iteration of the algorithm to recalibrate the QCP welfare function. The procedure iterates until prices and quantities are stable from one iteration to another.

3.2 Linearization of conditional factor demands from putty-clay technologies

For computing aggregated consumer's surplus we need to define and integrate a linear approximation of the energy demand system coming from the TD model. In the TD model, energy is used by the competitive final good producers that operated with Nested CES putty-clay technologies. The final good producer solves the program:

$$\begin{aligned}
\min_{E,N,K} \quad & \sum_t (P_{E,r,t}E_{r,t} + P_{N,r,t}N_{r,t} + RK_{r,t}K_{r,t}) \\
& \text{Equations (3)} \\
& F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta N_{r,t}, \Delta N_{r,t}) \geq \Delta Y_{r,t} \\
& Y_{r,t} = \overline{Y}_{r,t} \qquad (P_{\mathrm{y},r,t})
\end{aligned} \tag{4}$$

The dual variable P_{y} is the marginal production cost at the producer's optimum and is equal at equilibrium to the market price of the final good.
Because of the putty-clay structure of production, Problem (4) is dynamic. However, as showed in appendix B, we can reformulate this dynamic problem as a sequence of T independent static cost minimization problems where producers base their decision on a an index of present and future prices. The independent static problems can be written as:

$$\begin{aligned}
\min_{\Delta E_t, \Delta N_t, \Delta K_t} \quad & \left(P'_{E,t}\Delta E_{r,t} + P'_{N,r,t}\Delta N_{r,t} + RK'_{r,t}\Delta K_{r,t}\right) \\
& F_{r,t}(\Delta K_{r,t}, \Delta E_{r,t}, \Delta N_{r,t}) \geq \Delta \overline{Y}_{r,t} \qquad (P'_{\mathrm{y},r,t})
\end{aligned} \tag{5}$$

Where the price indexes, denoted by P' are derived from current prices $P_{r,t}$ using formula:

$$P'_{r,t} = \sum_{t \leq t' \leq T-1} (1-\delta_{\mathrm{y}})^{t'-t} P_{r,t'} + \frac{P_{r,T}P_{r,T-1}}{P_{r,T-1} - (1-\delta_{\mathrm{y}})P_{r,T}} \tag{6}$$

If we solve Problem (5) for the production function given in equation (2) we obtain the formulas for the conditional capital, electric and non-electric energy demands from the last vintage in the final good sector:

$$\Delta E_{r,t} = a_{E,r,t} P'^{\sigma_{KL}}_{\mathrm{y},t} P'^{-\sigma_{EN}}_{E,r,t} \Delta \overline{Y}_{r,t} \tag{7}$$

$$\Delta N_{r,t} = a_{N,r,t} P'^{\sigma_{KL}}_{\mathrm{y},t} P'^{-\sigma_{EN}}_{N,r,t} \Delta \overline{Y}_{r,t} \tag{8}$$

$$\Delta K_{r,t} = a_{KL,r,t} P'^{\sigma_{KL}}_{\mathrm{y},t} RK'^{-\sigma_{KL}}_{r,t} \Delta \overline{Y}_{r,t} \tag{9}$$

Taking the example of (7), we can show how these 3 conditional demand expressions can be linearized around equilibrium input prices and quantities . We note $\Delta \overline{E}_{r,t}$ and $\overline{P}'_{E,r,t}$ equilibrium electric energy demand and energy prices. From (7), they satisfy:

$$\Delta E_{r,t} = a_{E,r,t} \overline{P'}^{\sigma_{KL}}_{\mathrm{y},t} \overline{P'}^{-\sigma_{EN}}_{E,r,t} \Delta \overline{Y}_{r,t} \tag{10}$$

Combining (7) and (10), we obtain the expression:

$$\frac{\Delta E_{r,t}}{\Delta \overline{E}_{r,t}} = \left[\frac{P'\mathrm{y}_{,t}}{\overline{P'}\mathrm{y}_{,t}}\right]^{\sigma_{KL}} \left[\frac{P'_{E,r,t}}{\overline{P}'_{E,r,t}}\right]^{-\sigma_{EN}}$$

Then, neglecting the impact of the input price change on marginal cost (considering $P'\mathrm{y}_{,t}/\overline{P'}\mathrm{y}_{,t} = 1$) we linearize conditional demand at the vicinity of the equilibrium prices and quantities is:

$$\Delta E_{r,t}(P'_{E,r,t}) = \Delta \overline{E}_{r,t}\left[1 - \sigma_{EN}\left(\frac{P'_{E,t}}{\overline{P}'_{E,t}} - 1\right)\right] \tag{11}$$

From (11), we obtain the linear approximation of the inverse demand function for ΔE:

$$P'_{E,r,t} = \overline{P'}_{E,r,t}\left[1 - \frac{1}{\sigma_{EN}}\left(\frac{\Delta E_{r,t}}{\Delta \overline{E}_{r,t}} - 1\right)\right] \tag{12}$$

We can compute similarly the approximation of the inverse demand for ΔN and ΔK:

$$P'_{N,r,t} = \overline{P'}_{N,r,t}\left[1 - \frac{1}{\sigma_{EN}}\left(\frac{\Delta N_{r,t}}{\Delta \overline{N}_{r,t}} - 1\right)\right] \tag{13}$$

$$RK'_{r,t} = \overline{RK'}_{r,t}\left[1 - \frac{1}{\sigma_{KL}}\left(\frac{\Delta K_{r,t}}{\Delta \overline{K}_{r,t}} - 1\right)\right] \tag{14}$$

3.3 Welfare function portraying a inter-regional energy market equilibrium

The surplus of the consumers $S_{c,r}$ in region r is equal to the sum of surplus on the capital, electric and non-electric energy markets over the model's time horizon:

$$\begin{aligned} S_r &= \sum_t \Bigg\{ \int_0^{\Delta E_{r,t}} P'_{E,r,t}(\xi)d\xi + \int_0^{\Delta N_{r,t}} P'_{N,r,t}(\xi)d\xi + \int_0^{\Delta K_{r,t}} RK'_{r,t}(\xi)d\xi \\ &\quad - \left(\overline{P}'_{E,r,t}\Delta E_{r,t} + \overline{P}'_{N,r,t}\Delta N_{r,t} + \overline{RK}'_{r,t}\Delta K_{r,t}\right) \Bigg\} \end{aligned} \tag{15}$$

The total regional welfare $\mathcal{W}$ on the energy market is the sum of the consumer surplus and total firms' profits (Π_r) :

$$W_r = S_r + \Pi_r \tag{16}$$

In order to take into account the trade of energy commodities in MERGE, the maximand used to portray the partial equilibrium model is the sum of regional welfare.

$$\mathcal{W}_r = \sum_r W_r \tag{17}$$

The partial equilibrium model represents how various regional demands are satisfied by various regional competitive energy producers that may have the possibility of importing or exporting energy commodities.

3.4 Iterations between the top dow and the bottom up models

The information flows between the TD and the BU model at each iteration of the decomposition algorithm are summarily presented on figure 1. For a detailed description, the reader can refer to appendix C.

The TD model (see appendix C.1) is a NLP that includes the equations and the objective function of the MERGE macro submodel. The quantities of electric and non-electric energy $(\Delta E, \Delta N)$ and the total energy costs (EC) are capped. The optimization program gives the equilibrium prices for energy, non-electric energy, capital and final good. For energy the prices are equal to the dual variables associated to the constraints limiting the quantities. In addition, the TD model determines the final sector capital ΔK, consumption C and the production of the final good Y.

The BU model (see appendix C.2) wich is a QCP that includes a sum of regional welfare functions and the description of the energy system contained in the MERGE energy

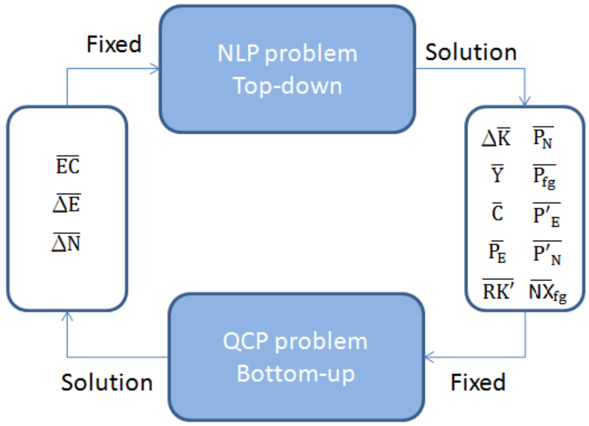

Figure 1: Information flows between the top-down and the bottom-up model

submodel. This function is calibrated using results of the TD model. More particularly, using electric and non-electric prices and quantities (P_E,P_N,P'_E,P'_N, ΔE,ΔN), final sector capital (ΔK) and its rental rate (P'_N). In addition, the TD output (Y), consumption (C) and export of final good ($NX_{\mathtt{fg}}$) are used in the BU problem to determine the remaining quantity of final good that can be used either to investment in the final sector, either to pay for the energy costs. The result of the BU model provides energy quantities and energy costs that will be used at the next iteration to cap the TD model.

These operations are repeated until convergence, i.e. until two successive quantities are close enough for a given distance measurement (in our case distance based on L^2 norm, see appendix for the exact formula.)

The decomposition algorithm is used for a given value of Negishi weights. These weights are explicit in the TD model, as they directly appear in the objective function. In the the BU, they are implicit, as they are reflected by the prices and quantities drawn from that TD model that are used to calibrate the various regional consumer surplus. Once the convergence of the decomposition algorithm is achieved, the weights have to be readjusted, based on the regional trade balances, and the decomposition method is used to find a new solution. In other words, the decomposition algorithm is embedded in the SJO method.

4 Numerical results with Load Duration curves in MERGE

One of the greatest determinants of the cost of reducing CO_2 emissions is the ability to integrate large loads of renewable intermittent sources (mainly wind and solar) into the electric supply. The MERGE model, which includes a single annual time segment with an average load level cannot address this issue. We take advantage of the decomposition algorithm to introduce a finer representation of the operations of electricity power genereation technologies. We implement a capacity expansion model[3] in MERGE. In such model the electricity industry needs to invest in the different technology as to serve a yearly demand

[3]Capacity expansion models have a long tradition in the power industry (Rinnooy Kan, 1983). Designed as optimization problems for the regulated monopoly industry, they can be interpreted in terms of equilibrium in a competitive environment. They have been adapted to price elastic demand.

described by load duration curve[4]. This allows us to better capture the long run impact of reducing emissions in particular the integration of large shares of intermittent sources. For data availabilities reason we only incorporate the capacity expansion model for the macro region Europe.

The capacity expansion submodel introduced in MERGE is briefly described, then simulation of scenario based on IEA New policies is presented, with an emphasis on power generation capacities.

4.1 Generation capacity expansion model

For integrating a capacity expansion submodel, the original MERGE electricity demand and supply systems have to be reformulated. Firstly, the representation of electricity demand, that used to be annual in MERGE is now described by a load duration curve[5] formed of $\mathcal{L}$ different time segments. Each time segment $\ell \in \mathcal{L}$ is characterized by an exogenous duration τ_ℓ and an endogenous demand level $EL_{r,t,\ell}$ (see Fig. 2). This demand level is assumed to be a fixed share $\alpha_{r,\ell}$ of the total annual demand which is price-elastic (eq. 18).

Secondly, electricity production is also disagregated. During each time segment ℓ, capacities must be operated to meet the demand (eq. 19). We denote by $GEL_{r,j,t,\ell}$ the hourly production of technology j for time segment ℓ.

$$EL_{r,t,\ell} = \frac{\alpha_{r,\ell}}{\tau_e ll} E_{r,t} \quad , \quad \ell \in \mathcal{L} \tag{18}$$

$$\sum_{j \in \mathcal{E}} GEL_{r,j,t,\ell} \geq EL_{r,t,\ell} \quad , \quad \ell \in \mathcal{L} \tag{19}$$

$$\sum_{\ell \in \mathcal{L}} \tau_\ell GEL_{r,j,t,\ell} = GE_{r,j,t} \; , \quad j \in \mathcal{E} \tag{20}$$

Some constraints are used to portray limitation of the availability of various power plants. Each plant cannot produce more than its capacity KE times an hourly availability factor $\mathsf{avail}_{j,\ell}$ (see (21)). For thermal power plant instance this factor takes into account the maintenance periods, where plants cannot be used; while for renewable it mainly represents the intermittency of supply due to weather conditions.

$$GE_{r,j,t,\ell} \leq \mathsf{avail}_{r,j,\ell} \times KE_{r,j,t} \tag{21}$$

Finally, we also impose an adequacy reserve margin to ensure security of supply for unexpected events affecting load and generation. We follow suit the methodology adapted by ENTSOE (2010) and add the following constraint:

$$\sum_{j \in \mathcal{E}} (1 - \mathsf{der}_j) KE_{r,j,t} \geq (1 + \mathsf{arm}) EL_{r,t,\ell} \quad , \quad \ell \in \mathcal{L} \tag{22}$$

where arm is an adequacy reserve margin (generally set between 5 and 10%) and der_j is a technology-specific derating factor that correct for the risk of unavailability of the power-plants. Note that for intermittent technologies, der_j is very close to one, as it takes into

[4]The load duration curve measures the number of hours per year the total load is at or above any given level of demand.

[5]The load duration curve measures the number of hours per year the total load is at or above any given level of demand.

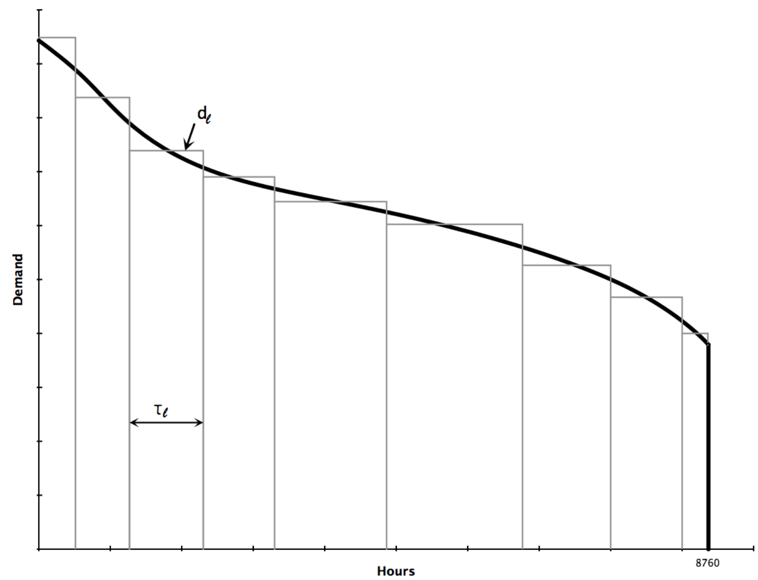

Figure 2: Load Duration Curve

account the risks due to weather conditions.

4.2 Scenario overview

The scenario simulated, largely in line with the IEA (2012b) "New Policies Scenario" (NPS), can be summarized as follows.

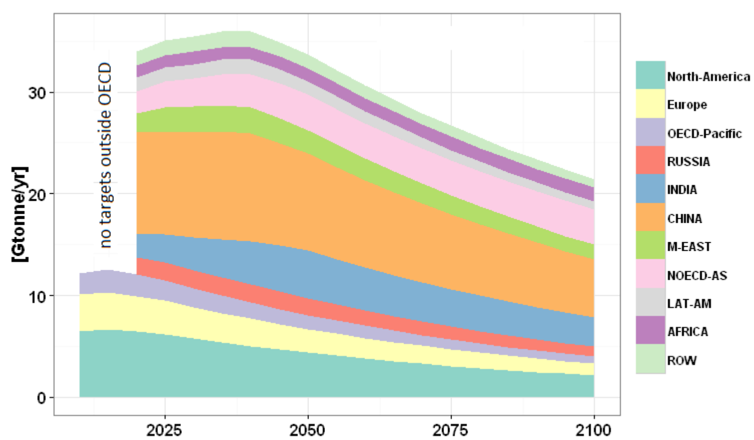

Figure 3: Regional energy related CO2 emissions targets

Regional potential GDP growth rates, shown in Table D correspond until 2035 to the IEA (2012b) NP assumptions . For the post-2035 periods they are set consistently with the the OECD long term GDP growth projections (OECD, 2012). The long term price elasticity of electric and non-electric energy demands are set to .3. The AEEI assumptions, given in Table D, are set such that the IEA (2012b) NPS electric and non-electric energy prices and consumptions are reproduced.

The scenario assumes a global emission policy, based on regional cap and trade for energy-related CO2 emissions. Sperate emissions markets progressively converge towards a global cap and trade. Prior to 2025 emissions are constrained in the OECD regions. From 2025 on, the OECD regions join a single emission market and emissions start being constrained in non-OECD regions. These later can,ot exchange emissions permits with OECD regions before 2055.
The distribution of regional emissions quotas is presented on figure 3. Until 2035, they are set in line with the emissions projected in the IEA (2012b) NPS. In the three OECD regions, the quotas decrease since the first times periods. In most of the OECD regions, the quotas increase until 2035 before being reduced, in particular in China, leading to a decreases in global emissions quotas. Note that for the periods after 2035, this emission policy is more stringent than in the by IEA (2012a) 4S scenario which continues the IEA (2012b) NPS after 2035 and does not project emissions reduction before the end on the century.

The technical and economic characteristics of power generation technologies are based on IEA (2010) and IEA (2011). The load duration curve for Europe is decomposed into 72 time segments to capture both the shape of the load duration curve as well as the joint distribution of the availability of wind-onshore, wind-offshore and solar pv. The Fossil fuel reserves are computed from EIA (2011), IEA (2011) and IEA (2012b). In addition, annual regional oil and gas production cannot exceed the IEA (2011) Current Policy scenario.

4.3 Convergence of the algorithm

The model is solved using the decomposition algorithms. The TD model contains 1614 (single) equations and 2014 variables, the BU model contains 62310 equations and 52541 variables. The first iteration of the TD model is initialized on a trajectory where macroeconomic variables and the aggregate electric and non-electric energy consumption increase at the rate of potential GDP growth.
Fig. 4 represents the logarithm of the error defined in appendix C.3 for the TD and the BU model at each iteration. We see that the TD and BU models converge in 157 iterations to the error term set to 10^{-6}. The convergence is quick during the first iterations before slowing down. Changes in the TD solution involves changes in the BU solutions, that is why the errors of the two models are closely correlated. Numerical attempts showed that when decreasing the stopping criteria error terms below 10^{-6} convergence was not realized, probably due to internal solvers accuracy.

4.4 CO_2 emission prices

Fig. 5 presents the CO_2 emission prices resulting from the model for the OECD regions. They tend are relatively high during the first time periods and then stabilize. These prices reflect a limited increase of the marginal abatement cost due to the limited emission reduction targets in OECD countries, combined with decreasing costs of green technologies. In addition Fig. 5 shows the convergence of CO_2 price in 2025 creates by the integration of regional OECD cap and trade systems. In the case of EU and North America, this convergence temporarily reduces by one third the CO_2 price.

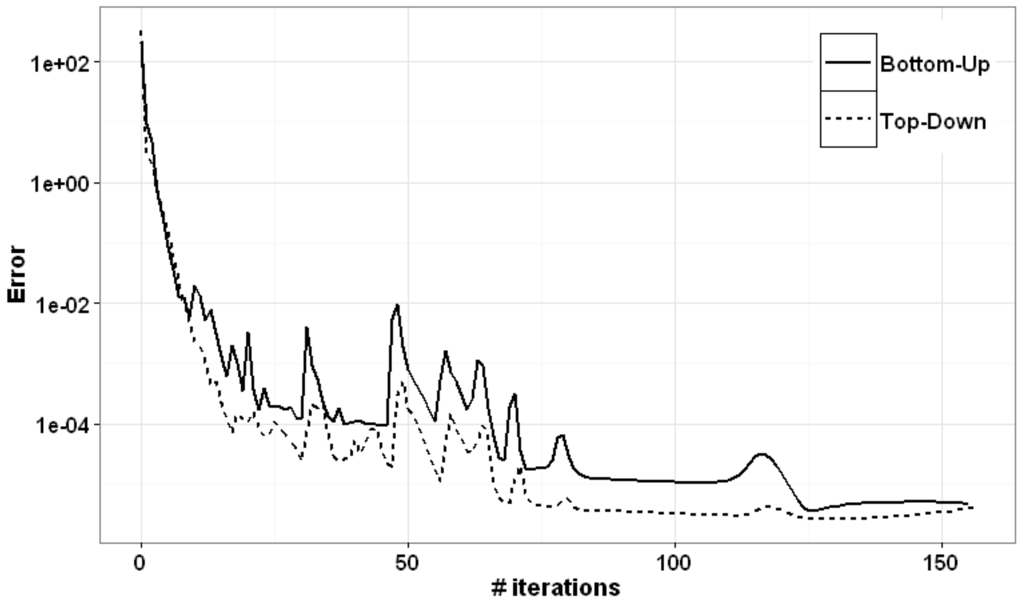

Figure 4: Logarithmic error

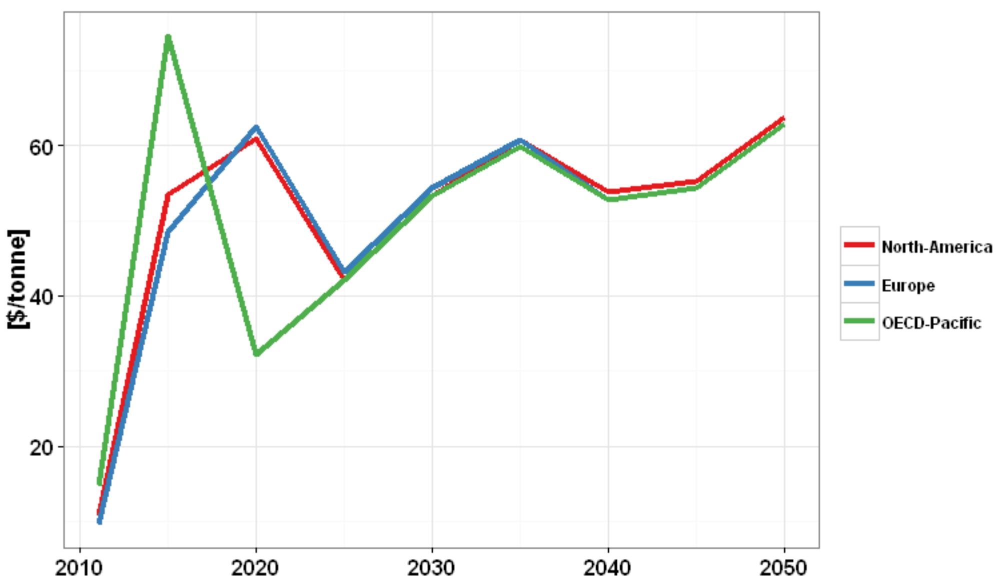

Figure 5: CO_2 emission prices for EU, North America and OECD Pacific

4.5 Load duration curve

Fig. 6 represents the EU load duration curve in 2020 and the correspondix optimal mix required to serve it. Generally speaking, plants are activated in the same order as the merit order, which is the variable cost for the production on 1 MWh.
Nuclear plants are operated at maximum capacity due to its very low marginal cost, so as biomass and lignite. This latter which keeps, due to very low fuel cost, a low total marginal cost despite relatively high CO2 prices. Renewable technologies which have almost zero

(hydro, wind, solar) are used at the maximum of their capacity. But their supply fluctuates due to their intermittent availibility.
The supply of coal and gas power plants, which have a higher marginal cost, is adjusted to demand. The relatively high CO_2 price, make gas CCGT more competitive than coal. Coal is used to only serve peak demand. Very high peak demand is met by gas OCGT plants, which produce only a few hours a year.

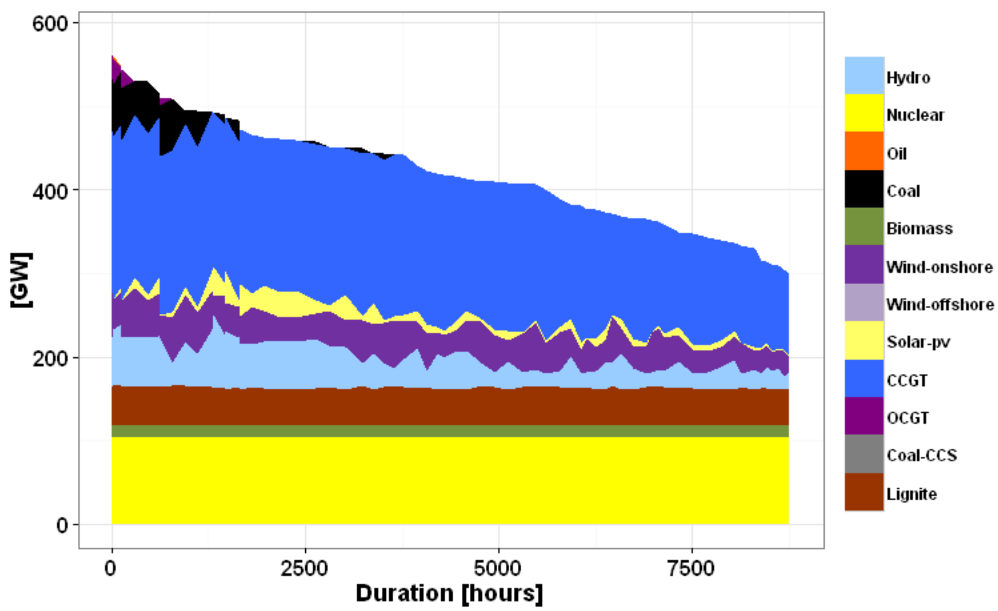

Figure 6: LOAD duration 2020

The aggregated EU load duration curve for the year 2050, given by Fig. 7, reflects a dramatic change in the EU electric system.
First, the share of fossil fuel-fired capacity has dropped. The mix is almost decarbonized (even if EU primary energy consumptions is not). Wind generation mainly coming offshore turbines dominates, but solar and nuclear also play a significant part. Coal is almost absent of the mix, and gas (CCGT and OGT) is used only a few hours a year.
The very high shares of intermittent capacities (wind and solar) create huge fluctuations on the supply side, that are compensated mainly by gas CCGT generation.
However, the fluctuation of production from renewable capacities is so important that excess of supply occasionally appears. This corresponds to zero electricity prices. These excesses of supply which cannot be fully offset by adjustment of nuclear and biomass capacities.

4.6 Capacities installed

The EU total yearly electricity production by technology from 2015 and 2050, presented on Fig. 8, gives more insights about the evolution on the energy mix. Renewable expands over the period, coal disappears after 2035, and the share of gas is almost neglectable after 2040. The wind onshore generation that was the main contributor to the expansion of renewable production until 2025 is progressively replaced by offshore generation, which has higher availability and whose costs have substantially decreased. Similar reasons combined

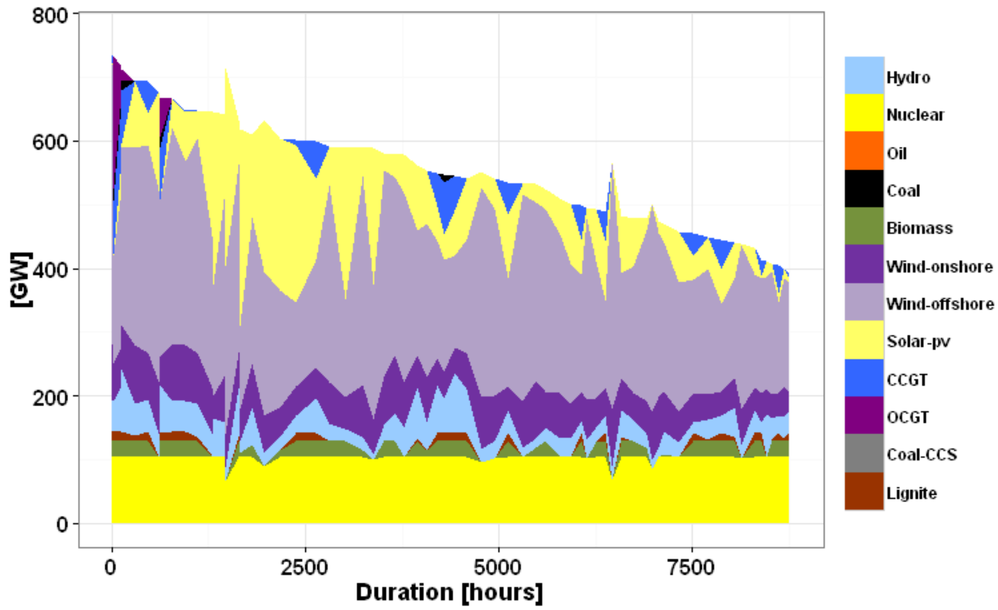

Figure 7: LOAD duration 2050

with another correlation with demand explain the expansion of solar generation between 2030 and 2035. But the progression of solar stops after 2035 and we see that on the long run the intermittent renewable technology privileged is wind offshore.

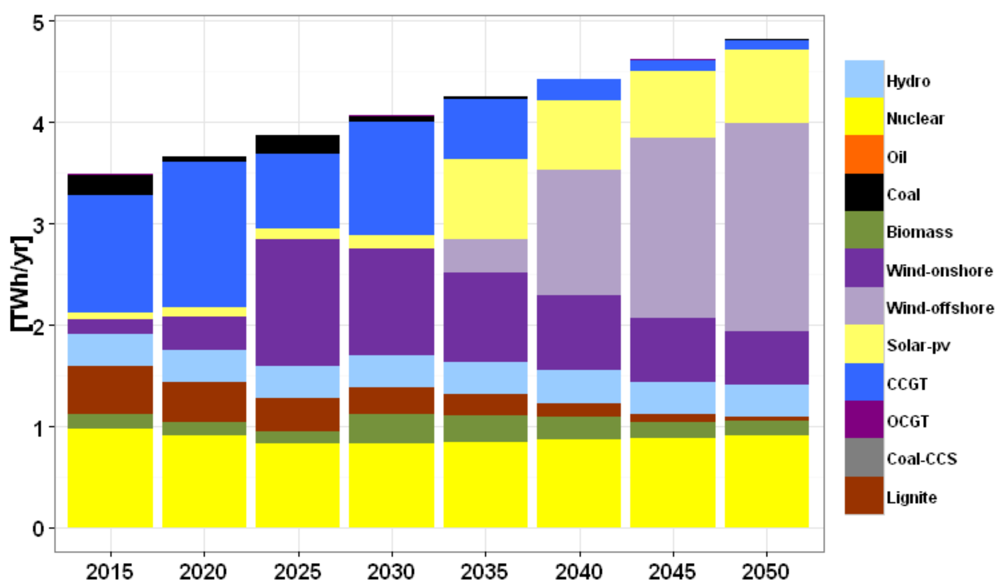

Figure 8: Electricity production in EU

The huge shares of intermittent wind generation that are shown on figures 7 and 8 can endanger the security of supply. The reserve are necessary to meet peak demand (see equation 22). Figure 9 shows that even if they are absent from the production mix, important

	2015	2020	2025	2030	2035	2040	2045	2050
Hydro	100	100	100	100	100	100	100	100
Nuclear	100	100	100	100	100	100	99.9	99.0
Coal	57.4	25.0	72	30.5	8.4	1.5	1.5	2.3
Lignite	100	100	100	100	98.2	88.7	61.2	46.9
Biomass	100	100	100	100	99.8	97.4	86.9	76.9
CCGT	100	99.1	56.7	95.6	72.3	40.7	22.2	19.3
OCGT	6.8	1.5	0.3	3.3	1.5	1.5	1.5	1.5

Table 1: Percentage of hours where production is at full capacity

gas-fired capacity remain quite important. Even, if they do not significantly contribute to production, but OCGT are installed. Since 2035, OCGT is the third technology in terms of installed capacity in GW, but it contribution to production is negligible. The role of OCGT is just to contribute to meet peak demand a few hours a year, and therefore their are used at full capacity only a very small fraction of the year, as Table4.6 shows. This table shows similar pattern for coal plants, and to a lesser extend for CCGT.

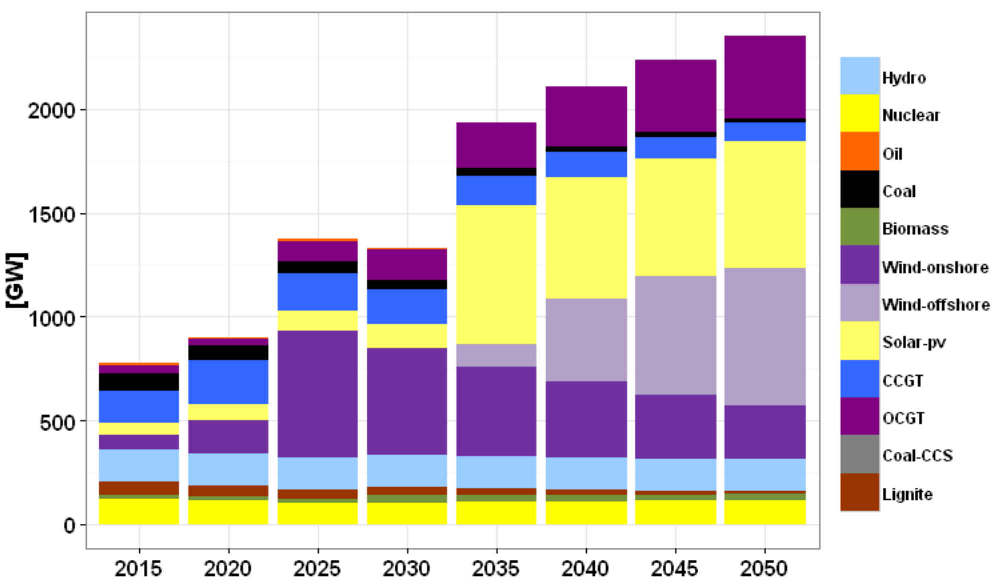

Figure 9: Installed capacities in EU

5 Conclusion

This paper showed how the top-dow bottom-up decomposition algorithm proposed by Bohringer and Rutherford (2006) in a static CGE setting can be extended to MERGE, which is a multi-regional dynamic forward-looking applied general equilibrium model. This extension required to types of adjustments of the algorithm. First, in order to represent the putty-clay technologies of the MERGE top-down submodel, the formulation of the consumer surplus function in the bottom-up model of the decomposition had to be adjusted.

In addition, in line with the NLP formulation of MERGE, the inter-regional trade flows were captured my means of joint optimization in both the bottom-up and the top-down submodel and the Negishi weight were sequentially adjusted at each convergence of the decomposition algorithm.

To illustrate possible applications, the algorithm was used for improving the representation of the electricity supply in MERGE that was based on average yearly demand and on a linear supply system, thus requiring a collection of *ad hoc* constraints limiting the progress of some technologies. This representation was replaced, for the EU region, by a stylized power capacity expansion model. This latter includes various load segments and explicit assumptions about key parameters such as capacity reserves requirements.
The results provided a projection of the capacities for the EU for the period 2015-2050, with a description of how traditional thermal capacity have to be developed based on their contribution to back-up the expanding intermittent renewable capacities.

Beyond the example given in the paper, the decomposition algorithm can be used for several other applications, as it make larger general top-down bottom-up equilibrium problems manageable with limited computational resources. Extensions of the bottom-up model model can be envisaged in order to represented some energy commodity markets with more detail about resource, supply technologies and trade flows. In addition, the size of the top-down models can be extended, for instance by increasing the number of sectors and goods in a dynamic forward-looking model by or by introducing a forward-looking component in a recursive dynamic model. Several other applications can be found in particular in topics that recently emerged in the applied general equilibrium model literature, such as household heterogeneity, intergenerational issues (with overlapping generation models), and uncertainty analysis (with stochastic programming).

References

Kenneth J. Arrow and Gérard Debreu. Existence of an equilibrium for a competitive economy. *Econometrica*, 22:265–290, 1954.

Cesar Beltran, Laurent Drouet, Neil Edwards, Alain Haurie, Jean-Philippe Vial, and Daniel Zachary. An oracle method to couple climate and economic dynamics. In Alain Haurie and Laurent Viguier, editors, *The Coupling of Climate and Economic Dynamics*, volume 22 of *Advances in Global Change Research*, pages 69–95. Springer Netherlands, 2005.

Christoph Bohringer. The synthesis of bottom-up and top-down in energy policy modeling. *Energy Economics*, 20(3):233 – 248, 1998.

Christoph Bohringer and Thomas Rutherford. Combining top-down and bottom-up in energy policy analysis: A decomposition approach. *ZEW-Centre for European Economic Research Discussion Paper*, (06-007), 2006.

Laurent Drouet, Marc Vielle, Maryse Labriet, and Richard Loulou. A master program that will drive the coupling of GEMINI-E3 and MARKAL/TIMES models. Reme working paper, Ecole Polytechnique Fédérale de Lausane, 2008.

Olivier Durand-Lasserve, Axel Pierru, and Yves Smeers. Sensitivity of policy simulation to benchmark scenarios in cge models: illustration with carbon leakage. CORE Discussion

Papers 2012063, Universit catholique de Louvain, Center for Operations Research and Econometrics (CORE), 2012.

EIA. *World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States*. Energy Information Administration, DOE, April 2011.

ENTSOE. System adequacy forecast. Technical report, European Network of Transmission System Operators for Electricity, 2010.

EPRI. PRISM 2.0: Regional Energy and Economic Model Development and Initial Application, US-REGEN Model Documentation. Technical report, Electric Power Research Institute, 2012.

Kenneth C Hoffman and Dale W Jorgenson. Economic and technological models for evaluation of energy policy. *The Bell Journal of Economics*, pages 444–466, 1977.

IEA. *Projected Costs of Generating Electricity*. International Energy Agency, OECD/IEA, Paris, 2010.

IEA. *World Energy Outlook*. International Energy Agency, OECD/IEA, Paris, 2011.

IEA. *Energy Technology Perspectives*. International Energy Agency, OECD/IEA, Paris, 2012a.

IEA. *World Energy Outlook*. International Energy Agency, OECD/IEA, Paris, 2012b.

Alan Manne. ETA-MACRO: A model of energy-economy interactions. Technical report, Electric Power Research Institute, 1977.

Alan Manne and Clas-Otto Wene. MARKAL-MACRO: a linked model for energy economy analysis. Informal report, Brookheaven National Laboratory, Departement of Applied Science, February 1992.

Alan Manne, Robert Mendelsohn, and Richard Richels. MERGE : A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy*, 23(1):17–34, January 1995.

Sabine Messner and Leo Schrattenholzer. Message–macro: linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy*, 25(3):267–282, 2000.

T. Negishi. Welfare economics and the existence of an equilibrium for a competitive economy. *Metroeconomica*, 12:92–97, 1972.

OECD. *OECD Economic Outlook (Preliminary Version*, volume 2012/1. OECD Publishing, April 2012.

William Pizer, Dallas Burtraw, Winston Harrington, Richard Newell, and James Sanchirico. Modeling economy-wide vs sectoral climate policies using combined aggregate-sectoral models. Technical report, Resource for the future,Washington, D.C., 2003.

S. Rausch and T. F. Rutherford. Computation of Equilibria in OLG Models with Many Heterogeneous Households. *Computational Economics*, 36(2):171–189, 2010.

Alexander H. G. Rinnooy Kan. Capacity expansionanalysis of simple models with applications. *Networks*, 13(2):303–303, 1983.

Tarr D. Rutherford, T. and O. Shepotylo. *Poverty and the WTO: Impacts of the Doha Development Agenda*, chapter The Impact on Russia of WTO Accession and The Doha Agenda: The importance of liberalization of barriers against foreign direct investment in services for growth and poverty reduction, pages 467–496. Palgrave Macmillan and the World Bank, Washington DC, 2006.

Thomas F. Rutherford. *Energy and Environmental Policy Modeling*, chapter Sequential joint maximization. International Series in Operations Research and Management Science 18. Kluwer, 1999.

Andreas Schäfer and Henry D. Jacoby. Technology detail in a multisector CGE model: transport under climate policy. *Energy Economics*, 27(1):1 – 24, 2005. doi: http://dx.doi.org/10.1016/j.eneco.2004.10.005.

Ian Sue Wing. The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework. *Energy Economics*, 30(2):547–573, March 2008.

A The integrated formulation of MERGE

$$\text{Max} \quad \sum_r nwt_r^\star \left\{ \sum_t \beta_{r,t} \overline{L}_{r,t} \log(\frac{C_{r,t}}{\overline{L}_{r,t}}) \right\} \tag{23}$$

$$Y_{r,t} = C_{r,t} + I_{r,t} + NX_{r,\texttt{fg},t} + EC_{r,t} \quad (P_{\texttt{y},r,t}) \tag{24}$$

$$\Delta Y_{r,t} = F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta E_{r,t}, \Delta N_{r,t}) \tag{25}$$

$$Y_{r,t+1} = Y_{r,t}(1 - \delta_{\texttt{y}}) + \Delta Y_{r,t} \tag{26}$$

$$K_{r,t+1} = K_{r,t}(1 - \delta_{\texttt{y}}) + \Delta K_{r,t+1} \tag{27}$$

$$E_{r,t+1} = E_{r,t}(1 - \delta_{\texttt{y}}) + \Delta E_{r,t+1} \tag{28}$$

$$N_{r,t+1} = N_{r,t}(1 - \delta_{\texttt{y}}) + \Delta N_{r,t+1} \tag{29}$$

$$\Delta K_{r,t+1} = \frac{1}{2}(I_{r,t+1} + I_{r,t}(1 - \delta)) \tag{30}$$

$$\sum_j GE_{r,j,t} \geq E_{r,t} \quad (P_{E,r,t}) \qquad j \in \mathcal{E} \tag{31}$$

$$\sum_j GN_{r,j,t} \geq N_{r,t} \quad (P_{N,r,t}) \qquad j \in \mathcal{N} \tag{32}$$

$$GE_{r,j,t} \leq \kappa_{r,j,t} KE_{r,j,t} \qquad j \in \mathcal{E} \tag{33}$$

$$KE_{r,j,t+1} \leq IE_{r,j,t} + KE_{r,j,t}(1 - \delta_j) \qquad j \in \mathcal{E} \tag{34}$$

$$PR_{r,j,t} \geq \sum_k \eta_{r,k,j,t} GE_{r,k,t} + GN_{r,j,t} + NX_{r,j,t} \qquad j \in \mathcal{P} \tag{35}$$

$$E\bar{M}_{r,t} - \Delta B_{r,t} + NX_{r,\texttt{co}_2,t} \geq \sum_{j \in \mathcal{E}} \phi_{j,t} GE_{j,r,t} + \sum_{j \in \mathcal{N}} \phi_{j,t} GN_{j,r,t} \tag{36}$$

$$\Delta B_{r,t+1} = B_{r,t+1} - B_{r,t} \tag{37}$$

$$H(E, IE, KE, GE, N, GN, PR) \leq A \tag{38}$$

$$EC_{r,t} \geq \sum_{j \in \mathcal{E}} (cs_{r,j,\texttt{op},t} GE_{r,j,t} + cs_{r,j,\texttt{ka},t} IE_{r,j,t})$$

$$+ \sum_{j \in \mathcal{N}} cs_{r,\texttt{op},t} GN_{r,j,t} + \sum_{j \in \mathcal{TR}} cs_{j,\texttt{tr},t} EXP_{r,j,t} \tag{39}$$

$$\sum_{r \in \mathcal{R}} NX_{r,j,t} = 0 \quad (P_{\texttt{nx},j,t}) \qquad j \in \mathcal{TR} \tag{40}$$

$$EXP_{r,j,t} \geq NX_{r,j,t} = 0 \qquad j \in \mathcal{TR} \tag{41}$$

where $nwt_r^\star$ are set so as to imply at optimum

$$\sum_{j \in \mathcal{TR}} P_{\texttt{nx},j,t} NX_{r,j,t} = 0 \qquad r \in \mathcal{R}$$

The integrated NLP formulation of MERGE used for the SJO is presented below. The objective function, (Equation 23) is a sum of regional inter-temporal utility functions weighted by the Negishi weighs $\alpha_{r,t}$. Equation (24) ensures that the output of the final sector Y is sufficient to meet demand for consumption, investment (I), net exports (NX) and energy costs(EC). The production function with putty clay technology is represented by Equations (25) to (29). Production from the new vintages (ΔY_t) requires a combination of new capital (ΔK_t), new labour ($\Delta \overline{L}$), new electric and non electric energy ($\Delta E_{r,t}$ and $\Delta N_{r,t}$). Total output (input) is the sum of previous period (output) decayed at rate ($\delta_{\texttt{y}}$)

and new vintage output (input). The capital included in a new vintages is provided by investments (Equation 30).
The productions from the various electric and non-electric technologies (GE and GN) sum up to total supply electric and non electric energy supplies (Equations 32 and **??**). The production with a given electric technology cannot exceed the total installed capacity (KE) multiplied by κ that is its exogenous maximum number of operation hour during the year (Equation 33). The installed capacity of a technologies decays at rate δ_j but can be expanded by new investments IE (Equation 34). For each energy product, primary supply (PR) must meet the demand for power (computed using heat rate η), direct use and net energy export (Equation 35). In Equation (36) we see that exogenous cap ($\overline{EM}$) represent regional emissions allowances (quotas) that must cover the emissions (computed using emissions factor ϕ) from power generation and direct energy use. The permits can be banked or traded internationally. The dynamics of the stock of banked permits (B) is given by Equation (37). The system of regional energy portfolio constraints are represented in a generic way by Equation 37.
The total regional cost of producing energy is given by equation (39) that accounts for operation and exploitation cost, capital costs, and transportation costs for the exported commodities.
The equilibrium between supply and demand in international commodity market is enforce by (Equation 40) while (Equation 41) merely ensures that there is no indeterminacy in imports and export flows for given level of net exports.

B Static reformulation of cost-minimization problem when technologies are putty-clay

This appendix shows how the producer's inter-temporal cost minimization problem over T time periods can be reformulated as T independent static problems. A similar demonstration is already given in appendix of (Durand-Lasserve et al., 2012).

The final goods producer inter-temporal cost minimization problem is:

$$\begin{aligned}
\min_{E,N,K} \quad & \sum_t (P_{E,r,t}E_{r,t} + P_{N,r,t}N_{r,t} + RK_{r,t}K_{r,t}) \\
& F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta N_{r,t}, \Delta N_{r,t}) = \Delta Y_{r,t} \\
& Y_{r,t} = \overline{Y}_{r,t} \quad (P_{\mathrm{y},r,t}) \\
& Y_{r,t+1} = Y_{r,t}(1-\delta_{\mathrm{y}}) + \Delta Y_{r,t} \\
& K_{r,t+1} = K_{r,t}(1-\delta_{\mathrm{y}}) + \Delta K_{r,t} \\
& E_{r,t+1} = E_{r,t}(1-\delta_{\mathrm{y}}) + \Delta E_{r,t} \\
& N_{r,t+1} = N_{r,t}(1-\delta_{\mathrm{y}}) + \Delta N_{r,t}
\end{aligned} \tag{42}$$

We can express the total output (inputs) as the sum of the output (inputs) of the present, past period vintages:

$$\begin{aligned}
E_{r,t} &= \sum_{t>t'\geq 0} \Delta E_{r,t-t'}(1-\delta_{\mathrm{y}})^{t'} + \overline{E}_0(1-\delta_{\mathrm{y}})^{t} \\
N_{r,t} &= \sum_{t>t'\geq 0} \Delta N_{r,t-t'}(1-\delta_{\mathrm{y}})^{t'} + \overline{N}_0(1-\delta_{\mathrm{y}})^{t} \\
K_{r,t} &= \sum_{t>t'\geq 0} \Delta K_{r,t-t'}(1-\delta_{\mathrm{y}})^{t'} + \overline{K}_0(1-\delta_{\mathrm{y}})^{t} \\
\overline{Y}_{r,t} &= \sum_{t>t'\geq 0} \Delta \overline{Y}_{r,t-t'}(1-\delta_{\mathrm{y}})^{t'} + \overline{Y}_0(1-\delta_{\mathrm{y}})^{t}
\end{aligned} \tag{43}$$

Replacing the inputs and output by these expressions, and dropping the initial condition from the objective function, the cost-minimization problem of the producer can be rewritten as :

$$\begin{aligned}
\min_{E,N,K} \; & \sum_{t} \sum_{t>t'\geq 0} \Big[(1-\delta_{\mathrm{y}})^{t'}(P_{E,r,t}\Delta E_{r,t-t'} + P_{N,r,t}\Delta N_{r,t-t'} + RK_{r,t}\Delta K_{r,t-t'})\Big] \\
& F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta N_{r,t}, \Delta N_{r,t}) = \Delta Y_{r,t}
\end{aligned} \tag{44}$$

If rearranging the terms in the sums, the problem can be formulated as:

$$\begin{aligned}
\min_{E,N,K} \; & \sum_{t}(P'_{E,r,t}\Delta E_{r,t} + P'_{N,r,t}\Delta N_{r,t-t'} + RK'_{r,t}\Delta K_{r,t}) \\
& F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta N_{r,t}, \Delta N_{r,t}) = \Delta \overline{Y}_{r,t}
\end{aligned} \tag{45}$$

The prices denoted by P' are indexes of current and future prices derived using formula:

$$P'_{r,t} = \sum_{t\leq t'\leq T-1} (1-\delta_{\mathrm{y}})^{t'-t} P_{r,t'} + \frac{P_{r,T}P_{r,T-1}}{P_{r,T-1} - (1-\delta_{\mathrm{y}})P_{r,T}} \tag{46}$$

These indexes take into account not only the current price, but also the sum of discounted prices weighted by the decay of the vintage at the corresponding period (first right-hand terms). The sum of future prices in post-terminal periods is approximated. This proxy (the second right-hand term) is made assuming that prices growth rate between $T-1$ and T is infinitely repeated after T.

Solving Problem 45 is equivalent to solving the following T independent problems:

$$\begin{aligned}
\min_{E_t,N_t,K_t} \; & (P'_{E,r,t}\Delta E_{r,t} + P'_{N,r,t}\Delta N_{r,t} + RK'_{r,t}\Delta K_{r,t}) \\
& F_{r,t}(\Delta K_{r,t}, \Delta \overline{L}_{r,t}, \Delta N_{r,t}, \Delta N_{r,t}) = \Delta \overline{Y}_{r,t}
\end{aligned} \tag{47}$$

C Equation of the top down and bottom-up models

Here we consider the $k+1$ iteration of the algorithm. The price and quantities that are set are note with a bar and a mention of the origin (the TD or the BU model).

C.1 Top-down model

$$\text{Max} \quad \sum_r nwt_r^\star \left\{ \sum_t \beta_{r,t} \overline{L}_{r,t} \log(\frac{C_{r,t}}{\overline{L}_{r,t}}) \right\} \tag{48}$$

$$Y_{r,t} = C_{r,t} + I_{r,t} + NX_{r,\mathtt{fg},t} + \overline{EC}_{r,t}^{\mathtt{bu}(k)} \tag{49}$$

$$\Delta Y_{r,t} = F_{r,t}(\Delta K_{r,t}, \Delta L_{r,t}, \Delta E_{r,t}, \Delta N_{r,t}) \tag{50}$$

$$Y_{r,t+1} = Y_{r,t}(1-\delta_{\mathtt{y}}) + \Delta Y_{r,t} \tag{51}$$

$$K_{r,t+1} = K_{r,t}(1-\delta_{\mathtt{y}}) + \Delta K_{r,t} \tag{52}$$

$$\Delta E_{r,t} = \Delta \overline{E}_{r,t}^{\mathtt{bu}(k)} \tag{53}$$

$$\Delta N_{r,t} = \Delta \overline{N}_{r,t}^{\mathtt{bu}(k)} \tag{54}$$

$$\Delta K_{r,t+1} = \frac{1}{2}(I_{r,t+1} + I_{r,t}(1-\delta_{\mathtt{y}})) \tag{55}$$

$$\sum_{r \in \mathcal{R}} NX_{r,\mathtt{fg},t} = 0 \tag{56}$$

$$EXP_{r,\mathtt{fg},t} \geq NX_{r,\mathtt{fg},t} = 0 \tag{57}$$

with $nwt_r^\star$ set so as to imply at optimum

$$\sum_{j \in \mathcal{TR} \setminus \mathtt{fg}} \overline{P}_{\mathtt{nx},j,t}^{\mathtt{bu}(k)} \overline{NX}_{r,j,t}^{\mathtt{bu}(k)} + NX_{r,\mathtt{fg},t} P_{\mathtt{nx},j,t} = 0$$

C.2 Bottom-up model

$$\text{Max} \quad \sum_{r,t} \Bigg\{ \overline{P}_{E,r,t}^{\mathtt{td}(k+1)} E_{r,t} + \overline{P}_{N,r,t}^{\mathtt{td}(k+1)} N_{r,t} - \overline{P}_{fg,r,t}^{\mathtt{td}(k+1)} EC_{r,t} + \frac{\overline{P'}_{E,r,t}^{\mathtt{td}(k+1)} \Delta E_{r,t}}{2\sigma_{EN} \Delta \overline{E}_{r,t}^{\mathtt{td}(k+1)}} (2\Delta \overline{E}_{r,t}^{\mathtt{td}(k+1)} - \Delta E_{r,t})$$
$$\frac{\overline{P'}_{N,r,t}^{\mathtt{td}(k+1)} \Delta N_{r,t}}{2\sigma_{EN} \Delta \overline{N}_{r,t}^{\mathtt{td}(k+1)}} (2\Delta \overline{N}_{r,t}^{\mathtt{td}(k+1)} - \Delta N_{r,t}) + \frac{\overline{RK'}_{r,t}^{\mathtt{td}(k+1)} \Delta K_{r,t}}{2\sigma_{KL} \Delta \overline{K}_{r,t}^{\mathtt{td}(k+1)}} (2\Delta \overline{K}_{r,t}^{\mathtt{td}(k+1)} - \Delta K_{r,t}) \Bigg\} \tag{58}$$

$$EC_{r,t} + I_{r,t} \leq \overline{Y}_{r,t}^{\mathtt{td}(k+1)} - \overline{C}_{r,t}^{\mathtt{td}(k+1)} - \overline{NX}_{r,t}^{\mathtt{td}(k+1)} \tag{59}$$

$$\sum_{r \in \mathcal{R}} NX_{r,j,t} = 0 \qquad j \in \mathcal{TR} \setminus \mathtt{fg} \tag{60}$$

$$\text{Equations (28) to (39)} \tag{61}$$

C.3 The convergence criteria

$$\sum_i \sqrt{\sum_t \left(\frac{X_{i,t}^k - \overline{X_{i,t}}^{BU(k-1)}}{\overline{X_{i,t}}^{BU(k-1)}} \right)^2} + \sum_j \sqrt{\sum_t \left(\frac{Y_{j,t}^k - \overline{Y_{j,t}}^{TD(k-1)}}{\overline{Y_{j,t}}^{TD(k-1)}} \right)^2} \leq \xi \tag{62}$$

where k refers to the number of iterations, $X_{i,t} \in \{\Delta E_t, \Delta N_t, \Delta K_t\}$ and $Y_{j,t} \in \{P'_{E,t}, P'_{N,t}, RK'_t\}$.

D Benchmark GDP growth and AEEI assumptions

	2010-2020	2020-2030	2030-2040	2040-2050
North America	2.6	2.2	2.2	2.1
European Union	2.0	1.8	1.7	1.6
OECD Asia Pacific	2.1	1.4	1.5	1.5
Russia	4.1	3.2	2.7	2.2
India	7.5	5.8	5.1	4.4
China	7.9	4.3	3.6	2.9
Middle East	4.3	3.8	3,6	3.5
Other Asia	5.0	3.2	3.7	4.2
Latin America	3.8	2.8	3.2	3.6
Africa	4.6	3.0	3.1	3.2
Rest of the world	3.6	2.7	2.7	2.6
World	4.1	3.1	3.0	2.9
Note: Average annual growth rate, in international 2010 USD, based on IEA (2011)				

Table 2: Benchmark regional GDP growth rates in MERGE

	Electricity		Other energies	
	2010-2020	2020-2035	2010-2020	2020-2035
Advanced economies	0.5	0.8	1.3	1.2
European Union	0.2	0.7	0.8	1.1
OECD North America	0.7	1.0	1.8	1.4
OECD Asia Pacific	0.3	0.8	1.3	1.0
Other economies	0.9	1.3	2.8	1.6
China	1.4	1.9	4.1	2.3
India	1.6	1.1	4.0	1.7
Other Asia	0.6	-0.6	2.0	0.8
Russia	1.6	1.9	2.5	1.5
Middle East	0.2	0.7	0.7	1.1
Latin America	0.8	0.8	1.1	1.0
Africa	1.3	0.4	2.4	1.2
Rest of the world	0.8	1.2	1.3	0.7
World	8.8	7.9	2.0	1.4
Note: Average annual growth rate				

Table 3: Autonomous energy efficiency improvement assumptions

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2014

CCSD	1.2014	Erin Baker, Valentina Bosetti, Karen E. Jenni and Elena Claire Ricci: Facing the Experts: Survey Mode and Expert Elicitation
ERM	2.2014	Simone Tagliapietra: Turkey as a Regional Natural Gas Hub: Myth or Reality? An Analysis of the Regional Gas Market Outlook, beyond the Mainstream Rhetoric
ERM	3.2014	Eva Schmid and Brigitte Knopf: Quantifying the Long-Term Economic Benefits of European Electricity System Integration
CCSD	4.2014	Gabriele Standardi, Francesco Bosello and Fabio Eboli: A Sub-national CGE Model for Italy
CCSD	5.2014	Kai Lessmann, Ulrike Kornek, Valentina Bosetti, Rob Dellink, Johannes Emmerling, Johan Eyckmans, Miyuki Nagashima, Hans-Peter Weikard and Zili Yang: The Stability and Effectiveness of Climate Coalitions: A Comparative Analysis of Multiple Integrated Assessment Models
CCSD	6.2014	Sergio Currarini, Carmen Marchiori and Alessandro Tavoni: Network Economics and the Environment: Insights and Perspectives
CCSD	7.2014	Matthew Ranson and Robert N. Stavins: Linkage of Greenhouse Gas Emissions Trading Systems: Learning from Experience
CCSD	8.2013	Efthymia Kyriakopoulou and Anastasios Xepapadeas: Spatial Policies and Land Use Patterns: Optimal and Market Allocations
CCSD	9.2013	Can Wang, Jie Lin, Wenjia Cai and ZhongXiang Zhang: Policies and Practices of Low Carbon City Development in China
ES	10.2014	Nicola Genovese and Maria Grazia La Spada: Trust as a Key Variable of Sustainable Development and Public Happiness: A Historical and Theoretical Example Regarding the Creation of Money
ERM	11.2014	Ujjayant Chakravorty, Martino Pelli and Beyza Ural Marchand: Does the Quality of Electricity Matter? Evidence from Rural India
ES	12.2014	Roberto Antonietti: From Outsourcing to Productivity, Passing Through Training: Microeconometric Evidence from Italy
CCSD	13.2014	Jussi Lintunen and Jussi Uusivuori: On The Economics of Forest Carbon: Renewable and Carbon Neutral But Not Emission Free
CCSD	14.2014	Brigitte Knopf, Bjørn Bakken, Samuel Carrara, Amit Kanudia, Ilkka Keppo, Tiina Koljonen, Silvana Mima, Eva Schmid and Detlef van Vuuren: Transforming the European Energy System: Member States' Prospects Within the EU Framework
CCSD	15.2014	Brigitte Knopf, Yen-Heng Henry Chen, Enrica De Cian, Hannah Förster, Amit Kanudia, Ioanna Karkatsouli, Ilkka Keppo, Tiina Koljonen, Katja Schumacher and Detlef van Vuuren: Beyond 2020 - Strategies and Costs for Transforming the European Energy System
CCSD	16.2014	Anna Alberini, Markus Bareit and Massimo Filippini: Does the Swiss Car Market Reward Fuel Efficient Cars? Evidence from Hedonic Pricing Regressions, a Regression Discontinuity Design, and Matching
ES	17.2014	Cristina Bernini and Maria Francesca Cracolici: Is Participation in Tourism Market an Opportunity for Everyone? Some Evidence from Italy
ERM	18.2014	Wei Jin and ZhongXiang Zhang: Explaining the Slow Pace of Energy Technological Innovation: Why Market Conditions Matter?
CCSD	19.2014	Salvador Barrios and J. Nicolás Ibañez: Time is of the Essence: Adaptation of Tourism Demand to Climate Change in Europe
CCSD	20.2014	Salvador Barrios and J. Nicolás Ibañez Rivas: Climate Amenities and Adaptation to Climate Change: A Hedonic-Travel Cost Approach for Europe
ERM	21.2014	Andrea Bastianin, Marzio Galeotti and Matteo Manera: Forecasting the Oil-gasoline Price Relationship: Should We Care about the Rockets and the Feathers?
ES	22.2014	Marco Di Cintio and Emanuele Grassi: Wage Incentive Profiles in Dual Labor Markets
CCSD	23.2014	Luca Di Corato and Sebastian Hess: Farmland Investments in Africa: What's the Deal?
CCSD	24.2014	Olivier Beaumais, Anne Briand, Katrin Millock and Céline Nauges: What are Households Willing to Pay for Better Tap Water Quality? A Cross-Country Valuation Study
CCSD	25.2014	Gabriele Standardi, Federico Perali and Luca Pieroni: World Tariff Liberalization in Agriculture: An Assessment Following a Global CGE Trade Model for EU15 Regions
ERM	26.2014	Marie-Laure Nauleau: Free-Riding on Tax Credits for Home Insulation in France: an Econometric Assessment Using Panel Data

CCSD	27.2014	Hannah Förster, Katja Schumacher, Enrica De Cian, Michael Hübler, Ilkka Keppo, Silvana Mima and Ronald D. Sands: European Energy Efficiency and Decarbonization Strategies Beyond 2030 – A Sectoral Multi-model Decomposition
CCSD	28.2014	Katherine Calvin, Shonali Pachauri, Enrica De Cian and Ioanna Mouratiadou: The Effect of African Growth on Future Global Energy, Emissions, and Regional Development
CCSD	29.2014	Aleh Cherp, Jessica Jewell, Vadim Vinichenko, Nico Bauer and Enrica De Cian: Global Energy Security under Different Climate Policies, GDP Growth Rates and Fossil Resource Availabilities
CCSD	30.2014	Enrica De Cian, Ilkka Keppo, Johannes Bollen, Samuel Carrara, Hannah Förster, Michael Hübler, Amit Kanudia, Sergey Paltsev, Ronald Sands and Katja Schumacher: European-Led Climate Policy Versus Global Mitigation Action. Implications on Trade, Technology, and Energy
ERM	31.2014	Simone Tagliapietra: Iran after the (Potential) Nuclear Deal: What's Next for the Country's Natural Gas Market?
CCSD	32.2014	Mads Greaker, Michael Hoel and Knut Einar Rosendahl: Does a Renewable Fuel Standard for Biofuels Reduce Climate Costs?
CCSD	33.2014	Edilio Valentini and Paolo Vitale: Optimal Climate Policy for a Pessimistic Social Planner
ES	34.2014	Cristina Cattaneo: Which Factors Explain the Rising Ethnic Heterogeneity in Italy? An Empirical Analysis at Province Level
CCSD	35.2014	Yasunori Ouchida and Daisaku Goto: Environmental Research Joint Ventures and Time-Consistent Emission Tax
CCSD	36.2014	Jaime de Melo and Mariana Vijil: Barriers to Trade in Environmental Goods and Environmental Services: How Important Are They? How Much Progress at Reducing Them?
CCSD	37.2014	Ryo Horii and Masako Ikefuji: Environment and Growth
CCSD	38.2014	Francesco Bosello, Lorenza Campagnolo, Fabio Eboli and Ramiro Parrado: Energy from Waste: Generation Potential and Mitigation Opportunity
ERM	39.2014	Lion Hirth, Falko Ueckerdt and Ottmar Edenhofer: Why Wind Is Not Coal: On the Economics of Electricity
CCSD	40.2014	Wei Jin and ZhongXiang Zhang: On the Mechanism of International Technology Diffusion for Energy Productivity Growth
CCSD	41.2014	Abeer El-Sayed and Santiago J. Rubio: Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change
CCSD	42.2014	Davide Antonioli, Simone Borghesi and Massimiliano Mazzanti: Are Regional Systems Greening the Economy? the Role of Environmental Innovations and Agglomeration Forces
ERM	43.2014	Donatella Baiardi, Matteo Manera and Mario Menegatti: The Effects of Environmental Risk on Consumption: an Empirical Analysis on the Mediterranean Countries
CCSD	44.2014	Elena Claire Ricci, Valentina Bosetti, Erin Baker and Karen E. Jenni: From Expert Elicitations to Integrated Assessment: Future Prospects of Carbon Capture Technologies
CCSD	45.2014	Kenan Huremovic: Rent Seeking and Power Hierarchies: A Noncooperative Model of Network Formation with Antagonistic Links
CCSD	46.2014	Matthew O. Jackson and Stephen Nei: Networks of Military Alliances, Wars, and International Trade
CCSD	47.2014	Péter Csóka and P. Jean-Jacques Herings: Risk Allocation under Liquidity Constraints
CCSD	48.2014	Ahmet Alkan and Alparslan Tuncay: Pairing Games and Markets
CCSD	49.2014	Sanjeev Goyal, Stephanie Rosenkranz, Utz Weitzel and Vincent Buskens: Individual Search and Social Networks
CCSD	50.2014	Manuel Förster, Ana Mauleon and Vincent J. Vannetelbosch: Trust and Manipulation in Social Networks
CCSD	51.2014	Berno Buechel, Tim Hellmann and Stefan Kölßner: Opinion Dynamics and Wisdom under Conformity
CCSD	52.2014	Sofia Priazhkina and Frank Page: Formation of Bargaining Networks Via Link Sharing
ES	53.2014	Thomas Longden and Greg Kannard: Rugby League in Australia between 2001 and 2012: an Analysis of Home Advantage and Salary Cap Violations
ES	54.2014	Cristina Cattaneo, Carlo V. Fiorio and Giovanni Peri: What Happens to the Careers of European Workers when Immigrants "Take their Jobs"?
CCSD	55.2014	Francesca Sanna-Randaccio, Roberta Sestini and Ornella Tarola: Unilateral Climate Policy and Foreign Direct Investment with Firm and Country Heterogeneity
ES	56.2014	Cristina Cattaneo, Carlo V. Fiorio and Giovanni Peri: Immigration and Careers of European Workers: Effects and the Role of Policies
CCSD	57.2014	Carlos Dionisio Pérez Blanco and Carlos Mario Gómez Gómez: Drought Management Plans and Water Availability in Agriculture. A Risk Assessment Model for a Southern European Basin
CCSD	58.2014	Baptiste Perrissin Fabert, Etienne Espagne, Antonin Pottier and Patrice Dumas: The Comparative Impact of Integrated Assessment Models' Structures on Optimal Mitigation Policies
CCSD	59.2014	Stuart McDonald and Joanna Poyago-Theotoky: Green Technology and Optimal Emissions Taxation
CCSD	60.2014	ZhongXiang Zhang: Programs, Prices and Policies Towards Energy Conservation and Environmental Quality in China
CCSD	61.2014	Carlo Drago, Livia Amidani Aliberti and Davide Carbonai: Measuring Gender Differences in Information Sharing Using Network Analysis: the Case of the Austrian Interlocking Directorship Network in 2009
CCSD	62.2014	Carlos Dionisio Pérez Blanco and Carlos Mario Gómez Gómez: An Integrated Risk Assessment Model for the Implementation of Drought Insurance Markets in Spain
CCSD	63.2014	Y. Hossein Farzin and Ronald Wendner: The Time Path of the Saving Rate: Hyperbolic Discounting and Short-Term Planning
CCSD	64.2014	Jessica F. Green, Thomas Sterner and Gernot Wagner: The Politics of Market Linkage: Linking Domestic Climate Policies with International Political Economy
CCSD	65.2014	Luca Di Corato, Cesare Dosi and Michele Moretto: Bidding for Conservation Contracts

CCSD	66.2014	Achim Voß and Jörg Lingens: What's the Damage? Environmental Regulation with Policy-Motivated Bureaucrats
CCSD	67.2014	Carolyn Fischer, Richard G. Newell and Louis Preonas: Environmental and Technology Policy Options in the Electricity Sector: Interactions and Outcomes
CCSD	68.2014	Carlos M. Gómez, C. Dionisio Pérez-Blanco and Ramon J. Batalla: The Flushing Flow Cost: A Prohibitive River Restoration Alternative? The Case of the Lower Ebro River
ES	69.2014	Roberta Distante, Ivan Petrella and Emiliano Santoro: Size, Age and the Growth of Firms: New Evidence from Quantile Regressions
CCSD	70.2014	Jaime de Melo and Mariana Vijil: The Critical Mass Approach to Achieve a Deal on Green Goods and Services: What is on the Table? How Much to Expect?
ERM	71.2014	Gauthier de Maere d'Aertrycke, Olivier Durand-Lasserve and Marco Schudel: Integration of Power Generation Capacity Expansion in an Applied General Equilibrium Model