

Economic Impacts of Future Changes in the Energy System—National Perspectives

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Abstract In a climate constrained future, hybrid energy-economy model coupling gives additional insight into interregional competition, trade, industrial delocalisation and overall macroeconomic consequences of decarbonising the energy system. Decarbonising the energy system is critical in mitigating climate change. This chapter summarises modelling methodologies developed in the ETSAP community

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to assess economic impacts of decarbonising energy systems at a national level. The preceding chapter focuses on a global perspective. The modelling studies outlined here show that burden sharing rules and national revenue recycling schemes for carbon tax are critical for the long-term viability of economic growth and equitable engagement on combating climate change. Traditional computable general equilibrium models and energy systems models solved in isolation can misrepresent the long run carbon cost and underestimate the demand response caused by technological paradigm shifts in a decarbonised energy system. The approaches outlined within have guided the first evidence based decarbonisation legislation and continue to provide additional insights as increased sectoral disaggregation in hybrid modelling approaches is achieved.

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1 Introduction—Regional Applied Hybrid Models

Global economic and environmental scenarios consistently show a trend of continuous decline in natural resource reserves, degradation of environmental quality, increasing vulnerability of economic growth as a result of environmental stresses, competition for natural resources, soaring energy prices and climate change. These scenarios partly rest on significant efforts by the scientific community over the past three decades to improve knowledge of the interactions between economic growth and the environment; particularly modelling methods have developed to become increasingly applied to the assessment of the environmental and economic consequences of various energy and greenhouse gas (GHG) policies. Policy makers need clear and consistent information concerning the real impact of energy and climate policies on the economy and the most cost-effective technology portfolio to achieve their goals. Separate use of top-down (TD) and bottom-up (BU) models do not adequately address all these aspects, which might lead to ineffective policies.

Hybrid models, that combine the technological detail of BU models with the economic framework of a TD, e.g. General Equilibrium (CGE) models, have been developed as an alternate method. Despite the extensive literature on hybrid models, there are few quantitative examples employing a ‘full-link’ (i.e. not focusing on only one sector) and ‘full-form’ BU and TD models. This chapter outlines several hybrid models considering both full-link, full form, and sectoral model developments as well as hard-linking MARKAL and TIMES MACRO models. All models presented are applied nationally within the Energy Technology Systems Analysis Programme (ETSAP) Community. The general rationale, motivation for regional and global model development are summarised in preceding chapter. This chapter focuses on the first national decarbonisation legislation, theoretical model updates, improvements and lastly learning outcomes from applied methods to national models.

2 Evidence Based UK Climate Legislation Using Hybrid Models

The energy modelling research community has long underpinned energy policy (Jebaraj and Iniyar 2006), in providing insight and numerate policy guidance (Huntington et al. 1982). The United Kingdom (UK) was the first government to legislate for mandatory GHG reduction targets, first aiming at a 60 % CO₂ reduction by 2050 relative to 1990 (BERR 2007). The ETSAP hybrid UK MARKAL-MACRO (UK MM) model was used extensively to provide the evidence base to guide discussion in the first iteration of analyses and represented a significant addition to UK energy-economy modelling capacity (FES 2003; DEFRA 2007; Strachan and Kannan 2008). UK-MM is a BU optimisation method that maintains sectoral technological detail, but endogenises aggregated price dependent energy

service demand dynamics via the single sector neoclassical growth model. It is the first step in assessing the competing elements of hybrid energy modelling: technological explicitness, microeconomic-realism and macroeconomic completeness (Bataille et al. 2006). It gave insights while public debate was still ongoing as to the costs, benefits, opportunities and energy security concerns of climate change under long term uncertainty (Pearce 2003; Nordhaus 2007). UK climate policy had been primarily driven by scientific and political competition (RCEP 2000; Stern 2006), while macroeconomic impact was not a significant concern in the short term. The UKERC UK-MM studies showed that the short term impacts were manageable (Strachan and Kannan 2008). This enabled public and policy discussion to focus on sector specific impacts, social impacts and industrial effects. Further, it moved the policy discussion from whether the UK should decarbonise or not, to how to decarbonise. Four subsequent studies combined modelling effort of the AMOS, E3MG, MDME3 and MARKAL-MACRO models to continue to assess the technical feasibility of the 60 % CO₂ reduction target, finding critical technologies and reducing uncertainty (Allan et al. 2007, 2012; Strachan et al. 2009). These modelling activities highlighted the critical nature of developments in the power sector, marginal technologies, resource availability, the cost of carbon and behaviour in relation to the potential impact upon economic activity (GDP). As a result of the 2008 climate change act, the climate change committee was founded, providing legally binding carbon budgets for the UK, and is investigating stronger measures of 80 % CO₂ reductions, beyond the power sector, by 2050.

In the wake of the 2008 economic crisis, with the resultant austerity measures, risk aversion, and reduced investment capital, implementing the carbon budgets have been more difficult than initially expected. In previous studies, ex-post analysis has shown errors in model forecasting in the EU (Pilavachi et al. 2008), and US (Winebrake and Sakva 2006), and notes particular care should be taken to avoid model bias entering energy policy when energy models are directly applied by policy makers (Laitner et al. 2003).

2.1 Modelling Method Summary

Like TIMES, MARKAL is a dynamic, technology rich linear programming (LP) energy systems optimisation model. It's objective function minimises total discounted costs, including capital, fuel and operating costs for resource, process, infrastructure, conversion and end use technologies. It is a partial equilibrium model with perfect foresight. MARKAL was extended with a hard-link to MACRO. The objective function of the hybrid model is the maximisation of discounted log of utility summed over all periods (t) with an end of horizon terminal investment term. Utility is derived as the log of consumption. National production is from energy, capital and labour, substitutable in a nested constant elasticity of substitution (CES) production function. Capital and labour substitute directly for each other based on optimal capital value shares in their aggregate. Aggregated capital and labour is

substitutable with a separate energy aggregate. Investment is recycled to build up a depreciating capital stock, while labour growth rates are defined exogenously.

The marginal change in production output is equivalent to the cost of changing its energy demand. This allows heterogeneous energy demand adjustment across sectors dependent upon marginal demand costs. However, shadow price responses need to be smooth to ensure marginal demand responses are realistic and allow model convergence. Autonomous energy service demand adjustment enables useful climate scenario analysis of demand responses that are decoupled from economic growth. A technical summary of the TIMES-MACRO model formulation follows in Sect. 3, while further technical detail of the UK-MM is available in Strachan and Kannan (2008).

2.2 Evidence Base for Policy

54 low-carbon “what if” scenarios were modelled with UK-MM to advise the UK energy white paper of potential costs of differing technology development pathways in a future with a 60 % reduction in CO₂ emissions (BERR 2007). The summary results are clustered into 4 representative scenarios, focusing on insights from the hybrid linkage, the timing of emissions constraints trajectories, fossil fuel costs and technology abilities (Strachan and Kannan 2008). The macroeconomic impact of the future changes to the UK energy system are summarised as percentage loss of projected GDP in Table 1. There is significant technical change across all sectors in all base case scenarios—before carbon constraints are applied—with car stock switch to hybrid vehicles and implementation of energy efficiency measures in building energy conservation. In the medium to long term (2030–2050) energy efficiency opportunities are exhausted and final energy demand grows, even with MACRO feedback. Higher or lower fossil fuel prices lead to lower (8 %) or higher (3 %) energy consumption respectively in 2050.

In carbon constrained scenarios, decarbonising the electricity sector is seen as the best technology pathway without behavioural change and demand adjustments, while allowing greater electricity consumption. The additional flexibility of demand endogeneity through MM is critical in accurately assessing the marginal cost of carbon. In MM 60 % CO₂ reduction scenarios, energy efficiency and conservation is maximised, with 10–15 % reductions in individual energy demand (compared to

Table 1 UK MARKAL-MACRO scenario analysis summary results

MARKAL-MACRO scenario run	% GDP loss			
	2020	2030	2040	2050
Central scenario	0.46	1.7	2.43	2.81
With accelerated technological change	0.45	1.6	2.35	2.58
With higher fossil fuel prices	0.45	1.54	2.27	2.64
With accelerated energy efficiency	−0.07	0.63	1.63	2.04

standard MARKAL runs) contributing considerably to lowering marginal CO₂ prices. In the short term it is noted that all carbon constrained scenarios have relatively benign impact upon GDP, while accelerated energy efficiency policies can have positive economic benefits via energy cost savings increasing alternative consumption. It is also noted that while there is a significant loss of GDP in the range of 2–2.8 % GDP in the long term to 2050, this impact is not seen as insurmountable. The marginal CO₂ price of the central scenario rises to €147/tCO₂ (\$189/tCO₂), while this price is estimated at €189/tCO₂ (\$243/tCO₂) without endogenous demand reductions from MM.

2.3 Discussion

UK energy policy makers have recognised the insights generated by hybrid energy-economy giving GDP and demand responses to energy system decarbonisation. Relevant policy makers were educated in formal energy-economic analysis and how to interpret decarbonisation scenario analysis results. Key staff members of the Committee for Climate Change were on the original UK-MARKAL project steering group. The additional flexibility of the MM demand endogeneity is seen as critical in estimating the marginal cost of carbon. There are notable trade-offs between optimum technological decarbonisation pathways and the impact that behaviour has on the marginal technology choices.

While seen as manageable, the cost impacts from the UK MM model are likely to underestimate the cost of CO₂ mitigation as a result of the lack of regional trade competitiveness or transitional effects. This is observed when comparing results from the studies in Sect. 3, and Sect. 2 in Chap. 19. Decarbonising faster than other nations creates a competitiveness disadvantage that UK MM does not account for. Resultantly inter-regional hybrid models are critical to account for global trade and competitiveness effects. Further experience from policy engagement sees the requirement for more detailed disaggregation of hybrid models to investigate spatial and socio-demographic effects. An extended treatment of natural capital stocks within nested CGE models is required to investigate realistic substitutability between natural and conventional capital as factors of production. A final lesson learned from the UK policy experience is the need for greater modelling transparency to enable replication of results. Next however, the theory behind the MACRO and MSA models—the work of Socrates Kypreos and Antti Lehtilla—are outlined in Sect. 3.

3 TIMES-Macro Stand Alone

Computer based models representing energy, economy and environmental interactions are specified, among others as non-linear (NL) optimization problems or as computable general equilibrium (CGE) simulation models (Arrow and

Debreu 1954). Optimization models when satisfying some maximization conditions give the same solution as CGE models (Capros et al. 1997). The multiregional bottom-up energy system model TIMES (Loulou et al. 2005), linked with the top-down macroeconomic module MACRO called TIMES-MACRO (TM) (Remme and Blesl 2006), is solved by maximizing an inter-temporal utility function for a single representative producer-consumer agent in each region. TM has been developed as part of the Implementing Agreement of the Energy Technology Systems Analysis Project (ETSAP) of the International Energy Agency to assess, among others, the whole energy system and climate change mitigation options and policies on the national, multiregional or global level. The multiregional TM models are large in size not solvable with direct NL optimization methods even when the most powerful commercial solvers and state of the art computers are used. On the other hand, a similar in size and structure model, the well-known MES-SAGE-MACRO of IIASA (Messner and Schrattenholzer 2000), is successfully and efficiently solved by decomposition methods. The mathematics to decompose and solve TM with an iterative algorithm is outlined below. The decomposition method converts TM to an energy part (TIMES) and a small size NL macroeconomic model, called TIMES-MACRO Stand-Alone (TMSA), where the energy model TIMES is substituted by appropriate quadratic cost supply functions (QSF). This outline continues describing the demand projections for TIMES and explain the multiregional TMSA, the Negishi (1972) welfare function and the iterative procedure applied to solve the problem based on the sequential equilibrium algorithm of Rutherford (1992) (Negishi 1972; Rutherford 1992). Finally the performance of the algorithm is explained and some resultant conclusions discussed.

3.1 Energy Service Demand Projections

The ETSAP family of models defines demands that reflect past trends and exogenous assumptions on population, GDP, energy intensity and technology penetration based on demand drivers and their elasticities. As most of the efficiency improvement options are included in the engineering model explicitly, and are selected if they make economic sense, the specific selection of autonomous efficiency improvement factors (*aeEIF*) applied below could be introduced to reflect mainly life style changes. A simple but useful relation for demand projections is Eq. 1:

$$\frac{D_{kt}}{D_{k0}} = \left[\frac{dr_{kt}}{dr_{k0}} \right]^{\alpha_i} \cdot \left[\frac{P_{kt}}{P_{k0}} \right]^{-\sigma_i} \cdot \prod_{\tau=1,t} (1 - aeEIF_{k\tau})^{ypp\tau} \tag{1}$$

where

- D_{kt} the demand projection for sector k and period t;
 D_{k0} the same demand for the starting year calibrated to energy statistics in line with the socio-economic assumptions and the efficiencies of the end-use devices valid in the starting year of analysis;
 dr_{kt} the demand driver;
 α_k the driver elasticity;
 σ_k the price elasticity;
 $aeEIF_{kt}$ the autonomous efficiency improvement factor per demand category;
 ypp_τ the years per period;
 P_{kt}/P_{k0} the index of relative price of demand in sector k.

TIAM (the global multiregional integrated assessment version of TIMES) assumes different growth rates and elasticities of demand drivers for each individual demand category. Usually some consistency checks of economic assumptions and the projections generated based on the equation above must be completed. IIASA for example adjusts projections to the results of MERGE (Manne et al. 1995), while ETSAP uses GEM-E3 (Capros et al. 1997).

3.2 The Multi-regional TIMES-SA Model

In the following section the global and multi-regional macroeconomic growth model is decomposed into a multi-regional partial equilibrium energy problem, e.g., TIMES and a multi-regional macroeconomic model maximizing the global welfare function.

3.2.1 The Macro Stand-Alone Formulation (MSA)

For the new stand-alone Macro formulation, the original Macro model had to be generalized to support multiple regions. In the multi-regional case the model is solved by maximizing the Negishi-weighted sum of regional utilities based on iterations between the stand-alone TM model (TMSA) and the standard TIMES model. The TMSA model explicitly considers only the trade of the numéraire good, as the trade in all energy products is defined in the TIMES model. The basic formulation of the original TM implementation can be rewritten by Eqs. 2–11:

$$\text{Max } U = \sum_{t=1}^T \sum_r nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(C_{r,t}) \quad (2)$$

$$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + NTX(nmr)_{r,t} \quad (3)$$

$$Y_{r,t} = \left(akl_r \cdot K_{r,t}^{kpvs_r \cdot \rho_r} \cdot l_{r,t}^{(1-kpvs_r)\rho_r} + \sum_k b_{r,k} \cdot DEM_{r,t,k}^{\rho_r} \right)^{\frac{1}{\rho_r}} \quad (4)$$

$$K_{r,t+1} = tsrv_{r,t} \cdot K_{r,t} + \frac{1}{2}(d_t \cdot tsrv_{r,t} \cdot INV_{r,t} + d_{t+1} \cdot INV_{r,t+1}) \quad (5)$$

$$K_{r,T} \cdot (growv_{r,T} + depr_r) \leq INV_{r,T} \quad (6)$$

$$DET_{r,t,k} = aeeifac_{r,t,k} \cdot DEM_{r,t,k} \quad (7)$$

$$EC_{r,t} = qa_{r,t} + \sum_k qb_{r,t,k} \cdot (DET_{r,t,k})^2 + amp_{r,t} \quad (8)$$

$$\sum_r NTX(trd)_{r,t} = 0 \quad \forall \{t, trd\} \quad (9)$$

$$aeeifac_{r,t,k} = \prod_{\tau=1}^t (1 - ddf_{r,\tau,k})^{\frac{d_t + d_{t+1}}{2}} \quad (10)$$

$$l_{r,1} = 1 \quad \text{and} \quad l_{r,t+1} = l_{r,t} \cdot (1 + growv_{r,t})^{\frac{d_t + d_{t+1}}{2}} \quad (11)$$

where

$C_{r,t}$	annual consumption in period t (variable)
$Y_{r,t}$	annual production in period t (variable)
$K_{r,t}$	total capital in period t (variable)
$INV_{r,t}$	annual investments in period t (variable)
$DEM_{r,t,k}$	annual demand in Macro for commodity k in period t (variable)
$DET_{r,t,k}$	annual demand in TIMES for commodity k in period t (variable)
$EC_{r,t}$	annual energy system costs in Macro in period t (variable)
akl_r	production function constant
amp_t	constant term to account for the full annualized investment cost of existing capacities in the starting period
$b_{r,k}$	demand coefficient for demand commodity k
$aeeifac_{r,t,k}$	autonomous energy efficiency improvement
dt	duration of period t in years
$ddf_{r,t,k}$	demand decoupling factor (calibration parameter)
$depr_r$	depreciation rate
$dfact_{r,t}$	utility discount factor for period t
$dfactcurr_{r,t}$	annual discount rate for period t
$growv_{r,t}$	growth rate in period t (calibration parameter)
$kpvs_r$	capital value share
$l_{r,t}$	annual labor growth index in period t
nwt_r	Negishi weight for region r

pwt_t	period-length-dependent weights in the utility function (to be introduced to in cases where the period lengths are not equal)
$qa_{r,t}$	constant term of the quadratic supply cost function
$qb_{r,t,k}$	coefficient for demand k in the quadratic supply cost function
$tsrv_{r,t}$	capital survival factor between periods t and $t + 1$
ρ_r	substitution constant
T	number of periods in the model horizon

The primary differences in relation to the standard Macro formulation are; (a) The use of Negishi weights in the objective function when the model is multi-regional; (b) The inclusion of the trade in the numéraire good $NTX(nmr)$ in the production function; (c) The introduction of the trade balances on the global level (Eq. 9); (d) The Negishi iterations balance for inter-temporal discounted trade deficits of a region over the full time horizon of the analysis; (e) The replacement of the full TIAM LP cost accounting by quadratic supply-cost functions for each demand commodity (Eq. 8).

3.2.2 The Standard TIMES LP Formulation

The second part of the decomposed model, the TIMES LP model, uses the standard TIMES formulation, which can be written in short as:

$$\text{Min } NPV = \sum_{r=1}^R \sum_{y \in \text{YEARS}} (1 + d_{r,y})^{\text{REFYR}-y} \cdot \text{ANNCOST}(r,y) \quad (12)$$

$$A \cdot x = b \quad \text{and} \quad x \geq 0 \quad (13)$$

where

NPV	net present value of all energy system costs
YEARS	the set of years within the model horizon
REFYR	reference year for discounting
$d_{r,y}$	capital discount factor for region r in year y
$\text{ANNCOST}(r,y)$	annual energy system cost in region r and year y
A	coefficient matrix for all other model equations
x	vector of all model variables
b	RHS constant vector for all other model equations
R	number of internal regions in the model

For a comprehensive treatment of the standard TIMES LP formulation, see Loulou et al. (2005). In order to make the LP formulation more analogous with the Macro objective function, the objective function of the standard TIAM code can be

rewritten in terms of period-wise average annual costs and period-specific discount factors, as follows:

$$\text{Min } NPV = \sum_{r=1}^R \sum_{t=1}^T pvf_{r,t} \cdot AESC(r,t) \tag{14}$$

where

- pvf_{r,t} present value factor for period t in region r
- AESC(r,t) annual energy system costs in region r and period t
- T number of periods t in the model horizon

The general specifications of the decomposition algorithm are described by Kypreos and Lehtila (2013).

3.2.3 The Algorithm and It’s Performance

In both MACRO formulations, the use of the MACRO model for evaluating policy scenarios requires that the demand decoupling factors (*ddf*) and labour growth rates (*growv*) have first been calibrated with the baseline scenario and the corresponding GDP growth projections. The core part of the calibration procedure is the updating of the demand decoupling factors and labour growth rates between successive iterations of the calibration algorithm.

In the TMSA implementation, all the basic mathematical formulas for the initial specification and updating the demand decoupling factors and labour growth rates are fully equivalent to those in the standard TM formulation introduced first by Kypreos (1996). The TIMES-MACRO documentation (Remme and Blesl 2006) contains the details on the calibration algorithm and follow the description of Kypreos and Lehtila (2013) in the ETSAP documentation (Kypreos 1996; Kypreos and Lehtila 2013).

The initial Negishi weights are proportional to the regional output share while the updated ones balance for inter-temporal trade deficits following the sequential optimization algorithm of Rutherford (1992). The weights are adjusted using the normalized price of the traded products, the trade excess and the inverse of the marginal regional utility and in that case, according to Rutherford the solution obtained is Pareto optimal.

$$\begin{aligned} NW_r &= \sum_{t,trd} \pi_{trd,t} \cdot NTX_{r,t,trd} + \sum_t \pi_{nmr,t} \cdot C_{r,t} \text{ with} \\ nwt_r &= NW_r / \sum_r NW_r \end{aligned} \tag{15}$$

One significant test run for the algorithm was the solution of TM for a single region as the problem could be solved with a direct optimization and the decomposition

method and results are directly comparable. The USA TMSA model validated well against the direct solution of the TM of USA as solutions are identical. However, the decomposed problem needs 2 min to be solved while the direct optimization takes more than 100 times longer. It is interesting to report the computer time needed to solve the calibration and the policy analysis case as function of the number of regions. The model starts in 2005 and covers up to 2060 in 7 time steps. A 6-region model takes about 32 min to be solved; a 10-region model needs 66 min and finally a 15-region model takes 100 min.

3.3 Conclusions

The large scale general equilibrium growth model TIMES-MACRO is solvable only when decomposed to the linear energy model TIAM and a non-linear macroeconomic stand-alone model (TMSA) where quadratic supply functions substitute for the energy system represented in TIMES.

The methodology is presented herein that allows projecting demands for energy services for a set of socio-economic assumptions, life style changes and energy intensities based on sectoral drivers, and its income and price elasticities. The regional demand decoupling factors (*ddf*) are introduced to calibrate the baseline case reproducing the same demands, although the MACRO model uses unitary income elasticity and the same elasticity of substitution across all sectors. The TMSA model then including these decoupling factors simulates the postulated GDP growth and the demands for energy. This is done with a minimum investment in respect of computation time. The execution times needed for low tolerance errors (less than 10^{-4}), is significantly reduced during both the calibration itself and when applying the model for a policy case. This can be done for either a single country model or for the multiregional and global TM model.

Although the quadratic supply cost function is a simple and approximate meta-model that substitutes for the full-scale energy model and the marginal prices are sensitive to small demand changes, the algorithm is able to give an exact calibration for the baseline case followed by good results for the carbon constrained case as the tolerance error in demand evaluation is below 10^{-4} . The prerequisite for a successful application of the QSF in representing energy and economy interactions is to have all the important system constraints determining the changes of the energy system linearized and included in TIMES. This is because the quadratic cost formulation allows for small changes around the demand variables when searching for optimal solutions and converges in small steps. For the first time the decomposition method proposed is able to solve the global TIAM-MACRO model with 15 regions in 1.5 h based on TMSA (in Windows 7, 64-bit workstation, solution in a single thread).

3.4 Ireland—Application of *TIMES-Macro Stand Alone*

The hybrid linking of the Irish Energy system model, Irish-TIMES is taking a two pronged approach. Firstly the linkage and calibration of the newly developed Macro Stand Alone model to form Irish-TIMES-MSA. Secondly a softlinking process is underway linking the National macroeconomic HERMES model to enable model comparison between the two approaches—aggregated production function and disaggregated sectoral production.

HERMES is a complete structural model of the Irish economy. The specification of the HERMES model is built on the assumption that firms are attempting to minimise their cost of production or maximise their profits and that households are attempting to maximise their utility. The energy system is no longer specifically modelled in the HERMES model. Energy is taken as an exogenously determined cost to firms and households through the international oil price taken from NIESR's NiGEM model. Carbon taxation is incorporated in the government's financial accounts as a revenue source paid by firms and households. It is through oil and carbon pricing, both of which are exogenously determined within HERMES, that energy system costs feedback into the economy.

The initial Irish-TIMES-MSA results outline energy system pathways for a reference scenario (REF), a carbon constrained scenario with CO₂ reductions of 80 % relative to 1990 levels (CO₂-80), and an equivalent scenario with the macroeconomic impacts integrated into the analysis. The MSA scenarios cause a 10 % reduction in final energy consumption by 2040 due to reduced demand as a result of increased energy system cost and a reduction of consumption in the economy. Interestingly this alters the fuel mix most notably in the transport and residential heating sectors as carbon constraints become less binding and so fuel switching is delayed. The loss of GDP in the CO₂-80 scenario rises to -1.5 %/year by 2050, with the CO₂-95 scenario at -2.5 %.

4 Portugal—HYBTEP

The lack of “full link”, “full form” models integration in other modelling studies has been overcome by the development of an integrated methodology to soft-link the extensively applied BU TIMES model (Loulou and Labriet 2008), with the CGE GEM-E3 model (Capros et al. 1997, 2014), used by several Directorates General of the European Commission. The hybrid platform, named HYBTEP (Hybrid Technological Economic Platform), applied to the Portuguese case, is defined by the soft-link between single country versions of the two models: TIMES_PT and GEM-E3_PT (Fortes et al. 2013). HYBTEP overcomes the main limitation of CGE models—failure in represent technology choices—considering the energy profile and prices from TIMES, and minimizes the drawback of BU

modelling—failure to represent adequately the link between energy and economy—as the changes in the sectors economic behaviour are set by GEM-E3 according to the BU technological choices.

4.1 Methods

HYBTEP was built by the following tasks, taking an approach close to Labriet et al. (2010).

- (i) Defining coherence between the two models. Correspondence and harmonization between the models sets and variables were set up, namely the economic sectors and energy commodities. Additional energy carriers were also added to GEM-E3_PT, namely biomass. This process resulted in thirteen economic sectors in HYBTEP from the aggregation of eighteen sectors from GEM-E3_PT and more than sixty demand categories of TIMES_PT. Moreover, a crucial step to achieve consistency among the models is the definition of common scenario assumptions, namely fossil fuel import prices, interest rates, energy constraints and policy conditions.
- (ii) A new energy module in GEM-E3_PT was programmed allowing the model to receive exogenously the energy consumption by energy carrier and sector. This was done by assuming fixed shares of total energy demand per sector with a Leontief technology (i.e. elasticities of substitution of the Constant Elasticities Substitution (CES) production function equal to zero) (Fig. 1). These changes further implied alterations to the definition of the price of the energy aggregate, which are also set exogenously according to the BU model energy system costs evolution per energy aggregate (ELFU).
- (iii) The interaction algorithm (Fig. 1) and the conditions for convergence between the models require careful planning and definition. TIMES_PT physical energy consumption and system costs evolution per sector are ‘translated’ in GEM-E3_PT monetary units through an energy link module and inputted in the CGE model as energy demand and energy prices. In addition, GEM-E3_PT technological change, as measured as increased efficiency in the energy system was defined by the output of the BU model. When a market policy instrument is being considered in TIMES_PT, e.g. an energy tax or a feed-in tariff, the respective economic value is also included in GEM-E3_PT, associated with the respective payer and payee sectors. GEM-E3_PT then compute economic drivers, such as sector domestic production, which are converted in energy services demand through a demand generator. Energy services are inputted into TIMES_PT and the model sets the least cost technological profile of the energy system. This cycle establishes a single iteration of the linked models. It continues until convergence is achieved between the models results, which are reached by assuming a stopping threshold, reflecting minimal energy service demand differences from iteration n and the previous $(n - 1)$ (Fig. 2).

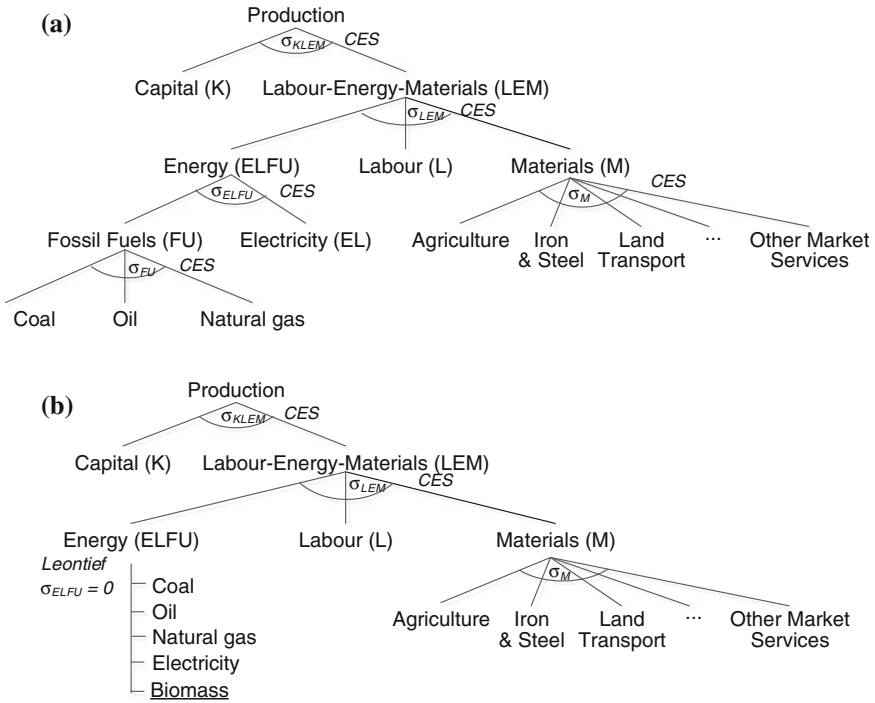


Fig. 1 GEM-E3_PT computable general equilibrium nested tree structure (*upper—*a) Original GEM-E3_PT structure (*lower—*b) adapted Leontief structure in HYBTEP

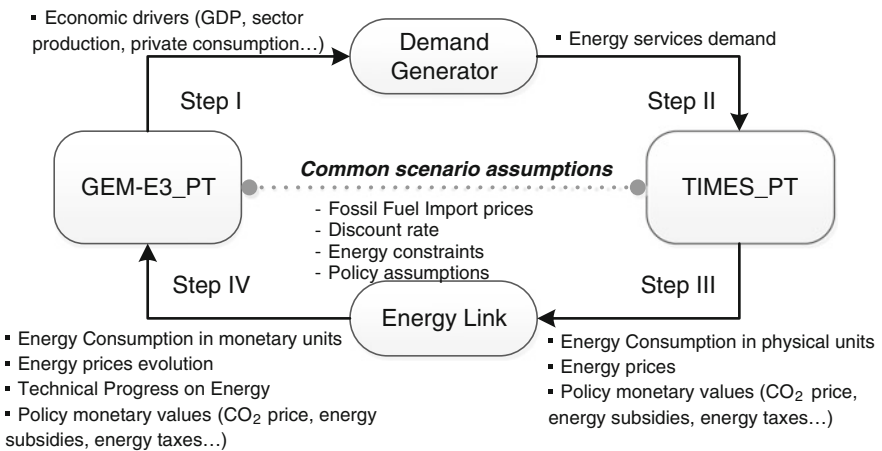


Fig. 2 HYBTEP soft-linking methodology (Fortes et al. 2014)

The additional advantages of HYBTEP in assessing the impact of climate and energy policies when compared with conventional BU model, were analysed under the following scenarios modelled to 2050:

- Current Policy Regulation (CPR) extends beyond 2020, the current Portuguese energy-climate policy within the EU climate-energy package, including a reduction in GHG emissions, and an increase in renewable energy.
- CO₂ price scenario (TAX) comprises in addition to CPR assumptions, a domestic carbon tax on GHG energy emissions from 25 €/t in 2020 up to 370 €/t in 2050.
- RES support scenario (RES) involves, in addition to CPR assumptions, a monetary incentive to renewable energy, from 50 €/MWh in 2020 to 191 €/MWh in 2050.

For all the scenarios it was assumed in GEM-E_PT a fixed government's deficit/surplus and additional revenues are recycled to economy to reduce endogenously social security tax. In addition to HYBTEP platform runs, the policy scenarios were run by the standard TIMES_PT and by TIMES_ED, assuming an energy service-price elasticity of -0.3 for almost all demand categories, and a sensitivity analysis considering higher (-0.5) and lower (-0.1) values.

4.2 Results

The HYBTEP results show, that under TAX and RES scenarios, the modelling tools present differences regarding energy consumption and GHG emissions. It is not possible to define a linear relationship between HYBTEP results and TIMES elasticities, as these vary across scenarios and in some cases years. Under the TAX scenario, HYBTEP outcomes are close to TIMES_ED(-0.1) values, with differences below 1 %. However, in the RES scenario the hybrid model reveals a lower endogenous elasticity, closer to TIMES_PT results.

In HYBTEP, the carbon tax induces an increase in production costs, but also represents a source of additional revenue to government. In this modelling exercise the income is recycled to the economy leading to a reduction in labour costs, which can partially offset the increase in energy costs in production. This economic framework that result in a GDP loss of -2.4 % in 2050 (versus a non-policy scenario), can justify the fact that HYBTEP is less responsive to energy prices than TIMES_ED(-0.3). In contrast, additional RES funding from the government means less available revenues to reduce social security contributions. The latter makes labour more expensive outweighing the decrease in energy system costs due to energy subsidies. The fact that HYBTEP results are close to the inelastic TIMES_PT, suggest that, the reduction of energy prices are offset by an increase in labour costs, leading to a small impact on demand for energy services. In 2050, RES scenario results in GDP gains of 2.8 %, mostly driven by exports increase. Besides ignoring this comprehensive economic context, and with exception of

the energy sector (e.g. power or refinery), TIMES neglects the linkages between the sector, i.e., the intermediate consumption. Variations in the production price of one sector, also affect domestic demand in other sectors production, which are not considered by the BU model.

Moreover, the sensitivity analysis of TIMES energy services elasticities highlights the impact of this parameter on the energy system profile. The BU model final energy consumption presented differences [TIMES_PT vis-à-vis TIMES_ED (-0.5)] of up to 14 and -12 % in TAX and RES scenarios, respectively. The uncertainty of elasticity parameters, due to the lack of national studies, increases the uncertainty of the model results when comparing with a more transparent approach from HYBTEP.

4.3 Discussion

HYBTEP represents an evolution in the methodological complexity describing a method of soft-linking 'full-form', multi-sector BU and TD CGE models, resulting in an integrated modelling platform. Since the main structures of the models are maintained, HYBTEP can accommodate an extensive group of technologies and contains a sector detailed economic matrix, considering sectors own characteristics and specificities. The major conclusion concerns the increase of transparency and accuracy of modelling outcomes achieved with HYBTEP, since, by assuming the economic framework of each sector, it enables understanding of the mechanisms behind energy demand evolution while taking into account the cost-effective energy profile from a technological model.

5 Sweden—TIMES-Sweden and EMEC

The Swedish study describes development of full-form soft linkages between the models EMEC (Environmental Medium Term Economic Model—a TD CGE model) and TIMES-Sweden (a BU energy system model). A robust and transparent method to translate simulation results between the two models is developed, resulting in intermediate 'translation models' between EMEC and TIMES-Sweden. EMEC provides demand input to TIMES, while TIMES provides feedback on the energy efficiency parameters, the energy mix, and the prices of electricity and heat. These 'translations' can also be used stand-alone to feed into other energy system models. The presented soft-linking process demonstrates the importance of linking an energy system model with a macroeconomic model when studying energy and climate policy. With the same exogenous parameters, the soft-linking between the models results in a new picture of the economy and the energy system in 2035 compared with the corresponding model results in the absence of soft-linking.

EMEC is a static computable general equilibrium model of the Swedish economy developed and maintained by the National Institute of Economic Research (NIER) for analysis of the interaction between the economy and the environment (Östblom and Berg 2006). The EMEC model includes 26 industries and 33 composite commodities including seven energy commodities. There is also a public sector producing a single commodity. Produced goods and services are exported and used together with imports to create composite commodities for domestic use. Composite commodities are used as inputs by industries and for capital formation. In addition, households consume composite commodities and there are 26 consumer commodities. Production requires primary factors (i.e. two kinds of labour and capital) as well as inputs of materials, transports and energy. Households maximise utility subject to an income restriction, firms maximise profit subject to resource restrictions, the provision of public services is subject to a budget constraint and the foreign sector's import and export activities are governed by an exogenously given trade balance. The model differs from many other CGE models by having a detailed description of the energy use, environmental economic instruments as well as emissions.

The main structure of TIMES-Sweden was designed within the NEEDS and RES2020 projects, and has since been further developed (Krook Riekkola et al. 2011). TIMES-Sweden covers the Swedish energy system divided into six main sectors (Electricity and heat, industry, agriculture, commercial, residential and transport), based on the structure of EUROSTAT database. Each sector includes 60 different demand segments that drive the model. The structure and many of the assumptions are similar to the JRC-EU-TIMES model, documented in Simoes et al. (2013).

Even though the two models have different scientific bases, they both assume cost-minimising behaviour by producers and household demands based on optimising behaviour.

5.1 Methods

The recognition that difference sets of connection points are needed depending on which direction the information is being transferred during the iteration process resulted in two different approaches in mapping of the connection points—one when transferring information from EMEC to TIMES-Sweden and another when transferring information in the opposite direction.

Energy system models are not well suited to address changes in demand due to economic growth. Thus the EMEC model will be the provider of demand drivers from which the demand for goods and services to TIMES-Sweden is estimated. This approach will not differ from running TIMES-Sweden stand-alone, when the demand drivers always are based on results from CGE models like EMEC, the difference will be that they are re-estimated for each iteration-run. All demand segments cannot be treated in the same way and there are cases where no

relationship exists between change in demand of a certain commodity and economic growth. Different approaches for translating the output from EMEC into usable input into TIMES-Sweden include; a direct approach based on economic development in a corresponding sector, an indirect approach based on an alternative activity economic development in one or several corresponding sectors, or an assumption of no connections.

Due to their broader focus, CGE models such as EMEC, are unable to explicitly address aspects of the energy system related to (i) changes in energy intensity due to introduction of new technologies, (ii) changes in the energy mix following changes in energy demand and, (iii) changes in electricity and heating prices due to competition of limited energy commodities between and within sectors. These aspects are the focus of the energy system output. To facilitate the transformation of results between TIMES and EMEC, the production function in the soft linked version of EMEC has been changed so that the elasticity between the different energy products in each sector is set to zero, i.e. the energy branch is assumed to be represented by a so-called Leontief structure with fixed input coefficients (Fig. 3).

5.2 Results

In EMEC, the reference scenario describes a possible outcome for the Swedish economy and energy demand in the long run. The reference scenario is based on the official macroeconomic forecast of NIER with the exception of energy efficiency

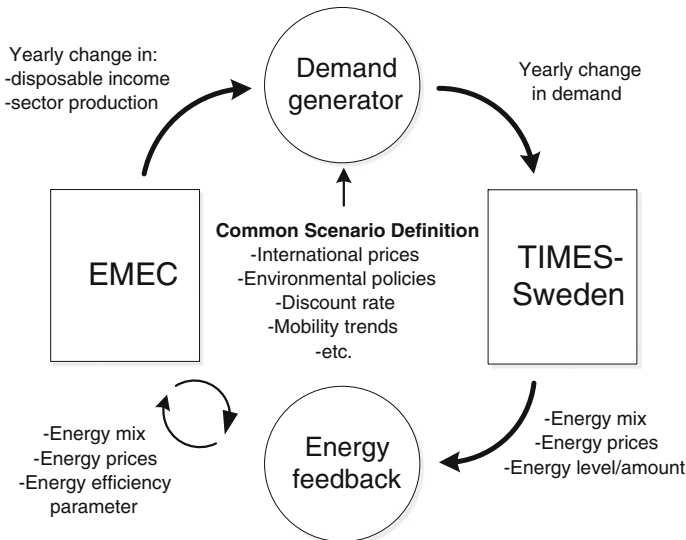


Fig. 3 Soft-linking between EMEC and TIMES-Sweden

parameters, which are determined by soft-linking the two models. In the climate scenario, the CO₂ tax is assumed to increase by 50 % and the CO₂ prices within the EU-ETS is increased from 16 to 30 €/tonne in 2020 and stays at this level to the end of the modelling period in 2035.

The iteration process (Fig. 4) starts with EMEC, whereby its macroeconomic outputs are fed into the translation model, providing a set of energy service demands for TIMES-Sweden. The models adapt to each other primarily in the first reference iteration R-2, and there-after only minor changes are made, while the models are considered converged within tolerance.

The lower demand in energy-intensive industries, after the reference iteration process, can be explained by a higher electricity price from TIMES-Sweden when compared to EMEC in isolation. TIMES-Sweden assumes fewer technology options in energy intensive industries to reduce their demand compared with EMEC, which assumes changes in energy demand based on substitution elasticities. Higher electricity prices and lower substitution possibilities imply increased production costs and a decreased demand for energy-intensive goods as their relative price increases. Soft-linking reinforces the trend towards higher increased demand for transport and services.

The climate scenario is analysed based on three different starting points: a non-linked reference scenario (Climate NL-ref), a non-linked climate scenario (Climate NL-Climate) and a soft-linked scenario (C-x Iteration). In the latter case, when the

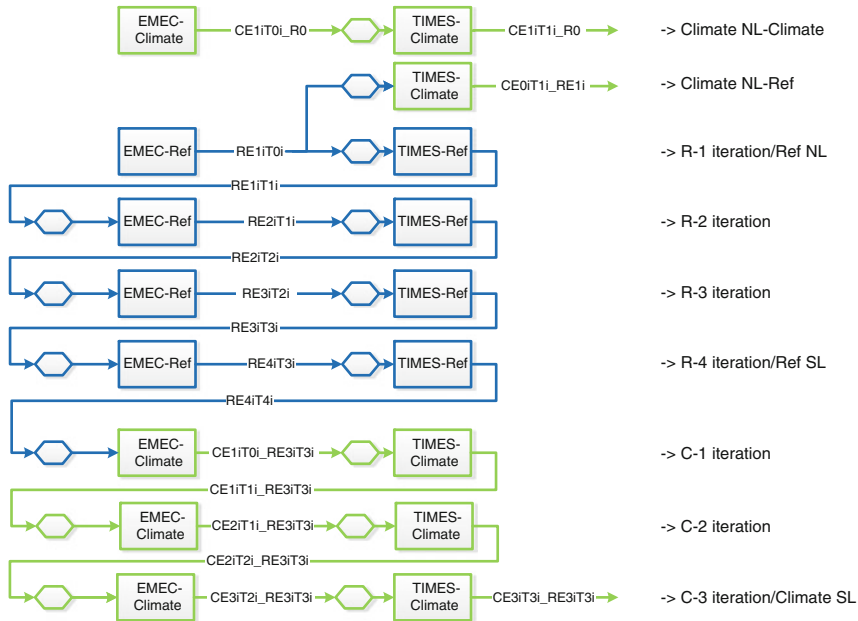


Fig. 4 The iteration scheme between EMEC and TIMES-Sweden

soft linked reference scenario is the starting point of the climate scenario iterations, the number of iterations does not affect the production level from EMEC to any greater extent. Hence, the differences between C-1 and C-3 are small compared with the differences between R-1 and R-2. The results of the EMEC model have already adjusted to mimic TIMES-Sweden's behaviour in the reference scenario. One reason is that the Swedish power system is almost carbon free, which in combination with the green electricity certificate scheme only gives marginal changes in the electricity price when the EU-ETS price is increased.

In order to test of the changes in the results from introducing the soft-linking process had a policy impact the resulting CO₂ trajectories from TIMES-Sweden were scrutinized. The results show the CO₂ emissions are significantly reduced with soft-linking. This is mainly a result of lower demand for energy services.

5.3 Discussion

Both EMEC and TIMES are based on national statistics which has permitted the build-up of detailed models. However the two models are based on two different statistical databases (national accounts versus energy statistics). The national account are structured to capture the main economic activities and thereby facilitate an robust analysis of the economy, while the energy statistics are structured in order capture the energy flows and thereby facilitate a robust energy analysis. When identifying connections points, several overlaps and mismatch were identified. Thus, instead of using common measuring points, we identify direction-specific 'connection points' to describe the interaction of model results from one model to the assumptions used in the other model.

The biggest challenge and uncertainty in soft-linking iteration is the price information from TIMES-Sweden to EMEC. The prices change between the base year in 2008 and the horizon end year 2035 were found to be exaggerated. The main explanation for this is that the calculated prices in the first modelling years do not include all costs. The optimization solves for the lowers total cost, but when the base years are fixed there is no need to include those cost figures when TIMES-Sweden is use stand-alone and comparing the results from different scenarios in a specific year. In contrast, the soft-linking process compares the price difference between two years with one scenario. This particular issue need to be solved in future studies.

Changes in investment flows, due to large structural changes in the energy system were aspects that could not be captured in a satisfactory way in this soft-linking methodology. The presence of a major restructuring of the economy, for example caused by the radical reduction of fossil fuel use, investment flows would most likely change substantially and affect the overall investment requirements and in turn give rise to significant general (dis)equilibrium effects.

6 South-African Electricity Sector—SATIM-el and SAGE

South Africa has a carbon-intensive economy. The energy sector is responsible for most of the country's emissions, with 78.9 % of total emissions from energy. These emissions have resulted from the extensive use of coal in the generation of electricity, the conversion of coal into liquid fuels, and coal for thermal uses in industry.

The Long Term Mitigation Scenarios (LTMS) study found carbon taxes to have the biggest emissions reduction potential compared to various other mitigation options (Winkler 2007). In a developing country like South Africa, it is important that policies and measures aimed at achieving the country's emissions reduction targets are not applied to the detriment of other national development objectives. The hybrid model linking the South African TIMES model (SATIM) to the extended South African General equilibrium model of the economy (e-SAGE) addresses this issue.

SATIM is an inter-temporal bottom-up optimisation energy model of South Africa built around the MARKAL-TIMES platform. SATIM uses linear or mixed integer programming to solve the least-cost planning problem of meeting projected future energy demand, given assumptions about the retirement schedule of existing infrastructure, future fuel costs, future technology costs, and constraints such as the availability of resources.

The e-SAGE model simulates the functioning of the economy and uses South Africa's 2007 Social Accounting Matrix (SAM) as data input, accounting for industries and commodities in South Africa, as well as factor markets, enterprises, households and the 'rest of the world'. The 2007 SAM has 61 industries and 49 commodities. It also has 9 factors of production, namely, land, 4 education based labour groups, and capital which is divided into 1 energy and 3 non-energy capital groups.

6.1 Methods

Alternate runs of SATIM and e-SAGE are performed from 2006 to 2040, each time exchanging information about fuel prices, demand, investment (capital growth), electricity production by technology group and electricity price. Given an initial demand, TIMES computes an investment plan, and a resulting electricity price projection, which is passed onto e-SAGE to see the impact, if any, that this new price projection has on the demand, which then go back to TIMES in the next iteration. The problem is that if both the price and capital growth are imposed onto e-SAGE for the entire model horizon, there is little room for demand to react. Demand tracks the investment (capital growth), which defeats one of the main points of using a CGE.

To circumvent this, only the price projection is imposed onto e-SAGE for the entire model horizon, and the production schedule and capital growth is only

gradually imposed. The result of this is that by the end of the planning horizon, we have used a demand projection that is consistent with price, and can react to price changes. Based on this consistency, we can analyse the economic impacts of the investment decisions that were made in the power sector subject to constraints defined in that sector, such as a nuclear programme or a renewables programme, or how the energy and economy would respond to CO₂ mitigation policies.

The following scenarios are run as a demonstration of the linked models for the purpose of evaluating mitigation actions:

1. A set of TIMES runs without the CGE model, but assuming the same demand as the Reference linked model run for all scenarios:
 - (a) A Reference case of the power sector without any mitigations actions (Reference).
 - (b) A CO₂ tax runs starting at \$5 (R48)/ton CO₂ in 2016, increasing to \$12 (R120)/ton CO₂ in 2025, approximating Treasury's proposed carbon tax.
 - (c) Two renewable energy scenarios:
 - 20 % share of centralised generation by 2030 and 30 % in 2040 (RE Prog 1); and
 - 30 % share of centralised generation by 2030 and 40 % in 2040¹ (RE Prog 2).
2. The same set of runs as above but this time with the linked CGE and TIMES models.

6.2 Results

Total capacity of the TIMES reference case reaches 103 GW in 2040, still dominated by coal with 55 GW (54 %). Coal also dominates production, maintaining the current share of around 81 % through to 2040. Gas (open cycle gas turbines and combined cycle gas turbines) capacity reaches 23 GW (23 %) for peaking and mid-merit loads. The remainder is made up of solar PV (13 %), hydro and pump storage (4 %) and nuclear and imports (6 %).

The currently proposed CO₂ tax level has a small impact on the system in this scenario. Total capacity is slightly higher at 106 GW in 2040, due to increased share of gas and solar PV that run at a lower capacity factor than coal. The coal share of capacity drops to 51 % and production to 79 %, whereas gas remains at around 23 % of total capacity. The coal production is mainly replaced by solar PV, increasing its share of production from 6 to 7 %.

¹ RE includes: centralised solar PV, solar thermal, wind, domestic and imported hydro, and biomass.

To reach a share of production of 30 % in 2040 in program 1 and 40 % in program 2, the RE share of capacity reaches 43 and 50 % by 2040. The high share of low-capacity technologies means that total capacity goes up to 120 and 126 GW, respectively. The RE program pushes the coal share of capacity further down to 30 and 19 % for the two programs, respectively. The gas share of capacity reaches 18 and 23 %.

The CO₂ emissions from the power sector of the reference scenario grow to almost double the 2010 levels reaching 430 Mton/annum in 2040. In the CO₂ tax scenario, the annual CO₂ drops by only 3 % relative to reference case. However, when using the more optimistic RE costs, a 20 % reduction is observed. When the penetration of low emission technologies is imposed directly with the RE programs, the CO₂ emissions drop more radically by 33 and 50 %, respectively by 2040.

Comparing the TIMES runs and the CGE-linked runs for the reference case and the CO₂ tax case, the reference cases are identical, given that they have the same demand, and fuel prices. In the CO₂ tax scenario though, there is a drop of the peak demand in the CGE-linked run, showing some demand response from the CGE to the higher electricity price.

All the policy scenarios result in slight GDP loss in 2040 relative to the reference case. In all the policy scenarios, the mining and metals sectors are the most negatively affected, mainly because of the electricity price increase, and the switch away from coal for some of the electricity production. The electricity sector grows quite significantly relative to the base with more investment taking place in this sector, however, not enough to avoid a net negative impact on GDP.

6.3 Discussion

The results so far indicate that the linked SATIM e-SAGE model is able to contribute to the goal of analysing the trade-off between mitigation and development objectives for South Africa. However, to gain further confidence in the results, more work is still needed in aligning both models, by ensuring consistency between other energy consuming sectors, not only in terms of their energy consumption, but also in terms of how the capital and labour costs computed in e-SAGE affect energy sector decisions in SATIM.

7 Danish—IntERACT

As a part of the Energy Agreement from 2012 all parties in the Danish Parliament except one agreed on an ambitious plan for phasing out fossil fuels for energy in Denmark. In 2035 the power and heating sector has to be without fossil fuels and all of the Danish energy system has to be independent of fossil fuels by 2050. As a part of the agreement and to support future planning, a new energy policy analysis model has to be developed.

The model outlined here is decided to be a combination of a CGE model for the Danish economy (CGE-IntERACT) linked with a TIMES model of the Danish energy system (IntERACT-TIMES-DK). The CGE and the TIMES model are being developed simultaneously to secure optimal structural fit and data harmonisation in the linking between the models. A soft-linking approach is chosen and energy demand in form of services are sent from the CGE to TIMES and fuel mix, energy use, energy cost and energy service prices are returned to the CGE.

The IntERACT project is developing a novel CGE approach modelling the energy service demand within its economic CGE model, rather than the typical approach of modelling specific energy goods such as oil, gas, coal or electricity. As has already been indicated in Sect. 5.3 the traditional approach is not well suited when analysing large scale technological changes such as in the case of a complete green transition and phase out of fossil fuels. The demands for comfortable room temperature, lighting, transport services and process energy are the basic needs of the economy, and it is the impact of the relative costs of these services that have significant influence on the economic behaviour.

The premise in the IntERACT model is that agents make economic decisions based on the relative prices of energy services, while the specific fuel use and the specific technology applied in order to obtain the energy service is secondary; i.e. economic utility or revenue is not derived from the amount of energy (PJ) of fuel consumed, but rather from the energy services the fuel actually delivers. This leads on from the concept of exergy and useful work as a productive element in the economy, as opposed to gross energy consumption. Agents maximise profit and utility using the costs of the energy service, using relative prices as usual. By using energy services in this method, the economic TD model creates an abstraction of energy and in a sense reduces the role of exact technologies. Indeed the TD model does not make any technological decisions to obtain a given amount of energy services. From the consumers perspective it does not matter how the room is heated (with an explicit technology choice), but rather how much the costs relative to inputs in the production or goods in the utility bundle vary.

8 Norway—Regional Effects of Energy Policy (RegPol)

The goal of the RegPol² project is to develop a hybrid energy-economy framework for Norway with special attention to the regional level, combining the technology rich bottom-up TIMES model with a top-down multi-sector economic computable general equilibrium (CGE) model. CGE-models focus on the interaction between different supply and demand sectors, and are developed to study effects of different policy proposals that apply different instruments within and across the sectors of an

² The RegPol project is financed by the Norwegian Research Council. Collaborative research partners are SINTEF Technology and society, NTNU and IFE.

economy. CGE-models usually do not include much technical detail, and have little information on the underlying infrastructure.

The majority of research has addressed the national and international level. The RegPol project focuses on the need to better understand how energy policies affect local decisions and how local advantages can be used actively in regional policy addressing implications for the energy sector. Both models will have a subnational geographical level with multiple regions. The TIMES model will have a geographical representation of the energy system, while the CGE model will describe the regional multi-sector economies plus trade and transport between regions. These models are called spatial CGE models (SCGE) and include modelling elements from new economic geography.

A regional model framework is needed to assess the effect of technology drivers on the deployment of technologies, localisation of new large scale production and changes in end use. Parameters, such as energy demand, population density, local electricity production, untapped resources, available energy infrastructure and geographical conditions influence the future regional development.

The model structures will be general, but a relevant geographical division for analysing energy policies consists of the Norwegian electricity price areas. Some areas have significant power surpluses while others have significant power deficits. Together with transmission constraints, this is relevant for location of both new production and new consumption. Some relevant analysis cases are:

- In Norway there is a political objective to build a substantial amount of renewable energy supported by green electricity certificates. Norway has excellent wind resources, and the RegPol project will analyse which project locations are advantageous, and how projects will affect regional development.
- The electrification of offshore oil and gas fields in order to avoid greenhouse gas emissions would constitute major electricity consumers. Such projects have created strained power situations, and should be analysed within a regional hybrid modelling framework such as RegPol.
- There has been increased focus on Norway's potential to store water in reservoirs. Norwegian hydropower could play a balancing role as a green battery within a European power system with a high share of power production from intermittent sources as wind and sun. This will require new production capacity and new interconnections to be built, both internally to access export links, and to the export markets.
- Development of the grid infrastructure is in itself an important question to analyse. Low transmission capacities may induce different price-levels between price areas, with corresponding consequences for regional industries and other demand.

The hybrid framework with TIMES and the SCGE model will be designed for efficient successive exchanges of adjusted solutions. Different designs for linking the models are investigated, both soft-linking, hard-linking and full integration. The higher data granularity, the more important it becomes to handle data exchange with

automatic routines. RegPol starts with a soft-linking approach, but seeks to automate the linking and embed it in the hybrid framework.

Since production and consumption takes place in different locations, the spatial characteristics are important in order to find optimal solutions and effective policies. Various policies (like energy taxes and subsidies) also have regional rates and different regional impacts. The combination of technological and economical models with regional resolution is well suited to improve current analyses and provide the best guidance for future sustainable solutions.

9 Critical Messages from Applied Hybrid Methods

There are many useful points to note in this state of the art review of IEA-ETSAP hybrid energy-economy modelling. A final synthesis of the critical messages from all of the model applications and discussions are summarised below.

A restructured low carbon world economy is imperative to mitigate climate change. Modelling results repeatedly show global CO₂ emissions are significantly lower in hybrid model decarbonisation scenarios as a result of demand adjustments. The range of the differences between isolated energy system CO₂ emissions and their comparable hybrid model is between -5 and -13 % by 2050 depending on the carbon intensity of the region in question's economy.

Economic impacts vary regionally again dependent upon the energy intensity of a nation's economy, the trade partnerships, competitiveness and level of development. Loss of GDP can be as high as 5 %/year by 2050 in developing countries, while up to 3 %/year by 2050 in developed countries depending on the implemented mitigation mechanisms and revenue recycling schemes. Short term economic gains are to be made in energy efficiency measures.

Both energy system models and CGE models play an important role in the existing energy and climate policy analyses. Even when running the two kinds of models in isolation, the models use assumptions which are based on results from the other model (directly and indirectly). Thus, by soft-linking energy system models and CGE models the energy and climate policy analysis becomes more transparent.

Hybrid Models have already played a critical role in carbon mitigation policy and should continue to play a key role in policy advice in upcoming COP talks. Hybrid energy-economy modelling has an increasingly key role to play in accurately modelling the economic impact of climate mitigation, while addressing the most cost-effective technological solutions.

Furthermore, hybrid linking displays non-linear, sectoral non-uniform demand responses that cannot be captured with demand price elasticities, increasing the understanding and transparency of the model results. Model methodological and documentation transparency is a critical moving beyond publishing and presenting papers. Replicability is near impossible and makes difficult the traditional scientific process. A move to more open models is required for more rigorous validation of models and model results.

A challenge and source of uncertainty in soft-linking hybrid models is the price information from bottom up optimisation models to top down models. The price change between the base year and the end of horizon year are found to be exaggerated. The main explanation for this is that the calculated prices in the first modelling years do not include all costs. The optimization solves for the lowest total cost, but when the base years are fixed there is no need to include those cost figures. In contrast, the soft-linking process compares the price difference between two years with one scenario. This particular issue needs to be solved in future studies.

Changes in investment flows, due to large structural changes in the energy system are difficult to satisfactorily capture in typical soft-linking methodologies. A major restructuring of the economy as a result of a radical reduction of fossil fuel use would most likely change investment flows substantially and affect the overall investment requirements. In turn this would give rise to significant general (dis)equilibrium effects resulting in model uncertainty.

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