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The ETM in E3ME43

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1.1 Introduction

Background to the ETM

The Energy Technology Model (ETM) is a dynamic bottom-up technology simulation treatment which represents the take-up of a number of energy supply options, both conventional and low-carbon. The model was originally developed to generalise earlier work by Anderson and Winne (2004)[1] to form the basis of a new energy technology component in the global model E3MG[2]. The submodel has now been incorporated into E3ME[3]. At present it covers all technologies used in electricity supply, although it will be developed to cover other energy carriers in due course.

E3ME thus includes the capacity to model endogenously an array of low-carbon energy options for electricity supply that could potentially emerge in the future, even though their costs are currently high relative to those of fossil fuels. The operational feature of the model is that unit costs for many new technologies are largely declining, due to innovation, R&D investment, and learning-by-doing. The lower costs will induce higher investment in non-carbon energy options if carbon prices rise. The process of substitution is also highly non-linear, involving threshold effects. The costs and the availability of natural resources, such as wind and tidal energy, vary between regions, so that the different European countries can be expected to specialise in different portfolios of low-carbon energy supply.

1.2 The mechanics of the ETM

The Choice of Technologies

The ETM models the process of substitution, allowing for non-carbon energy sources to meet a larger part of European energy demand as the prices of these sources decrease with investment, learning-by-doing and innovation. Following the demand for various existing energy carriers (fuels), substitution will take place conditional on the possibility of supply of various energy sources. On the supply side the range of possibilities is very large, and there is considerable scope for substitution between them. Table 1 provides a listing of energy technologies, where possible substitution patterns are identified by a y in the appropriate cells.

For each type of energy demanded there is usually a technology or fuel 'of choice' – what might be termed a marker technology – against which the alternatives will have to compete. In terms of electricity markets, E3ME assumes that the marker technology was dirty coal up to 1995 and CCGT gas thereafter.

In practice, the unit values of alternatives will vary widely relative to the unit costs of the marker technology. In the case of coal for electricity generation, costs differ between stations and to some extent across regions – due to proximity to the coal fields, the sulphur content of the coal, the availability of cooling water, site conditions etc. The costs of the marker technology may also vary greatly; if the marker

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[1] Anderson, D., and Winne, S. (2004) 'Modelling Innovation and Threshold Effects in Climate Change Mitigation', Working Paper No 59, Tyndall Centre for Climate Change Research, www.tyndall.ac.uk/publications/pub_list_2004.shtml.

[2] http://www.camecon.com/suite_economic_models/e3mg.htm. See also Barker et al (2006) and Köhler et al (2006).

[3] The online model manual is at http://www.camecon-e3memanual.com/cgi-bin/EPW_CGI

technology is a gas-fired plant, its costs, like those of coal, will differ between sites and regions and, of course, with the price of gas.

Table 1: Options for meeting energy demands

Energy Technologies	**Solid fuels**	**Oil fuels**	**Gas**	**H_2**	**Elect-ricity**	**Biomass Tradit-ional**
Carbon fuels:						
1: Coal – clean	y	y	y	y	y	y
2. Coal – dirty	y		y		y	y
3. Oil fuels – clean		y			y	y
4. Oil fuels – dirty		y			y	y
5. Gas – central	y		y	y	y	y
6. Gas – micro CHP	y		y	y	y	
7. Gas – f.c. vehicle		y				
Carbon neutral:						
8. Nuclear electricity				y	y	
9 Hydro electricity					y	
10. Biomass crops	y	y		y	y	y
11. Biomass wastes: CHP	y		y	y	y	y
12. Wind – intermittent				y	y	
13. Wind – with storage					y	
14. Solar PV – intermittent				y	y	
15. Solar PV – with storage					y	
16. Solar thrml – intermittent				y	y	
17. Solar thrml – w/gas					y	
18. Solar thrml – w/storage					y	
19. Marine – intermittent				y	y	
20. Marine – with storage					y	
21. Geothermal					y	
22. Coal with carbon sequestration						
23. Gas with carbon sequestration						
24. Hydrogen – central	y		y	y	y	
25. Hydrogen – micro CHP	y		y	y	y	
26. Hydrogen – f.c. vehicles		y				

Frequency Distribution

In the ETM, the frequency distribution of feasible technologies could be represented by the ratio between the cost of all alternatives and the marker technology. Let P_{it} denote the price of he marker relative to that of the alternative *i* (Anderson and Winne, 2004, equation 1):

$$P_{it} = \frac{C_t^N (1+T_t)}{C_{it}(1+G_t)} \qquad (1)$$

where C_t^N and C_{it} denote the present worth of the costs of using the technologies per unit of output, the superscript *N* in the former referring to the fuel of choice. T_t represents taxes (for instance carbon taxes) on the former and G_t taxes on the latter (either may be negative if the energy source is subsidised).

When the ratio C_t^N / C_{it} is greater than unity, the alternative technology costs less than the marker technology. The ratio may also show a wide frequency distribution, and it is likely that the mean value will fall below unity. This does not mean, however, that all alternative applications in all locations will be uneconomical.

Let C_t^N and C_{it} now denote the mean values of the costs of the marker and substitute technologies and P_{it} the mean value of the price ratio. An increase in the price ratio can be brought about in two ways. One is to increase taxes on the marker technology but not on the substitute (say through a carbon tax). The second is through an innovation which reduces the costs of the substitute relative to the marker. In both cases, the effect is to shift the distribution of costs, leading to a larger number of applications of the substitute technology through increased investments.

Investment in Technologies

There are some crucial features of electricity investment that relate to the electricity network:

- the problem of intermittency for some renewables, eg wind, means that there must be backup supplies to avoid occasional shortfalls
- optimal load factors vary across technologies, so that the mix of technologies in use will affect the overall generation available at any time at normal levels of prices
- new large-scale suppliers require new connections to the grid

These network characteristics have implications for efficiency and security of supply. The regulators of the grid have obligations for forward planning to match expected demand with planned capacity.

The implication is that electricity investment is not adequately modelled as that of a representative firm maximising profits in a fully competitive market under constant returns to scale. In the electricity industry, the firms are typically large and diverse; investment projects are diverse; and system changes can be significant in relation to the whole economy.

The ETM in E3ME takes the network features into account by representing the investment decision as one taken institutionally by a social planner following rules promoting efficiency under social, economic and political restrictions. Some investment projects, eg nuclear stations, have to be sanctioned explicitly by the government. In E3ME, therefore, the investment of nuclear stations will be restricted for some regions in accordance with nuclear policies. Desired capacity will determine the size of the investment, and will depend on load factors, desired generation (modelled through a stochastic electricity demand function for each fuel user group in E3ME) and the ratio between maximum generation (for peak loads) and average generation. Since there is a considerable lag between the decision to invest and the investment coming on stream (a lag of up to 10 years is allowed in E3ME), desired capacity and therefore desired generation has to be projected.

The key factor driving the investment decision is cost minimisation over the first 11 years of the project. It is assumed that decisions are decentralised, such that investors view their objective as minimising the costs of supplying a required amount of electricity. No assumptions are made about the overall objective of the firms involved. Economic instruments are included to provide incentives for different technologies. Functional forms and parameters are largely imposed, with testing and adjustment so that the historical data are explained by the model. The classifications adopted are as follows: there are 28 generic technologies; each technology has 21 characteristics; and the cost-benefit calculations are done by 9 categories.

There are four sets of data in the cost-benefit NPV classification for new electricity investment:

1. capital costs
2. non-fuel current costs
3. fuel costs
4. any GHG reduction benefits from the new electricity investment, valued at the emission allowance prices expected in the future

The overall net costs are calculated in €/MWe. The capital and non-fuel current costs vary across the different electricity investment technologies and are calibrated to EU conditions, starting with the information provided by Anderson and Winne (2004). The projected fuel costs in the NPV calculation are derived from the E3ME projections and depend on which of the 12 energy carriers distinguished are used by the technologies.

Specific technological progress has been included in the E3ME ETM by a bottom-up representation of technologies using energy in the electricity industry, with learning curves and responses to real energy prices. As the real cost of carbon rises in the system, learning-by-doing reduces the unit costs of the technologies to respond to increases in the costs of carbon through costs of permits and taxes, the outcome is a wave of extra investment in the electricity industry.

Investment shares between the technologies in electricity generation technologies are based on the following equation (Anderson and Winne, 2004, equation 6):

$$S_{it} = S_{it-1} + a_i\, S_{it-1}\left(\hat{S}_{it-1}(1 + S_{it-1} - \sum\nolimits_i S_{it-1}) - S_{it-1}\right)\left(P_{it} - P_{it-1}\right) \qquad (2)$$

where S is market shares in new investment in technology i, $\hat{S}_{it}$ is a maximum share attainable by any given technology and P is the price ratio of technology i to a marker technology or numeraire (typically CCGT). The equation is a modified logistic, with the responses dependent on the differences over time of the technology's price relative to the marker technology. If the price falls, the technology will be adopted at increasingly faster rates; eventually the rates diminish as saturation is approached.

Solving the model

The solution is iterative until a consistent converged set of results is achieved. Procedural rules are introduced for the system to respond to over- or under-utilisation of capacity and for fossil fuel capacity to be scrapped. The solution is tested on historical data to establish its properties and ensure that it simulates the main features in the data.

1.3 Parameters in the ETM

The investment decisions as well as the calculation of lifetime costs rest on a number of parameters. A list of the parameters used is outlined in Table 2. Tables 3a to 3d outline the parameter values for the various electricity generating technologies, both carbon emitting options and carbon neutral ones, initially used in E3ME. These values are derived from Table 13.8 in Anderson and Winne, 2004, where a full explanation of parameter values is included. They have subsequently been adjusted for E3ME.

Regional Disaggregation

Ideally, the parameters would differ between regions, reflecting differences in behavioural patterns that can sometimes be significant in size. This is especially true for renewable energy since resources (wind, tidal, solar and biomass) as the costs of exploiting them is dependent on local conditions and therefore varies between countries. However, with the available data, at this stage parameters will be assumed to be equal across regions. This assumption will be relaxed with the forthcoming availability of technology disaggregated MARKAL data provided by the PSI[4].

Table 2: Parameters required for the ETM

Characteristic	Units
1. Unit capital costs	US$/kW
2. Unit coal input	Mtoe or GJ/GWh
3. Unit gas input	Mtoe or GJ/GWh
4. Unit oil input	Mtoe or GJ/GWh
5. Unit CO2 emissions	kg/kWh or GJ
6. Unit SO2 emissions	kg/kWh or GJ
7. Unit NOx emissions	kg/kWh or GJ
8. Unit PM10 emissions	kg/kWh or GJ
9. Load factor	ratio
10. Lifetime	years
11. Installation lag	years
12. Development lag	years
13. Learning rate	% of per unit rate
14. Substitution parameter	
15. Minimum cost	US$/GJ
16. Technical limits	% of total supply
17. Infrastructure costs	US$/GJ
18. Other unit costs (eg O&M)	US$/GJ

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[4] Policy Studies Institute, London. See www.psi.org.uk

Table 3a: Parameters for Vector of Substitutes for Electricity: Fossil Fuel, Nuclear and Hydro Alternatives

Parameter or Quantity	Gas: Central	Gas: Micro-CHP	'Clean' coal	'Dirty' coal	Nuclear	Hydro
Initial Costs:						
• variable UScents/kWhe	2.2	2.0	1.8	1.8	1.1	0.0
• Fixed US$/kW	450	2200	1200	1000	2200	1500
• Average USCents/kWhe	3.0	4.0	3.6	3.3	4.4	3.5
Efficiency, kWhe/kWh of fuel %	55	50	40	40	-	-
Load factor %	80	50	80	80	80	50
Waste heat utilised, % of fuel input	-	25	-	-	-	-
Unit CO_2 emissions g/kWh	350	350	870	870	0.0	0.0
Unit NO_x emissions g/kWh	0.09	0.09	0.9	9.0	0.0	0.0
Unit SO_2 emissions g/kWh	0.0	0.0	0.5	10.0	0.0	0.0
Unit PM_{10} emissions g/kWh	0.0	0.0	0.16	16.0	0.0	0.0
Lifetime of plant, yrs	25	25	30	30	30	40
Leadtime for investment, yrs	4	1	5	5	7	6
Development lag, yrs	1	10	1	1	3	1
Substitution parameters						
• stndrd dvn: % mean	numeraire	0.3	0.2	0.2	0.2	0.4
• the parameter *a*	-	6.0	10.0	10.0	10.0	4.0
Learning rate	0.25	0.35	0.2	0.2	0.1	0.1
Minimum costs US$/kWhe	3.0	2.5	3.0	2.7	3.5	3.5
Technical limits, % total market	None	None	None	None	75	10
Initial market shares, %	18	-	24	20	17	17

Source: Anderson and Winne (2004) with adjustments.

Table 3b: Parameters for Vector of Substitutes for Electricity: Biomass, Wind and Solar PV

Parameter or Quantity	Biomass crops	Biomass wastes: CHP	Wind: intermittent	Wind: with storage	PV: intermittent	PV: with storage
Initial Costs:						
• variable UScents/kWhe	1.7	0.0	0.0	0.0	0.0	0.0
• Fixed US$/kW	1800	1800	1200	3400	4000	11000
• Average USCents/kWhe	4.5	2.6	6.0	6.8	30.0	33.0
Efficiency, kWhe/kWh of fuel %	40	30	-	-	-	-
Load factor %	80	80	35	70	22	45
Waste heat utilised, % of fuel input	-	45	-	-	-	-
Unit CO_2 emissions g/kWh	0.0	0.0	0.0	0.0	0.0	0.0
Unit NO_x emissions g/kWh	0.9	0.9	0.0	0.0	0.0	0.0
Unit SO_2 emissions g/kWh	0.5	0.5	0.0	0.0	0.0	0.0
Unit PM_{10} emissions g/kWh	0.16	0.16	0.0	0.0	0.0	0.0
Lifetime of plant, yrs	25	25	25	25	30	30
Leadtime for investment, yrs	4	4	2	3	1	1
Development lag, yrs	1	1	1	10	1	10
Substitution parameters						
• stndrd dvn: % mean	0.3	0.3	0.3	0.3	0.5	0.5
• the parameter *a*	6.0	6.0	6.0	6.0	3.0	3.0
Learning rate	0.2	0.2	0.25	0.25	0.3	0.3
Minimum costs US$/kWhe	3.5	1.8	2.5	3.0	4.0	4.5
Technical limits, % total market	10	10	20	None	20	None
Initial market shares, %	1	1	1	-	-	-

Source: Anderson and Winne (2004) with adjustments.

Table 3c: Parameters for Vector of Substitutes for Electricity: Solar thermal, Marine and Geothermal						
Parameter or Quantity	Solar thrml: intermittent	Solar thrml + gas	Solar thrml: with storage	Marine: intermittent	Marine: with storage	Goethermal
Initial Costs:						
• variable UScents/kWhe	0.0	1.7	0.0	0.0	0.0	0.0
• Fixed US$/kW	3000	3250	7000	2500	6000	2000
• Average USCents/kWhe	16.0	5.5	18.5	10.0	12.0	3.5
Efficiency, kWhe/kWh of fuel %	-	30	-	-	-	-
Load factor %	25	80	50	35	70	80
Waste heat utilised, % of fuel input	-	-	-	-	-	-
Unit CO_2 emissions g/kWh	0.0	0.0	0.0	0.0	0.0	0.0
Unit NO_x emissions g/kWh	0.0	0.0	0.0	0.0	0.0	0.0
Unit SO_2 emissions g/kWh	0.0	0.0	0.0	0.0	0.0	0.0
Unit PM_{10} emissions g/kWh	0.0	0.0	0.0	0.0	0.0	0.0
Lifetime of plant, yrs	30	30	30	25	25	30
Leadtime for investment, yrs	3	3	5	3	2	3
Development lag, yrs	3	3	10	10	10	1
Substitution parameters						
• stndrd dvn: % mean	0.3	0.3	0.3	0.3	0.5	0.5
• the parameter *a*	6.0	6.0	6.0	6.0	3.0	3.0
Learning rate	0.3	0.3	0.3	0.3	0.3	0.2
Minimum costs US$/kWhe	3.5	2.1	5.3	4.0	6.0	2.5
Technical limits, % total market	10	50	50	40	30	10
Initial market shares, %	-	-	-	-	-	-

Source: Anderson and Winne (2004) with adjustments.

Table 3d: Parameters for Vector of Substitutes for Electricity: Coal and Gas with Sequestration, Hydrogen centrally produced and Hydrogen for micro-CHP

Parameter or Quantity	Gas: with CO_2 sequestration	Coal: with CO_2 sequestration	H_2: centrally produced	H_2: micro-CHP
Initial Costs:				
• variable UScents/kWhe	2.5	1.8	5.2	0.2
• Fixed US$/kW	800	2500	800	2200
• Average USCents/kWhe	3.8	6.0	6.5	3.5
Efficiency, kWhe/kWh of fuel %	48	40	50	50
Load factor %	80	80	80	50
Waste heat utilised, % of fuel input	-	-	-	30
Unit CO_2 emissions g/kWh	0.0	0.0	0.0	0.0
Unit NO_x emissions g/kWh	0.09	0.9	0.0	0.0
Unit SO_2 emissions g/kWh	0.0	0.5	0.0	0.0
Unit PM_{10} emissions g/kWh	0.0	0.16	0.0	0.0
Lifetime of plant, yrs	30	30	30	25
Leadtime for investment, yrs	4	5	5	2
Development lag, yrs	5	5	10	10
Substitution parameters				
• stndrd dvn: % mean	0.3	0.3	0.3	0.3
• the parameter *a*	6.0	6.0	6.0	6.0
Learning rate	0.2	0.2	0.3	0.3
Minimum costs US$/kWhe	3.5	4.5	4.5	3.5
Technical limits, % total market	None	None	None	None
Initial market shares, %	-	-	-	-

Source: Anderson and Winne (2004) with adjustments.

The fact that fuel-cost parameters are assumed equal across regions can be attributed to the single market mechanism within the EU. Several of the parameters can also be based on international values, for example world oil prices and values for emission coefficients would not vary between countries. Country variations in total emissions will differ enormously per unit of output; but this can be almost wholly attributed to the choice of technologies, for example the ‘vintages’ in use, or the extent of ‘clean’ technologies in use. Thus, the main variation between countries will ultimately lie in the differences in policies, not in underlying parameters.

There are two exceptions to this. The first concerns the technical limits to the amount of a resource that can be used (ie available supply), the main example being the availability of land for biomass production (this is not currently featured in the ETM). The second exception is the substitution parameter which varies inversely with the standard deviation of the distribution of possibilities, ie the parameter will be greater in a country with few potential technologies that are relatively close substitutes and where switching can occur fairly rapidly, as in the UK. The substitution parameter will be smaller when the frequency distribution of potential technologies is fairly wide, for example in a country with wind and biomass and perhaps even solar power.

1.4 Conclusions

The developments outlined in this paper have resulted in energy technologies being explicitly included in E3ME for the first time, through a bottom-up representation of technologies using energy in the electricity industry, with learning curves and responses to real energy prices. As the real cost of carbon rises in the system, learning-by-doing reduces the unit costs of the low-carbon technologies as the scale of adoption increases. When technological change is induced as a response to price signals such as increases in the costs of carbon, through costs of permits and taxes, the outcome is a wave of extra investment, initiated in the electricity sector, but diffusing rapidly to other industries. The investment decision is assumed to be made by a fully informed social planner who decides what electricity demand has to be met in the future, and considers what type of supply is required to meet this demand.

1.5 References

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