AUDIT OF CAMBRIDGE ECONOMETRICS'S MDM-E3 COMBINED HEAT AND POWER SUB-MODEL

A report to the Department of Environment, Food and Rural Affairs (DEFRA)
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30 April, 2005
(edited on 28 May, 2005)

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SUMMARY

This report summarizes an audit of the combined heat and power (CHP) sub-model of the MDM-E3 UK macro-econometric model, and the projection of CHP capacity through 2010.[1] This review details how the CHP sub-model works, and is integrated into the wider MDM-E3 model. A detailed assessment of the CHP sub-model examines in turn the sectoral categorization of energy demands, the CHP plant type definition based on historic data, the net present value calculation and the CHP diffusion process into niche markets. The results of the model are then explained focusing on the underlying key factors, model robustness and sensitivity calculations. Finally the report concludes with recommendations for future analytical work on CHP uptake, including alternate modelling approaches.

The integrated MDM-E3 macro-economic modelling approach provides a very detailed treatment of the UK economy in terms of industry type, commodity flows, trade and interdependencies and underlying economic drivers. The CHP sub-model is tightly connected to the main model as well as to the energy and electricity sub-models. As such it is able to depict the full sectoral and economy-wide impacts of energy policies (such as the Climate Change Levy and its exemptions), including those designed to support CHP market penetration. In contrast, energy systems models (ESM) would have to mimic such policies through competing technology costs and system variables such as the dispatch order of power plants, while simpler investment appraisal models cannot examine such broad impacts.

An overarching modelling issue in the MDM-E3 econometric approach is its reliance on a range of input data sources, including a limited dataset on past CHP technology uptake. This is not to say that the model assumes that the near-future (through 2010 in this analysis) will be identical to the near-past. Rather the model depicts new (altered) investment conditions (including an elegant treatment of carbon reduction and CHP support mechanisms), and uses the historical data to estimate what proportion of resulting opportunities for CHP will be taken up. This is done through breaking down the potential demand for CHP in individual sub-sectors (based on representative CHP plant as historically installed), calculating a net present value for schemes, and then letting the model choose a proportion of economical plants based on a diffusion function fitted to historical responses. However there are two drawbacks of this approach. The first is a restricted flexibility within a sector in choosing the CHP technology type and its operation. The second is an inability to model completely new CHP technology types such as domestic or micro CHP, as well as very large combined site or macro-CHP. For these, even if a representative plant was assigned then there is no historical basis to determine its relative uptake.

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[1] Cambridge Econometrics (2003), *Modelling Good Quality Heat and Power Capacity to 2010: Revised Projections*, Cambridge UK.

In assessing how the model is operating in this analysis, two key yardsticks are its robustness and sensitivity. One strength of this MDM-E3 analysis is that it operates robustly under highly non-linear conditions, i.e., not giving explosive or non-intuitive results over the very wide range of parameters tested. An extensive form fitting estimation process for the functional form for CHP diffusion was undertaken using a defendable sum of differences approach due to the relative paucity of data. However this process emphasized that a key variable is the market uncertainty facing new CHP adopters.

Modelling market uncertainty is critical in this and any future analysis of CHP uptake. In this approach, given the assumptions of cost minimization for all types of investors, market uncertainty was expressed via the discount rate and an additional hurdle for new CHP investors. It is an appropriate modelling mechanism given the testing of alternate diffusion functional forms. However, future modelling approaches should strive to ground the investment penalty (or other mechanism to express uncertainty) based on the risks faced in alternate market conditions. This would be aided by additional data collection both 1990-1995 and especially for 2003-04 in order to have data on CHP uptake under different market conditions.

In terms of sensitivity, the model results are directionally intuitive as shown in the extensive sensitivity analysis. That is, the increase or decrease in CHP capacity was as expected based on changes in key input variables. However the magnitude of the model sensitivity may not be as intuitive. This is because the model's sensitivity is firstly dampened through a block of exogenously specified CHP capacity via (non-modelled) specific support policies, which are locked into each model run. As a result the model results themselves are skewed upwards as half of new CHP capacity occurs through exogenous CHP support policies. This both raises the distribution of possible CHP capacity levels around a median of 8.1 GWe through 2010, and also gives a false impression of a lower bound of around 6.5 GWe of CHP capacity.

A second dampener on sensitivity is that key variables are imposed on the model. These include macro drivers such as overall economic and sectoral growth that define the overall potential size of the energy and hence CHP market, and especially that the fuel-electricity price differential that is critical in determining the relative economics of co-generating power and heat. A key modelling extension would be to endogenize these driving factors (i.e., let the MDM-E3 generate them as part of its iterative solution). This would allow assessment of alternate views of the UK economy, global fuel prices and the investigate of any correlation in fuel and electricity prices. In addition, sensitivity analysis would be of interest on both CHP capital costs and the impact of carbon prices, notably the potentially significant driver of the EU CO_2 emissions trading system (EU-ETS).

For complementary modelling approaches of CHP uptake under various policy drivers, it is not recommended to compare MDM-E3 with a simplistic 'bottom up' energy plant investment appraisal approach These models are too crude to capture system wide drivers or constraints, generally embody only one perspective on optimal plant and its configuration, and essentially revolve around a net present value (or similar investment calculation) that are already implicitly contained in MDM-E3 or an energy systems model (ESM). A superior complementary modelling approach would be to compare the macro-econometric results from MDM-E3 with such an energy systems model (for example, the UK MARKAL model). This is especially relevant as the primary output of this analysis is technology capacity as opposed to wider economic variables. Modelling using an ESM model would allow a full dynamic cost optimisation approach based on the same industrial demand growth and relative costs of CHP plant (and hence NPV calculations) as used in MDM-E3. However, the CHP uptake would be based upon forecast retirals of existing capacity and on energy system constraints rather than a pre-set diffusion function. An ESM approach could also address the uptake of micro- and macro-CHP technology alternatives. However, the ESM modelling team would have to embody the policy and economic drivers within the relative technology costs and system variables (a process that MDM-E3 handles itself).

1. Introduction

a. Background to CHP model analysis

Combined heat and power, or CHP, technologies are highly-efficient and well-established in the UK. Through the on- or near-site use of heat, that is inevitably created when generating electricity, overall conversion efficiencies can approach 80-90% (measured using higher heating values). The produced electricity can either be used by the host site, hence offsetting electricity purchases, or fed into the electricity grid network and sold onto other users. As a result CHP technologies can offer energy and hence cost savings versus the conventional paradigm of remote electricity generation and transmission to the site together with distribution of a fuel (e.g., via natural gas pipelines) for heat generation on-site using conventional boiler plant. Depending on the electricity and heat generation technologies it replaces, CHP can also deliver significant cuts in carbon dioxide (CO_2) emissions, local air pollutants [including sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO) and particulate matter], and enhance security and diversity of energy supply.

The risk (or downside) for an investor in CHP, is a larger capital outlay than merely investing in on-site heat boiler plant, the requirement to match the heat outputs of the CHP plant to the long-term heat demands of the site, greater exposure to movements in input fuel prices and greater exposure to movements in UK electricity prices if significant amounts of power are being exported and sold to the grid. Large-scale CHP technologies are used in industrial sectors with significant heat demands for steam or hot water, while small-scale CHP technologies are used for smaller industrial units and commercial buildings, with future micro-CHP technologies becoming applicable to domestic housing.

In light of potential environmental benefits, to support the CHP industry in keeping with sustainable development goals, and to ensure that UK industry has access to the most efficient energy supply technologies, the UK Government has a policy target of 10 GWe of good quality CHP by 2010 under its good quality CHP program. As of 2002, there was approximately 4.7 GWe of GQ CHP capacity representing only 6.3% of the total UK electrical capacity of 77 GWe.[2] Therefore the target of more than doubling installed CHP capacity in less than a decade represents a significant challenge, particularly in the face of recent market and regulatory uncertainty in the UK energy markets, and the recent trend towards a smaller differential in the price of natural gas (the fuel of choice for many CHP units) and grid supplied electricity (commonly called the 'spark-spread').

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[2] DUKES (2004) Digest of UK Energy Statistics, Tables 5.10 and 6.1, UK Department of Trade and Industry, London.

b. Overview of the CHP sub-model audit

In response to the UK Government target of 10 GWe of GQ CHP capacity by 2010, the Departments of Trade and Industry (DTI) and Environment, Food and Rural Affairs (DEFRA) commissioned Cambridge Econometrics (CE) to analyse the growth of CHP capacity in the UK through 2010. This was modelled using CE's Multi-sectoral Dynamic Model of the UK Economy (MDM-E3). This macro-econometric model is designed to capture the underlying characteristics of the UK economy, the evolution of major industrial sectors, and the impacts of a range of government policies. A critical part of this analysis was the construction and integration of a CHP sub-model within MDM-E3.

MDM-E3's CHP sub-model has been calibrated using detailed CHP plant data from the GQ CHP programme and has utilized CHP industry feedback on various model parameters. The sub-model is fully integrated into the overall model structure. Building on an earlier analysis,[3] it was used to project CHP capacity through 2010 in response to market conditions and a range of government support mechanisms. The updated analysis was reported in Cambridge Econometrics (2003), *Modelling Good Quality Heat and Power Capacity to 2010: Revised Projections*, Cambridge UK.

The focus of this audit is to give an explanation of how the CHP sub-model works, to assess the analytical approach detailed in the above report and to offer suggestions for improved and extended analysis of CHP capacity projections.

c. Report structure

Section 2 of this report gives a brief overview of the MDM-E3 model, as it was used for generating CHP projections. Section 3 focuses on the CHP sub-module, detailing how it is integrated into the overall MDM-E3 model and giving an explanation of sectoral categorization of energy demands, CHP plant definitions based on historic data, the NPV investment calculation and the CHP diffusion process into niche markets. Section 4 assesses the model results, focusing on the robustness and sensitivity of the model output. Section 5 concludes with an overall assessment of the CHP sub-model and analysis, and options for future modelling.

2. Overview of the MDM-E3 Model

a. Structural (modular) elements

MDM-E3 is a fully integrated energy-economic-environment model of the UK economy. As a macro-econometric model it consists of a set of input-output (I/O) coefficients that summarize the structure of the UK economy in terms of industry type, commodities,

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[3] Cambridge Econometrics (2002), *Modelling Good Quality Heat and Power Capacity to 2010*, Cambridge UK

expenditures (consumer and government) and foreign trade and investment. These are designed to capture the interdependencies and monetary flows within the economy. These interdependencies are then updated using a series of orthodox time series econometric relationships. Both the I/O matrix and econometric equations are based on standard government data sources for the UK. MDM-E3 can project out to 2025, although projections for the further future based on historical trends may require re-examination if existing trends are deemed unrealistic in the longer term.

The main (economic) model generates aggregate demands using a consumption function with associated investment equations. Supply side responses include trade performance, employment changes and industry level productivity growth. Resultant economic activity and prices are disaggregated by 49 economic activity types. Specific to the energy sectors this includes the demands and price of input fuels and also of electricity.

Within MDM-E3 a number of sub-models, notably energy, electricity supply and emissions then update specific prices and demands which are fed back into the main model to update the I/O matrix. The energy sub-model utilizes standard data sources from the DTI for primary energy prices, and considers aggregate energy demands in terms of sectoral activities (with transportation and household energy use taking consumer preferences into account), technological progress (exogenous at present), energy use relative to substitutable inputs, and temperature changes. These aggregate demands are then met using various fuel types based on relative (final) energy prices, and a hierarchical structure of fuel specialization. A similar updating and feedback process occurs with the electricity supply sub-model which simulates the electricity generation sector meeting seasonal and diurnal demands (and margins) with appropriate investment in new plant, mothballing of old capacity and adjustment of operational load factors. Finally an emissions sub model calculates sectoral emissions output using standard emission coefficients which can then be utilized in analysis of emissions constraint policies, and to give feedbacks from environmental damages

A full description of the MDM-E3 model is given in Cambridge Econometrics (2003)[4] and in Barker et al (1995)[5]. A key point on the MDM-E3 model is that its modular structure allows detailed examination of the UK's energy sector and resultant feedbacks into an integrated economic framework. A second key point is the reliance on available data sources which vary by coverage and collection methodology.

b. Relationship with external assumptions for this analysis

Specific to the analysis of CHP projections through 2010 a number of external assumptions were imposed on the model. Primarily these were the imposition of macroeconomic

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[4] Cambridge Econometrics (2003), *Modelling Good Quality Heat and Power Capacity to 2010: Revised Projections*, Cambridge UK

[5] Barker T., P. Ekins, and N Johnson (1995) *Global Warming and Energy Demands*, Routledge, London/New York.

variables including the rate of economic and manufacturing growth, and on energy variables including real market prices of electricity, natural gas and other input fuels. Within these overall parameters, the model will endogenously solve for sectoral (industrial) market shares, and technology choices in the energy and electricity sub-models.

However, it is important to note that the model's sensitivity will be limited by the imposition of both external forecasts of productivity and in the specification of energy prices. In addition, reconsideration of fuel price assumptions including a global oil price of less than $30 per barrel in light of current and near-term market conditions is warranted. Furthermore, consideration of the correlation of fuel and electricity prices, notably in the relation between natural gas and electricity prices given the growing electricity generation market share of natural gas (particularly flexible plant that operates at the margin), and in the relation between natural gas and coal prices given the elastic long-run global supply of coal (currently assumed to be priced above $30 per tonne) is warranted. The analysis provides a good parametric analysis on fuel prices assumptions but without any indication over which scenarios may be more likely.

c. Comparison to other energy-economic models

MDM-E3 and its associated family of macro-econometric model developed by Cambridge Econometrics are well established and have been comprehensibly peer reviewed in a number of academic settings. In addition, these models have been used in a range of model comparisons, including the Energy Modelling Forum (EMF) and the Innovation Modelling Comparison Project (IMCP).

In comparison to computable general equilibrium (CGE) models, MDM-E3 has a number of advantages. It has a greater disaggregation of the UK economy, and it has a far richer technology set within its energy and electricity sub-models. This allows more realistic investment patterns in alternate energy technologies and fuels as opposed to a aggregate view nested set of elasticities. One disadvantage is its exogenous relationships with the world economy, both in terms of trade flows and also in terms of imported fuels.

In comparison to energy systems models (ESM), MDM-E3 has the advantage of being able to elegantly represent economic instruments including emission trading prices, taxes, subsidies and other support mechanisms. This is especially true if the policy instrument is directed at specific industrial sectors. Encapsulation of these policies in an ESM framework would require an implicit specification onto technology costs or demand responses. However ESM models are superior in being able to specify the component costs of energy and fuel options, as well as in their ability to represent technological improvements.

One potential general disadvantage of MDM-E3 is its reliance on existing data sources to predict the future responses of the UK economy and energy sector. This is a common issue in this type of econometric modelling. However it requires a conclusive set of arguments as to why economic impacts would differ in the next 25 years from the range of responses over the past 25 years, or why wider economic trends should be moderated or accelerated as we move forward in time. And importantly, recent trends should be a better guide to nearer-term analyses, such as the projection of CHP capacity through 2010.

Finally, specific to energy and CHP, there are a range of detailed investment appraisal models. These models attempt to hone in on of the ‘actual’ costs of investing in competing energy supply options but are far too simplistic in their representation of overall energy flows, industry structure and the wider economy to be of use in this type of sectoral analysis.

3. Characterization of the CHP Sub-model

a. Integration within model

The CHP sub-model is fully integrated within the energy, electricity and emissions sub-models, and to the wider economic model of MDM-E3. It should be noted that the impact of CHP uptake on the UK economy is very small (for example a doubling of CHP capacity by 2010 is projected to alter GDP by less than 0.01%). This is due to this amount of CHP uptake being a marginal shift in the energy sector which is relatively small in its contribution to the UK’s GDP, and that energy use is only one component of productivity of various sectors. Furthermore, this argues that the benefits of a using a macro model to analyse CHP uptake is more relevant in the specification of government support policies (such as the Climate Change Levy [CCL]) rather than in the economic impacts of CHP uptake. Of course the impacts of greater CHP diffusion will be relatively larger on the energy sector and electricity supply industry respectively.

b. Underlying assumptions

The first underlying assumption in the consideration of CHP uptake is that of cost minimization. Whether the CHP investment is being made by a single end user, in partnership with a CHP supplier, or on behalf of the host site by an energy services company, the sole criteria is cost minimization. No other investment criteria, including exposure to risk, is considered largely because investment flows to different parties in the investment cannot be broken out.

The second underlying assumption is that the CHP plant is primarily sized for on-site heat demands, with electricity either being used on-site or exported for sale on the national grid. This methodology is reasonable if one considers the inability to economically distribute large amounts of heat, and the costs of storing or dumping large amounts of heat. It should be noted that alternate (more flexible) sizing strategies can be employed using smaller scale CHP technologies, particularly when a portfolio of on-site CHP units are available to be switched in and out to meet a range of energy demands, and if a collaborative venture has been agreed between host sites and distribution utilities.[6]

c. Generation of sectoral energy demands

The first step in the analysis of CHP uptake is the assessment of sectoral energy demands according to the fuel use by each of MDM-E3's 49 industry classifications. This essentially derives 49 niche markets for CHP. A proportion of these will be available for CHP uptake based on the relative costs of CHP uptake versus the conventional alternative on on-site heat boiler plant and electricity purchase.

d. Fitting of CHP plant types

For each industry sector, a representative CHP plant is chosen based on historical characteristics of CHP units in that sector. For example a sector with a large heat load (and associated prior investment in CHP plants with high heat to power (HPR) ratios) would then have this type of CHP plant available to it, and the model would choose it if was an economical option. There is no substitution between plant types in a particular sector. The CHP plant is fired on the lowest cost available fuel. Note that as a completely data driven model, and as most existing CHP capacity is gas fired combined cycle gas turbines (CCGT) this combination is the one most often considered for new investment.

The CHP plant types themselves are based on an aggregated set of historical CHP investments as reported under the government's good quality CHP programme. CHP technologies were classified based upon technology type, size and economic sector. A standard statistical technique was used to expand the available data set to approximate the CHP technologies available to each of MDM-E3's sectors.

e. Methodology for CHP investment decision process

The model first calculates the net present value (NPV) of investment for all of the CHP plant types (by sector) based on the fixed and variable costs of the CHP plant itself (including electricity export), and on the fixed and variable costs of the alternative of separate electricity purchase and on-site heat generation. Given the range of site specific factors in any investment decision a (normal) probability distribution is assigned to the NPV of each CHP plant investment, so that even with a negative NPV (i.e. CHP investment being on average more expensive), some CHP diffusion may occur in a given sector on the basis that a percentage of sites will have more favourable investment criteria.

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[6] Strachan, N. and H. Dowlatabadi (2002) *Distributed Generation and Distribution Utilities*, Energy Policy Vol. 30, No 8, pp. 649-661.

f. Methodology for CHP diffusion process

For all CHP investment options with a positive NPV (i.e. CHP plant is cheaper than the conventional alternative) these are taken up by the model in two stages. First if the MDM-E3 economic model projections have an expansion of a particular sector, this is classified as ‘greenfield’ industrial development and the economic CHP is installed as a priority. Second, for the existing industrial base, for CHP plants where the economics are favourable these are installed based on a diffusion function that is derived from eight years of historical data from the GQ CHP database. The functional form of this diffusion equation relates how profitable a CHP investment would be to the likelihood of it actually being installed. Note there is no information on the existing energy capital stock (both CHP and heat boiler plant) in terms of its likely retirement date. For both categories, the uptake of CHP is driven solely by fitting the diffusion function to the rate of CHP uptake from 1995-2002.

A last step is for the model to install capacity based on time lags from decision to investment. There is the option that in this period, planned investments are not carried out due to changes in economic profitability, but as the time paths of the underlying economic costs criteria (notably fuel prices and investment costs) are smooth, there is little chance of the investment economics to change sufficiently to scrap the planned investment.

g. Model fitting and testing

Owing to the relative paucity of only 8 years historical data, formal econometric techniques could not be used for the testing of the NPV calculation and fitted functional form. Instead a parametric approach of varying key parameters and calculating the sum of differences between the model output and historical data (in terms of output CHP capacity) over the available time period was undertaken. This is a useful and appropriate exercise.

Within the assumed function form the most sensitive parameter was a NPV penalty; an investment hurdle designed to mimic additional investment uncertainty stemming from future risk of changing on-site energy requirements and in the electricity tariff paid for exports. This investment penalty was fitted at £1.4M / MWe and represent a doubling or near tripling of investment costs for most CHP investments. Further illustrating the importance of understanding market risk was that the next most sensitive parameter was the discount rate used, with the median value of 15% already having some risk premium incorporated. Clearly, assessing the impact of market risk on the uptake of CHP is critical.

Of less sensitivity was the price elasticity between different investment options, illustrating the ease within a given industry sector of choosing between the least cost energy supply option, the obsolescence factor which governs the retirement rate of energy plant, and the investment lag time between the investment decision and plant start date.

h. External stakeholder considerations

Some model parameters, notably investment costs of CHP plant types and investment time lags, were updated following a consultation exercise with the CHP industry. Cambridge Econometrics made a good faith effort to incorporate this feedback into their model parameters, but were hampered in this by the scarcity and lack of specificity of responses from the industry representatives.

i. Additional CHP support measures

Finally, it is important to note that a large proponent of the CHP capacity projected by the MDM-E3 model was not analysed but rather was 'hotwired' into the model based on advice on the results of CHP support mechanisms already in place. These assumed contributions included the CHP quality improvement programme, the community energy programme, the uptake of CHP capacity already in the advanced planning stage and the uptake of micro-CHP aimed at the domestic market.

It should be noted that the Climate Change Levy exemptions for CHP fuel use, the extension of the CCL exemption for CHP electricity exports, tariff penalties under NETA, enhanced capital allowances, business rate exemptions, and the UK ETS are modelled explicitly the MDM-E3. In addition, all new CHP capacity is integrated with the energy and electricity sectors within the model and their impact is further reflected in the macroeconomic outputs of the main model.

4. Assessment of Model Results

a. Overview of results

From a base capacity of approximately 4.7 GWe in 2002, the base case for CHP capacity in 2010 is 8.1 GWe. This represents a very significant increase in CHP capacity in a short time period. The model is sensitive to a range of input factors notably in movements in natural gas and electricity prices and in support measures that impact the prices of these commodities. However only the most extreme movements in energy prices allows the CHP target of 10 GWe to be met, indicating the very small likelihood of this occurring (especially considering any likely correlation between natural gas and electricity prices). The lower bound of all the model results is around 6.5 GWe in 2010, and is reflective of the external assumptions that constrain the flexibility of the model and which may give a false sense of optimism that at least this level of CHP capacity will be met.

a. Principle underlying factors

The first key factor underpinning the results is the impact of basing the CHP investment process on historical data. This leads to an uptake of CHP investment by industrial sector that appears very proportional to what has gone before in terms of CHP plant type and input fuel. While this consistency can be viewed as validating the model results, it is also an indictment of the constraint the model places on what technologies are available to be utilized by any given investor.

A second key factor is the impact of exogenous policy driven CHP uptake. In addition to the CHP quality improvement programme, community energy programme, uptake of CHP capacity in the advanced planning stage and the uptake of micro-CHP, the model results include one example of what could be termed ‘macro-CHP’ or the investment in very large-scale CHP at an industrial setting with sufficient heat load to justify such a facility. This leads to an additional 0.8 GWe of CHP capacity (as gas-fired CCGT) coming on stream in 2004. The impact of such non-modelled CHP addition effectively means there is a lower bound on installed capacity in 2010 of around 6.5 GWe, irrespective of changing investment conditions or the impact of modelled CHP policy support measures. This ‘hot-wiring’ of the results is a weakness of the analysis specification and gives unjustified confidence in the low bound for CHP capacity in 2010.

A third key factor is the exogenous imposition of key variables, notably the relative difference between electricity and natural gas prices (or the ‘spark-spread’) and the projected overall size of the UK economy. The latter determines the aggregate demand for energy provision and hence for CHP, while the former is a critical driver of the relative economics of co-generating electricity and heat on-site. An improved approach from a modelling perspective would be to allow MDM-E3 to endogenously generate these variables. This would have the added advantage of being able to investigate any correlations in movement of energy prices

A fourth key factor is the treatment of market uncertainty and risk, currently through both the discount rate and an investment penalty. The penalty which only applies to non-greenfield, and non-existing CHP sites reflects the uncertainty imposed by CHP of having to guarantee on-site heat demands in the longer term and greater exposure to movements in electricity export tariffs. In the absence of better data and/or non-anecdotal insights into how the CHP market is responding to the current perceived level of risk and how this will evolve through the next decade, the use of a simple investment penalty is an appropriate mechanism for this type of model.

b. Robustness of the model results

The model results illustrate that the CHP-model is robust. This means that the model is capable of handling the assorted and interacting non-linearity embedded within it and does not produce spurious or explosive results for the parameter ranges tested in the report.

Within the assumed functional form for CHP diffusion, the most sensitive parameter was a NPV penalty, and investment hurdle designed to mimic additional investment uncertainty stemming from future risk of changing on-site energy requirements and in the electricity tariff paid for exports. This investment penalty was best fitted at £1.4M / MWe and represents a doubling or near tripling of investment costs for most CHP technologies. Further illustrating the importance of understanding market risk was that the next most sensitive parameter was the discount rate used, with the median value of 15% already having some risk premium incorporated. Clearly, assessing the impact of market risk on the uptake of CHP is critical. In any future analysis of CHP uptake, an explicit evaluation of changing market dynamics and hence any reduction in this risk premium would be advantageous.

Of less importance for the robustness of results were the price elasticity between different investment options, illustrating the ease within a given industry sector of choosing between the least cost energy supply option, the obsolescence factor which governs the retirement rate of energy plant, and the investment lag time between the investment decision and plant start date.

c. Sensitivity analysis on the model results

The sensitivity analysis on the uptake of CHP as detailed in CE's report illustrated that the CHP sub-model was behaving correctly in a directional sense. That is, it was intuitive in the increase or decrease of CHP capacity based on changes in input variables (e.g., natural gas prices). A far more complex issue is whether the rate of change in CHP uptake is reasonable. It should be noted that the exogenous macro-assumptions imposed on the MDM-E3 model for this analysis limited the overall flexibility of the model and may have hampered its overall sensitivity.

A considerable effort was made in parametric uncertainty analysis of variations in electricity and gas prices. The +/- 20% and 40% fuel movements did not reflect standard deviations in the probability of fuel price movements but were rather an assessment of reasonable annual shifts in fuel costs. A further set of parametric sensitivity analysis was conducted on the penalty for non-guaranteed electricity export levels in terms of reduced tariffs paid to CHP under the new electricity trading arrangements (NETA). This range was set under advice from the DTI. Finally sensitivity work was carried out on the exemption of CHP electricity supply from the renewables obligation (RO) finding a relatively small impact on CHP uptake due to a relatively small shift in the price of exported electricity from the CHP installations that do export.

However no sensitivity analysis was carried out on investment costs, operation and maintenance (O&M) costs, economic growth rates or on emission trading scheme (ETS) prices. Furthermore only the UK ETS was considered, the potential impact of the much larger EU ETS scheme was not modelled in this analysis. The impact of the EU-ETS is potentially either minor or very large dependent on the carbon price set by the market (particularly in the post-2007 second phase of the EU ETS), the conventional plant (and hence carbon savings) that MDM-E3 finds is replaced by cost-effective CHP, and the allocation of permits to existing or new energy producers and plants.

5. Conclusions

a. Overall assessment of the CHP sub-model methodology

The integrated MDM-E3 modelling approach encapsulates an excellent treatment of the range of sectoral and economy wide policies designed to support CHP market penetration. The CHP sub-model itself is tightly integrated into the model as a whole. However, as the CHP proportion of the relatively small energy sector makes little impact on the overall UK economy, this limits the usefulness of MDM-E3's calculation of the complete range of output macro-economic variables.

A simultaneous strength and weakness of the MDM-E3 econometric approach is its reliance on a range of input data sources and historical trends. Generally, and especially for projections only till 2010, this is not a constraint on the overall model's performance as it requires a convincing argument as to why the economy's responses and underlying trends should be so different in the near-future as compared to the near-past. This data reliance issue question is more open ended in the case of only eight years of CHP uptake data and the recent market discontinuities in terms of fuel price shifts and electricity trading arrangements. Extended data collation pre-1995 would be advantageous till the point where the CHP technologies being adopted were significantly different in terms of their costs and performance. Of even more value would be data on CHP uptake in 2003-04, in order to assess the success of CHP suppliers in marketing units under very different conditions and to assess whether planned units were in fact installed.

In terms of model fitting, the limited years of available data is not such a constraint in itself. While there is no use of formal econometric fitting techniques, the sum of differences approach employed is adequate to get a sense of the robustness of the diffusion functional form employed.

The starting points of cost minimization as the basis of investment, a heat led sizing methodology and the definition of 49 niche markets for CHP in terms of industry classifications are all valid. If the timeframe of the analysis was longer and/or there was more than anecdotal evidence of a new CHP operational and financing paradigm, then relaxing this modelling basis could help analysing more fundamental shifts in energy services and the paradigm of CHP uptake.

The CE modelling team undertook a defendable and valid effort to expand the GQ CHP dataset in defining their CHP plant typology. However, one weakness of the MDM-E3 approach is its reliance of representative plant types based on historical uptake. The first main drawbacks on this is the lack of flexibility of a given sector in choosing the CHP size and technology and in running that unit with altered (optimised) load factors or other operational variables. The second drawback is that MDM-E3 cannot adequately model micro- or macro-CHP technologies. Even if a representative plant for these technologies is assumed, there is no historical basis on which to allocate its availability for use in particular sectors.

Within the diffusion function for CHP investment, the investment penalty is an appropriate mechanism to characterize market uncertainty in light of an evolving market structure. Clearly however this is a critical variable in the analysis and future modelling could test alternate functional forms and/or ground the investment penalty based on the risks faced in alternate market conditions.

Last, the CE modelling team made a good faith effort to take the CHP industry viewpoints onboard, particularly in the investment capital costs and in the time lags from investment decision to the plant coming on-line. However this consultation process was hampered by the scarcity and lack of specificity of the industry responses.

b. Overall assessment of the CHP sub-model results

The report detailing the modelling of CHP uptake in the UK through 2010 is a very well written and transparent piece of analysis. Overall the model operates robustly under highly non-linear conditions, i.e., not giving explosive or non-intuitive results over the range of parameters tested.

The model results are skewed by around half of new CHP capacity occurring through a range on exogenously imposed assumptions over the effectiveness of CHP support policies, including the CHP quality improvement programme, community energy programme, uptake of CHP capacity in the advanced planning stage, the uptake of micro-CHP, and the uptake of large-scale or ‘macro-CHP’ schemes. These external assumptions both raise the distribution of possible CHP capacity levels around a median of 8.1 GWe through 2010, and also gives a false impression of a lower bound of around 6.5 GWe of existing and new CHP capacity.

The model results are directionally intuitive as shown in the sensitivity analysis on input variables tested, notably electricity and gas prices, discount rates, the NPV investment penalty, and electricity export tariffs. It would be advantageous to extend this sensitivity work to CHP capital costs, and non-fuel variable costs.

However the magnitude of the model sensitivity may not be as intuitive. This is because the model’s sensitivity is dampened through the existence of the stock of exogenously specified CHP uptake, because macro-variables including overall economic growth are imposed, and because electricity and natural gas prices are predetermined. This last point is of particular importance as it restricts the investigation of correlation between fuel and electricity prices, the differential of which is critical in the economics of CHP plant.

c. Areas of improvement/extension for future analytical work on CHP

In terms of the MDM-E3 CHP sub-model, it is difficult to propose structural modelling updates (for example in the definition of representative plant types) that do not require a significant time commitment. In its place, a number of recommendations are made that could allow the model's sensitivity and robustness to be better defined. The first is to re-run this analysis allowing MDM-E3 to define both the full set of macro-variables and the range of input fuel and electricity prices. The specification of the latter is particularly crucial to the economics of CHP investment. The second recommendation is to fit alternate diffusion functional forms, and if possible base these on an extended historical data set. With or without more data, categorizing the investment penalty as at least a qualitative function of market risk (and for future policies that alter market conditions) would be an interesting exercise. A third recommendation would be to remove the exogenously defined CHP uptake from non-modelled support policies, or at least systematically alter them according to the sensitivity case run. For example, the uptake of micro-CHP will also be affected by movements in electricity and natural gas prices. A fourth recommendation would be to include and model the EU-ETS program and specifically the carbon outputs of both displaced electricity and replacement CHP plant, as the EU-ETS is potentially a major driver of CHP uptake. A final recommendation is additional sensitivity work on CHP capital and non-fuel variable costs.

In terms of alternate CHP modelling options, it is not recommended to compare MDM-E3 with a simplistic 'bottom up' energy plant investment appraisal approach, as these models are too crude to capture system wide drivers or constraints. A superior complementary modelling approach would be to compare the macro-econometric results from MDM-E3 with a energy systems model (ESM) undertaking dynamic cost optimisation (for example, the UK MARKAL model). This is especially relevant as the primary output of this analysis is technology capacity as opposed to wider economic variables. Modelling using such an ESM model would allow a full optimisation approach based on the same industrial demand growth and relative costs of CHP plant (and hence NPV calculations) as used in MDM-E3. However, the CHP uptake would be based upon forecast retirals of existing capacity and on energy system constraints rather than a pre-set diffusion function. An ESM approach could also address the uptake of micro- and macro-CHP alternatives. Ideally a modelling extension would be to run the ESM model in a probabilistic mode to categorize the likelihood of various parametric sensitivity scenarios.