A Planning and Analysis Framework for Evaluating Distributed Generation and Utility Strategies

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Plans ...

Many are the plans in a man's heart, but it is the LORD's purpose that prevails.

Proverbs 19: 21

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Abbreviations

AVC	Automatic Voltage Control
CEGB	Central Electricity Generating Board
CCL	Climate Change Levy
CHP	Combined Heat and Power
DG	Distributed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
DOC	Directional Over-Current
DTI	Department of Trade and Industry (UK)
ESI	Electricity Supply Industry
GSP	Grid Supply Point
IIP	Information and Incentives Project (an OFGEM scheme)
IPLAN	Interfacing Program Language (within PSS/E)
IPP	Independent Power Producer
IRR	Internal Rate of Return
KPI	Key Performance Indicators
kW	Kilowatt
LDC	Line Drop Compounding
MCDM	Multiple Criteria Decision Making
MW	Megawatt
MWh	Megawatt-hour
NFFO	Non Fossil Fuel Obligation
NGC	National Grid Company
NPV	Net Present Value
OFGEM	Office of Gas and Electricity Markets
PSP	Pool Selling Price
PSS/E	Power System Simulator for Engineers
REC	Regional Electricity Company
RPI	Retail Price Index
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition

SMART	Simple Multiattribute Rating Technique
TO	Transmission Operator
TSA	Tariff Support Allowance
VBA	Visual Basic for Applications (macro language in Microsoft Excel)

Abstract

The numbers of smaller scale distributed power generation units connected to the distribution networks of electricity utilities in the UK and elsewhere have grown significantly in recent years. Numerous economic and political drivers have stimulated this growth and continue to provide the environment for future growth in distributed generation. The simple fact that distributed generation is independent from the distribution utility complicates planning and operational tasks for the distribution network. The uncertainty relating to the number, location and type of distributed generating units to connect to the distribution network in the future makes distribution planning a particularly difficult activity.

This thesis concerns the problem of distribution network and business planning in the era of distributed generation. A distributed generation strategic analysis framework is proposed to provide the required analytical capability and planning and decision making framework to enable distribution utilities to deal effectively with the challenges and opportunities presented to them by distributed generation.

The distributed generation strategic analysis framework is based on the best features of modern planning and decision making methodologies and facilitates scenario based analysis across many utility strategic options and uncertainties. Case studies are presented and assessed to clearly illustrate the potential benefits of such an approach to distributed generation planning in the UK electricity supply industry.

Acknowledgements

The author would like to thank the many colleagues within the Centre for Electrical Power Engineering at the University of Strathclyde who have supported his research work since the beginning of 1997. There are too many instances of support to mention individually and their contributions have ranged from detailed, and sometimes lengthy, technical discussions relating to specific problems to encouraging words of a more general nature.

Jim McDonald has provided the supervision, motivation, resources and opportunities which have made this research project possible and have sustained me throughout the last three and a half years. The time and energy invested in this project and in my professional development have gone far beyond the call of duty and I owe a debt of gratitude for this.

This research project has been conducted with considerable co-operation from the industrial sector. Colleagues at Rolls-Royce, East Midlands Electricity, Scottish Power, Eastern Electricity, Power Technologies Limited and Oxford Economic Research Associates have provided many useful ideas and suggestions along with data, analysis tools and grant funding for the project. My thanks to those who have supported my research in these ways. Rolls-Royce, EPSRC and the Scottish Higher Education Funding Council provided partial financial support for this project.

My parents, family and friends have provided much needed encouragement throughout this project while my parents in particular have inspired me to achieve all that I could in life and were influential in guiding me into electrical engineering research as a career. Thanks folks.

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Chapter 1

INTRODUCTION

1.1 Summary of Thesis

Restructuring of electricity markets and advances in generation technologies, in tandem, have created an environment for the continued growth of small-scale generation embedded within distribution networks closer to the point of end use of electrical energy. Recent environmental pressures, trends and legislation have also contributed to the proliferation of smaller generating units connected to electricity distribution networks. In contrast to larger scale 'central' transmission connected generating units these smaller generating units, connected to distribution networks, are commonly known as distributed generation, embedded generation or dispersed generation. The term distributed generation will be used in this thesis is taken to be synonymous with both embedded generation and dispersed generation throughout.

Distributed generation results in a set of commercial, economic, engineering and financial issues for distribution network planning, operation and management. This thesis identifies and discusses this set of issues and presents a formal method of structuring them for further discussion, analysis and planning decision support.

Restructuring of electricity markets has also resulted in distribution networks being progressively planned and operated on an 'open-access' basis with an accompanying increased level of uncertainty regarding the nature and location of distributed generation. Existing distribution system planning has centred on techniques for load forecasting, substation location and capacity and feeder route design. However, such planning techniques take little account of distributed generation. One further assumption in traditional power system planning practice now challenged is that of the integrated utility with franchise rights for generation, transportation and retail supply of electricity. This thesis takes advantage of the current opportunity for developments in power system planning techniques to provide greater understanding of distributed generation at a time of great uncertainty for distribution utilities in the UK and elsewhere.

As noted, distribution planning has traditionally focussed on the problems of timing, location and sizing of investments in substation and circuit reinforcements. Generation (and especially independently owned generation) has not previously been an important consideration for distribution companies. However, in addition to complicating the distribution planning problem, distributed generation provides a new set of options in the planning, design and operation of distribution networks.

This thesis outlines a strategic analysis framework for the evaluation of the issues and attributes associated with distributed generation. In addition to quantifying the problems, the framework enables the assessment of potential strategic options for distribution companies. The proposed strategic analysis framework relates directly to the distributed generation issue set that is fully developed in this thesis. Existing distribution planning models and software tools are incorporated into the strategic analysis framework. The modelling options for quantification of the impacts of distributed generation are discussed fully. One set of modelling and simulation techniques are carried forward into an implementation of the specified strategic analysis framework.

The proposed framework is comprehensive, flexible, and scenario-based providing robust solutions to distribution problems relating to distributed generation. Acceptable strategies can be selected using multiple criteria decision-making methods. Each of these characteristics of planning methodologies (and others) will be defined and discussed with the corresponding benefits outlined.

Case studies relating to the impact of distributed generation are presented with the aim of supporting the argument put forward for the comprehensive strategic analysis framework for distributed generation. The variables considered in the case studies relate to uncertainties in generation technologies, locations and volumes and the options open to a distribution utility to harness the benefits of distributed generation.

This research took three main items of literature for its basis. Firstly, a PhD thesis by Redmond (Redmond, 1994) provided a background in the UK electricity supply industry and outlined some of the many challenges facing the privatised electricity companies operating in the UK market. One of the techniques investigated by Redmond was multiple attribute tradeoff analysis (MATOF) for utility strategic decision making. The idea of strategic decision making has moulded the distributed generation framework to focus on decisions and in practical terms the production of quality information to support decisions. MATOF had been developed extensively at Massachusetts Institute of Technology (MIT) and used to assist in major strategic planning activities relating to the generation mix in New England, USA. In a PhD thesis, Andrews (Andrews, 1990) analyses planning processes at great length and lays down an open, analytical, scenario based approach to planning which facilitates the treatment of uncertainties, complexity and controversy which invariably arise in major decisions. These insights into planning processes have motivated an in-depth study of power system planning activities (chapter 4). The third item of literature which formed a foundation for this research was a digest from an Institution of Electrical Engineers (IEE) colloquium on embedded generation (Institution of Electrical Engineers, 1996). The diversity of perspectives and the complexity and uncertainty of the issues in the area of distributed generation indicated that this was an area where structured planning techniques could yield benefits. Based on these foundations the general methodology of research has been to:

- specify and understand the issues of distributed generation;
- identify and specify clearly the major problems for distribution companies arising from distributed generation;
- develop a strategic analysis and planning framework for distributed generation focused on the distribution utility perspective;
- utilise the strategic analysis framework to quantify and understand a set of more critical distributed generation issues.

This has led to the development of a general methodology for distributed generation analysis which has been termed the 'distributed generation strategic analysis framework'.

The use of the distributed generation strategic analysis framework has shown that there are major potential benefits arising from distributed generation which distribution companies can harness given the right set of policies and strategies. The strategic analysis framework provides the means of developing and refining strategies for distributed generation although the development of such policies has been beyond the scope of this work.

1.2 Principal Contributions

The principal contributions represented in the material presented herein can be summarised as:

- The identification, categorisation and exposition of issues relating to distributed generation and distribution utilities.
- The proposition and development of a general methodology for evaluating the impact of distributed generation on utility networks and businesses and for assessing distribution utility strategies for managing distributed generation. The general methodology has grown from analysis of the set of issues for distributed generation.
- The specification of a strategic analysis framework including the integration of sophisticated market, power system and utility financial models. The strategic analysis framework described in this thesis takes account of the best features of modern planning methods. It is believed that the

flexibility of the strategic analysis framework enables the integration of many existing techniques although the implementation of the framework has been restricted for the purposes of this study.

- The first integrated technical and economic planning and evaluation approach to specifically address the distribution network and distributed generation requirements within a restructured and unbundled electricity industry as found in the UK.
- The quantification and interpretation of the impact of distributed generation on distribution utility networks and businesses based on an implementation of the distributed generation strategic analysis framework which includes the integration of detailed economic, technical and financial models.
- The demonstration of the effectiveness of the proposed planning and analysis framework through its application to meaningful case studies.

1.3 Distributed Generation Planning

The contributions offered by this thesis must be viewed in the context of existing work. The work of other contributors in this field can be summarised in the following three areas.

- Distributed generation issues
- Modern planning requirements
- Distributed generation planning methods

Many contributors have added to the general understanding of the issues of distributed generation. The most comprehensive and early contribution in the UK which brings together aspects of distributed generation market from an economic and technical viewpoint is Fairey and Redfern (Fairey and Redfern, 1996). This paper brings many years of background in the UK electricity supply industry along with a detailed knowledge of distribution engineering. The authority of these authors to review the field of distributed generation is without challenge in the UK.

Several major contributors in the power system planning field have been lent on in the development of ideas on what has been loosely termed 'modern planning requirements' in this thesis. Berrie has great authority to talk about 'electricity economics and planning' and does so in a book of that title (Berrie, 1992). Northcote-Green, Willis and Gonen each have a weighty reputation within the distribution planning field and discuss many of the distribution planning methodologies in their papers and books.

Hirst has been one of the major contributors over the years in the area of incorporating uncertainty into power system planning. The work of Clint Andrews and Steve Connors on multiple criteria decision making in power system strategic planning acted both as a motivation and a source of knowledge for the research reported here in this thesis. Each of these contributors has brought new insights to the field of power system planning and distribution system planning, and although the methods are primarily focused on more traditional generation and distribution network expansion planning, the generalities of their techniques have been drawn out for more general use in the strategic planning framework presented in this thesis.

Within the specific area of distributed generation planning, the significant contributions are more sparse. Most contributions arise from the viewpoint of distributed generation existing as an additional option in integrated resource (least cost) planning. The Pacific Gas and Electric work on the 'distributed utility' stands out as a landmark in changing attitudes to distributed generation as a valuable resource (Weinberg et al, 1991). The research by Weinberg and colleagues identifies many areas of distributed generation value within the United States electricity industry structure. Many of these areas of value exist in the UK also but there are important differences between the US and the UK in the treatment of distributed generation as will become evident later.

Willis and Scott (Willis and Scott, 1994) describe a method of integrating distributed generation, demand side management and distribution automation into the distribution planning process. In short the integration of distributed generation into distribution planning activities (even when distributed generation is an option the utility can control as in the method they propose) makes the analytical activities far more complex and, hence, time consuming.

Dugan *et al* (Dugan et al, 1999) have proposed a method for distributed generation which focuses on minimising network capacity costs in the distribution network. This is achieved through integrating distributed generation into a planning framework which considers the costs of electrical losses, network capacity reinforcement and power quality improvements.

Nishiya *et al* (Nishiya et al, 1995) describe a generation siting optimisation approach to distributed generation planning. The theme of optimising the location of distributed generation is also adopted by Kim *et al* (Kim et al, 1998). In these methods, the size location and operational strategy of distributed generation units are optimised to produce a distribution system with minimal losses and generation fuel costs. These optimisation techniques for distributed generation planning clearly take the perspective of a vertically integrated utility with control over network and generation.

A distribution utility approach to independent distributed generation is proposed by *Seitz* et al (Seitz et al, 1997). The crux of the paper relates to a formalised approach to generation connection and operation within the distribution network. This enables a fair and transparent mechanism for generation connection and operation including generator developer access to information on limitations to generation connection in particular areas of the distribution network.

1.4 Overview of Thesis

Chapter 2 provides background to electricity industry restructuring which has created the environment for the proliferation of independently owned distributed generation. Chapter 3 describes the issues relating to embedded generation and the impact they have on the power system. Chapter 4 provides a general background to distribution system planning and a detailed discussion of desired features of modern planning methods. The need for new methods to deal with the growing issue of distributed generation is clearly identified. The proposed distributed generation strategic analysis framework is presented in Chapter 5 and a practical implementation of the framework is described in Chapter 6.

Chapter 7 provides details of a case study utilising the framework including the description of possible utility strategic options plus analysis of the results of the case study. Chapter 8 discusses the merits of the strategic analysis framework and draws conclusions about its application for assessing the impact of distributed generation and resulting utility policy and provides some suggestions for further work.

1.5 Published Work

The author has published extensively in the areas of analysis and planning for distribution systems and distributed generation in the period 1997 to 2000. All journal and conference papers published in this period are listed below under the appropriate year.

1997

G.W. Ault, R. Driver, J.R. McDonald, "The Economics of Embedded Generation in the UK Power Market", POWERGEN'97 Conference, Dallas, USA, December 1997.

1998

F. Edwards, J.R. McDonald, G. Ault, J. Hill, "Dynamic modelling of distribution networks with embedded generation", 33rd Universities Power Engineering Conference, Edinburgh, Sept. 1998, pp473-476.

G. Ault, J.R. McDonald, "Analysing how UK distribution networks are currently responding to embedded generation and examining how this might affect future investments in and performance of the network", IIR Conference on 'Successfully Overcoming the Practical, Commercial & Integration Challenges of Embedded Generation', London, December 1998.

1999

P. Espie, G.W. Ault and J.R. McDonald, "Multi-Criteria Decision Making Methods for Distribution Utility Embedded Generation Strategy Development," Proceedings of the 34th Universities Power Engineering Conference, Leicester University, UK, Vol 2, Sept. 14-16, 1999, pp. 551-555.

J. Padullés, G.W. Ault, C.A. Smith and J.R. McDonald, "Fuel Cell Plant Dynamic Modelling for Power Systems Simulation", Proceedings of the 34th Universities Power Engineering Conference, 14-16 September 1999, Leicester, UK. Vol. 1, pp. 21-25

G.W. Ault, A. Cruden, J.R. McDonald, "Assessing the impact the expected increase in embedded generation will have on the planning and operation of distribution systems", IIR Conference on 'Preparing for the impact of RETA and current Government Reviews on Embedded Generation', London, December 1999.

2000

G.W. Ault, J.R. McDonald, "Planning for distributed generation within distribution networks in restructured electricity markets", IEEE Power Engineering Letters, Power Engineering Journal, Vol. 20, No. 2, pp. 52-54, February 2000.

P. Espie, G.W. Ault, J.R. McDonald, "Multiple criteria decision making in distribution utility investment planning", Submitted and accepted for Electric Utility Deregulation and Restructuring, and Power Technologies Conference - DRPT 2000, April 2000, London, pp 576 –581.

J. Padullés, G.W. Ault and J.R. McDonald, "An Approach to the Dynamic Modelling of Fuel Cell Characteristics for Distributed Generation Operation", Proceedings of the IEEE Power Engineering Society Winter Meeting 2000, 23-27 January 1999, Singapore.

J. Padullés, G.W. Ault, J.R. McDonald, "An Integrated SOFC Plant Dynamic Model for Power Systems Simulation", Journal of Power Sources, Vol. 86, March 2000, p. 495-500.

G.W. Ault, A. Cruden, J.R. McDonald, "Specification and testing of a comprehensive strategic analysis framework for distributed generation", IEEE PES Summer Meeting, July 2000, Seattle, USA.

C.E.T. Foote, G.W. Ault, G.M. Burt, J.R. McDonald, J.P. Green, "Towards a structured methodology for distribution network design applications", 35th Universities Power Engineering Conference, Belfast; 6th-8th September 2000.

In addition to these authored and co-authored papers, are acknowledged contributions from industrial partners for the following papers:

J.E. Hill, R.A. Driver, I. Ritchey, H. Middleton, G.A. Taylor, "An Alternative Design of Electricity Supply Infrastructure", 12th CEPSI, Thailand, November 1998. *(Acknowledged contribution).*

K.F. Shrimpton, A.G. Sheard, "A Grid Disconnection Relay for Small Power Producers", IMechE Seminar on Steam Turbine Governing & Overspeed Protection, London, May 1998. *(Acknowledged contribution).*

D. Openshaw, "Assessing the Commercial Impact of Embedded Generation on UK Distribution Systems," *IEE Colloquium on 'Economics of embedded generation'*, vol. IEE Digest No. 98/512, pp. 4/1-4/7, 1998.

The following papers have been submitted pending review or publication:

G.W.Ault, "Assessing how the growth of embedded generation will affect the security and reliability of distribution networks", IIR Conference on 'Security and reliability in electricity distribution', London, September 2000.

G.W.Ault, J.R.McDonald, A.Cruden, R.C.Knight, "Prospects for a load security contribution from embedded generation", IEE/IMechE Seminar on 'Embedded Generation – Opportunities & Experience', London, October 2000.

G.W.Ault, J.R.McDonald, A.Cruden, "Planning Dispersed Renewable Generation with Geographical Information Systems", 16th International Conference and Exhibition on Electricity Distribution – CIRED 2001, Amsterdam, June 2001.

Table 1-1 details the reports issued by the author in the course of his work on distributed generation analysis and planning during the period of research for this thesis.

Report Reference	DATE	Title
RR/MAT/TR/1997-002	Jul 1997	Distributed Generation Project – Issue Set.
RR/MAT/TR/1998-006	Jun 1998	Work Package 2.1 – 'Effects of Embedded Generation on Network Characteristics – Simulation Results'.
RR/MAT/TR/1998-005	Jun 1998	Work Package 1.1 – 'Test Distribution Network Simulations to Assess the Effects of Embedded Generation on Power Import Levels'.
EE/MAT/KT/1998-001A	May 1998	Eastern Electricity Networks Business Impact of Embedded Generation – Validated Knowledge Transcript – Network Strategy.
EE/MAT/KT/1998-002A	May 1998	Eastern Electricity Networks Business Impact of Embedded Generation – Validated Knowledge Transcript – Generation Business.
EE/MAT/KT/1998-003A	Jun 1998	Eastern Electricity Networks Business Impact of Embedded Generation – Validated Knowledge Transcript – Energy Trading.
EE/MAT/KT/1998-004	May 1998	Eastern Electricity Networks Business Impact of Embedded Generation – Knowledge Transcript – Commercial Development, System Pricing and Distribution Contracts.
OXERA	Apr 1999	Embedded Generation in the Eastern Electricity Network: Final Report.
EE/MAT/PR/1998-007	Nov 1998	Eastern Electricity Embedded Generation Project: Scenario Simulation Process, Method and Software Description.
EME/EP/TR/1999-001	Feb 1999	East Midlands 132/11kV Network Design Study: Boston-Sleaford Area.
CEPE/PSMS/TS/1999-001	Jan 1999	Integrated Embedded Generation Analysis Research Project: High-Level Model Specification.
CEPE/PSMS/TS/1999-002	Feb 1999	Integrated Embedded Generation Analysis Research Project: High-Level Model Data Schedule.

Report Reference	DATE	Title
CEPE/PSMS/TS/1999-003	Mar 1999	Integrated Embedded Generation Analysis Research Project: Economic Model Specification.
CEPE/PSMS/TS/1999-004	Apr 1999	Integrated Embedded Generation Analysis Research Project: Distribution Price Control Mechanism.
CEPE/PSMS/TS/1999-005	Jun 1999	Integrated Embedded Generation Analysis Research Project: Planning Methodologies Review.
CEPE/PSMS/TS/1999-006	Jul 1999	Integrated Embedded Generation Analysis Research Project: High-Level Model Options.
CEPE/PSMS/TR/1999-007	Sep 1999	Integrated Embedded Generation Analysis Research Project: Scenario Identification for Case Study.
CEPE/PSMS/TS/1999-008	Jul 1999	Integrated Embedded Generation Analysis Research Project: Case Study Definition.
CEPE/PSMS/TR/1999-009	Nov 1999	Integrated Embedded Generation Analysis Research Project: Consolidated Issue Set for Distributed Generation in the United Kingdom.
CEPE/PSMS/TR/1999-010	Nov 1999	Integrated Embedded Generation Analysis Research Project: Financial Model Review.
CEPE/PSMS/TR/1999-011		Integrated Embedded Generation Analysis Research Project: Reference Utility Definition.
CEPE/PSMS/TR/1999-012	Dec 1999	Integrated Embedded Generation Analysis Research Project: Review of Results of 1st Iteration of Loch Case Study.
CEPE/PSMS/TR/2000-001	Jan 2000	Integrated Embedded Generation Analysis Research Project: Financial Analysis Results.
CEPE/PSMS/TR/2000-002	May 2000	Distributed Generation Strategic Analysis Research Project: Construction, Simulation and Analysis of Distributed Generation Scenarios.

Table 1-1: Published reports by the author relating to distributed generation analysis and planning.

In addition to published papers and reports, the author has made numerous invited presentations relating to the work of this thesis to commercial and governmental organisations:

- Scottish Power Technology
- National Grid Company
- Rolls-Royce
- GE-Harris
- Scottish Executive
- East Midlands Electricity
- Eastern Electricity
- Norweb
- Scottish Power - Power Systems
- ICL

1.6 Chapter 1 References

Andrews, C.J. (1990) *Improving the Analytics of Open Planning Processes: Scenario-based Multiple Attribute Tradeoff Analysis for Regional Electric Power Planning* [Doctor of Philosophy Thesis], Massachusetts Institute of Technology, Boston, USA.

Berrie, T.W. (1992) *Electricity Economics and Planning*, 1st Ed., Peter Peregrinus Ltd. (IEE), London.

Dugan, R.C., McDermott, T.E., and Roettger, W.C. (1999) "Distribution Planning with Distributed Generation", *Proceedings of the 4th Annual IEEE Latin American Power Conference*, pp. 35-44, 1999.

Fairey, T.G., and Redfern, M.A. (1996) "The Implications of Connecting Embedded Generation to an Electricity Utility Supply Network", *Proceedings of the 31st Universities Power Engineering Conference (UPEC96)* vol. 3, pp. 824-827, 1996.

Institution of Electrical Engineers (1996) "The impact of embedded generation on distribution networks". Colloquium Digest No. 1996/191, October 1996.

Kim, J.O., Nam, S.W., Park, S.K., and Singh, C. (1998) "Dispersed generation planning using improved Hereford ranch algorithm", *Electric Power Systems Research* vol. 47, (no. 1), pp. 47-55, 1998.

Nishiya, K., Kita, H., Hasegawa, J., Haga, Y., Minagawa, K., Simazu, K., and Nakamura, H. (1995) "Optimal Planning for Introducing Dispresed Generating Sources in Power Systems Based on an Economical Viewpoint", *Electrical Engineering in Japan* vol. 115, (no. 8), pp. 68-81, 1995.

Redmond, J.A. (1994) *Planning, Trading and Competitive Issues Arising Within the U.K. Privatised Power Industry* [Doctor of Philosophy Thesis], University of Strathclyde, Glasgow.

Seitz, T., Haubrich, H.J., and Schweer, A. (1997) "Structural design of medium-voltage networks considering dispersed generation", *Proceedings of CIRED 1997* vol. 6, pp. 6.3.1-6.3.5, 1997.

Weinberg, C.J., Iannucci, J.J., and Reading, M.M. (1991) "The Distributed Utility: Technology, Customer, and Public Policy Changes Shaping the Electrical Utility of Tomorrow", *Energy Systems and Policy* vol. 15, pp. 307-322, 1991.

Willis, H.L., and Scott, W.G. (1994) "Advanced Engineering Methods for Optimizing and Integrating Distribution Planning with Demand-Side Management and Dispersed Generation", *Proceedings of the 38th IEEE Rural Electric Power Conference* vol. Cat. 94CH3362-1, pp. A1-1 to A1-9, 1994.

Chapter 2

THE CHANGING ELECTRICITY SUPPLY INDUSTRY IN THE UNITED KINGDOM

2.1 Summary of Chapter 2

This chapter establishes the recent fundamental changes in the electricity industry in the UK which have provided a springboard for growth in distributed generation. The changes in industry structure, ownership and regulation have resulted in major forces influencing the distribution function of the electricity supply chain. This chapter outlines how these drivers, plus a number of other legislative and technological innovations created the foundations for the growth in distributed experienced to date and the further growth now expected. Specific mention is made of the effects of restructuring and regulation on the now private distribution companies as it is from a distribution perspective that distributed generation will be analysed in later chapters.

The three main drivers of distributed generation growth are: the ongoing process of electricity industry restructuring including competition and the introduction of regulation; environmental concerns and accompanying legislation, and; advanced in distributed generation technologies. These three drivers have combined to form an ideal foundation for growth of distributed generation.

Introduction to these three areas forms the background to further discussions of the potential effects of distributed generation and requirements for new distribution planning techniques as developed in later chapters of this thesis.

2.2 Electricity Industry Restructuring

The Electricity Act of 1989 ushered in a new era for the electricity supply industry in the UK. The majority of the industry was transferred from public ownership to private ownership on 'vesting day' in April 1990. Simultaneously, competition was introduced into the wholesale market for electricity through the creation of the Electricity Pool. An electricity regulator was established to oversee the transition to full competition of some areas of the industry while overseeing the activities of the natural monopoly areas of the industry on an ongoing basis. Similar transitions from public to private ownership and from integrated to unbundled structure were also occurring on the international stage at around the same time.

The objectives of the electricity supply industry restructuring in the UK were numerous and often conflicting which resulted in a less than optimal transition from state owned monopoly to private enterprise. The main objectives of the government in electricity industry restructuring in the UK were to:

- Remove capital burden for large scale electricity industry investments from government
- Raise money for the Treasury
- Enhance efficiency in the electricity supply industry through the rigours of the private capital markets
- Reduce the power of the coal mining industry
- Reduce the end price of electricity for consumers
- Enhance the general performance of the electricity industry
- Provide the path to privatisation to enhance political popularity

The conflicts between objectives resulted in some major flaws in the new industry structure which continue now to receive attention. In one sense, however, it is unfair to apportion blame for the deficient areas of electricity industry structure since the restructuring process was nothing short of a government experiment on a massive scale.

Many other countries have also pursued electricity industry restructuring within the same general time-scales as the UK. Australia and New Zealand, for example, initiated ESI restructuring programmes shortly after the UK but each have adopted different models for industry structure based on mixes of ownership and unbundling of generation, transmission and distribution. The US has adopted a state by state approach to restructuring with some states (such as California) moving quickly to full wholesale competition in generation and retail competition in supply. The European Union (EU) passed a directive in 1997 to obligate each member country to open the retail market in supply to competition for larger customers. Many countries, such as Germany, have taken the opportunity to go much further than the EU directive dictates, restructuring their electricity market to enable full competition in the wholesale market and the retail market while moving the utility companies into private ownership.

Since 1990 the electricity supply industry has been in a constant state of flux with further restructuring activity, increased corporate activity in take-overs, mergers and acquisitions, continued high levels of regulatory intervention and the transition to full competition of the retail electricity market amongst other areas.

Figure 2-1 illustrates the states of the electricity industry before 1990 and then immediately after 1990 with some of the recent changes lumped together under the heading Post Utilities Bill/ Post 1998. 1998 was the year of transition to full retail competition whereby twenty three million customers in the UK could choose their supply company rather than be bound to the local distribution and supply company.

	Pre-1990	Post-1990	Post-Utilities Bill Post-1998
GENERATION	CEGB	GenCos	GenCos
TRANSMISSION	CEGB	NGC	NGC (TO)
DISTRIBUTION	Area Boards	REC	DNOs
SUPPLY	Area Boards	REC	SupplyCos

Figure 2-1: Changing structure of the Electricity Supply Industry in the UK.

A number of new entities have been created in the UK electricity supply industry (as they have been elsewhere in the world). Two major generation companies were formed (National Power and PowerGen) in 1990 which inherited the majority of the non-nuclear generation plant of the Central Electricity Generating Board (CEGB). The more modern nuclear plant was floated privately some years later as Nuclear Electric and Scottish Nuclear Limited. The older nuclear plant remains in government hands to this day under the banner of Magnox Electric. Many new independent generation companies have entered the market since 1990 raising the level of competition in the wholesale market although this has not had the expected result of lower end use prices and higher levels of service. An increasing number of the new generation stations are connected not to the transmission system but to the distribution system. This so-called 'distributed generation' will be discussed in more detail in section 2.4 and is the focus of the ideas developed in this thesis.

The transmission system in England and Wales moved into the ownership of twelve Regional Electricity Companies (RECs) in 1990 as an interim measure until the National Grid Company (NGC) gained autonomous status in 1995. NGC own and operate the transmission system and also undertake the operation of the electricity market system (The Electricity Pool).

The Area Boards who distributed electricity from transmission system to consumers and also retailed (supplied) the electricity to consumers maintained their regional natural monopoly franchises and moved from state to private ownership in 1990. The electricity retail markets in each area have been progressively opened to competition with the 1MW (annual peak demand greater than 1MW) market opening to external competition in 1990, the 100kW market opening to external competition in 1994 and the full retail market (including the smallest domestic consumers) opening to competition during 1998 and 1999 as the RECs commissioned new systems to cope with very large numbers of customers.

The Utilities Bill, which is being heard in parliament as this thesis is being written, enshrines the concept of separation of natural monopoly and competitive business areas in the electricity supply industry. The owner-operators of transmission and distribution systems cannot own generation in their own franchise area except with strict measures in place (so-called 'Chinese walls') to stop collusion or cross subsidy between competitive and natural monopoly business areas. This has resulted in many RECs selling their retail businesses to third parties and concentrating on the business of electricity distribution. The term distribution network operators (DNOs) is now commonly used to describe the distribution only players. As this thesis is written two major supply business sales have been announced, one by Norweb who is selling its retail business, Energi to Texas Utilities (TXU) of the US and the other by British Energy who are selling their SWALEC electricity supply business to Scottish & Southern Energy.

In an article that assesses the results of the restructuring of the electricity supply industry in the UK John Casazza outlines changes arising from three key areas of the restructuring process (Casazza, 1997):

1. privatisation
2. competition
3. regulation

The following trends have emerged in the electricity industry since the restructuring in 1990 and are attributed to the process of privatisation:

- increased tariffs
- sale of public assets at low prices
- use of coal gradually reduced
- reduction of utility staff levels
- improved management remuneration and morale

- increased attention to customer concerns
- increased cost of capital due to higher risks of lending to private utilities
- new tax revenues from private utilities
- evolution of subsidies mechanisms for utility companies

This assessment suggests that the outcomes from the privatisation process have been a mix of positive and negative. The mixed results arising from privatisation (and other aspects of restructuring) have been one of the key factors in ensuring that restructuring has become an ongoing process in the UK rather than a *fait accompli.*

Many commentators have commented that the only certainty in the electricity supply industry in the UK at present is change itself (with reference to the ever-changing structure and modes of operation of the industry). The process of change initiated by the initial stimulus in 1990 has continued to move apace. Since 1990 the ownership of many of the private electricity utility companies has changed. Both East Midlands Electricity and also Eastern Electricity have had two owners since their initial flotation into the hands of public shareholders. East Midlands Electricity was first taken over by Dominion Resources of the US before being bought by PowerGen, the large UK generator. Eastern Electricity was initially taken over by Hanson, the UK-US conglomerate, before being bought by Texas Utilities (TXU) of the US. In addition to general ownership changes, the industry has become more fragmented due to the unbundling of many of the services traditionally found in the same company while at the same time becoming more consolidated in some areas. For example, the function of distribution, meter operations, electrical contracting, electricity supply and electrical equipment retailing (e.g. domestic 'white goods') were all undertaken by the pre-1990 Area Boards but are now often owned by as many separate companies. On the other side of the coin, specialists have appeared in some areas, consolidated around one or more electricity supply chain functions and gained market share across a wide geographical area. Electricity supply is one example of this type of consolidation with a smaller number of serious players (e.g. Texas Utilities/Eastern Electricity and Scottish Power) acquiring greater market share through a variety of strategies. Others, who have failed to achieve a nominal critical mass, have been forced out of the supply market.

In addition to ownership and unbundling, Regulation also continues to evolve with new measures continually being brought into force to elicit the required behaviour from the industry participants. One stated aim of regulation in the UK electricity industry is to introduce competition wherever possible within the electricity supply chain. In general, competitive forces (in the ideal case) improve performance and create downward pressure on prices towards the marginal cost of production. If the ideal competitive market produces the optimal economic outcome then it is sensible to aim to introduce competition wherever possible. The electricity regulator in the UK (now called the Office of Gas and Electricity Markets or OFGEM) has introduced competition in the wholesale and retail electricity markets thus forcing generators and supply companies, respectively, to compete with each other. Competition has also been introduced in a number of other minor areas within the electricity supply chain such as meter reading and network construction.

The introduction of competition has resulted in a number of changes in the UK electricity market (Casazza, 1997):

- unbundling of generation and transmission into separate businesses
- formation of the Electricity Pool
- removal of costs basis for wholesale power
- merit order dispatch based on bid prices from generators
- generators paid at market clearing price
- shift to natural gas fired generation technologies
- open access to the transmission system
- retail competition introduced in stages
- no central planning
- financial derivatives to reallocate risks in volatile wholesale electricity market

Competition cannot be introduced effectively (or economically) in the natural monopoly areas of transmission and distribution. Mechanisms have had to be designed to regulate the natural monopoly activities in such a way that monopoly power is not exercised to the detriment of consumers or other industry players. The remaining natural monopoly players in the UK industry are the transmission and distribution network operators.

The general mechanism for regulating the natural monopoly areas of the industry is through a price control mechanism. Through this mechanism the aggregate revenues collected by natural monopoly companies are limited to a rise in line with the retail price index (RPI) minus a factor which reflects the view of the electricity regulator on the scope for efficiencies leading to price reductions. If the monopoly companies perform better than the regulator's assumption on efficiency gains, then the companies make more profits and if the companies do not produce efficiency gains in line with the regulator's assumptions then their profits reduce. In this manner the natural monopoly companies are provided with financial incentives to become more efficient as would be the case if they were subject to competition. The price control mechanism is discussed further as it applies to distribution (section 2.2.1).

When competition or price control regulation is deemed to be insufficient to produce efficiencies within the electricity industry then more serious measures are required to elicit the desired responses from participants. This form of structural regulation has been witnessed in the UK electricity industry in recent years.

The most striking recent case of major structural changes in the electricity industry initiated by OFGEM is the revision of the electricity trading arrangements. In 1998, OFGEM, in response to perceived deficiencies in the Electricity Pool system for trading electrical energy, published a review of possible revisions to the electricity trading arrangements (Office of Electricity Regulation, 1998). The reviews of the Pool system highlighted a number of serious defects in the Pool as an open competitive market system and proposed a restructuring of the electricity market to move it into line with trading arrangements for many other commodity products. Within a relatively short period of time the electricity trading arrangements have been revolutionised in response to the call of the regulator. This is prime example of the sort of structural regulation which has continued since the initial round of restructuring in 1990.

This section has discussed several aspects of restructuring, competition and regulation with many more aspects omitted. The message from all of this is that the electricity industry in the UK is now a highly dynamic arena where individual players vie for competitive edge. Throughout the opening chapters of this thesis it will be shown that distributed generation is becoming one of the fastest growing areas in the electricity industry with many accompanying challenges and opportunities. In part the impetus for growth in distributed generation has come from industry restructuring and competitive forces. Other than the obligation for distribution companies to be impartial towards distributed generators, no regulatory measures have yet been taken for or against distributed generation. The experience of recent years has shown that where the regulator believes that some measure could act for the good of competition, and by implication for the good of customers also, then new regulations or guidelines have been introduced quickly and forcefully. Given the many benefots of distributed generation, the coming years may see even more drive for distributed generation through some direct regulatory measure.

2.2.1 Electricity Distribution

Distribution has been unbundled from the other activities in the electricity supply chain and the Utilities Bill which is progressing through the UK Parliament at present will secure the concept of the distribution company as a natural monopoly service provider. In this role the distribution company will be obliged to offer transparent and non-discriminatory access to their distribution network for any licensed party. Licensed parties include generators and supply companies. Supply companies will use the distribution network for the purpose of transporting electrical energy bought on the wholesale market for sale to customers at load points (also known as distribution system exit points). Generators will sell electrical energy to supply companies at point of generation connection to the distribution system. Many other variations on these two basic modes of use of the distribution network are possible with the main differences being in the commercial arrangements regarding purchasing and selling electrical energy.

The distribution company receives regulatory controlled revenues for the provision of basic distribution services which are delivered within strict technical regulations. The allowed revenue for the provision of these services is based on a price control formula which is linked to the retail price index. The regulatory price control formula for a UK distribution company is shown in Equation 2-1.

$$M_{dt} = \frac{\left(1 + \frac{\mathrm{RPI}_t + \mathrm{X}_d}{100}\right)}{D_t}\left\{\left(\mathrm{P}_{ut-1} + \mathrm{P}_{mt-1}\right) \times 0.5 \times \left(\frac{\sum P_{0i} D_{it}}{\sum P_{0i} D_{it-1}} + \frac{\mathrm{C}_t}{\mathrm{C}_{t-1}}\right) + \mathrm{P}_{Lt-1}\left(AL_t - \mathrm{L}_t\right)\right\} - \mathrm{K}_{dt}$$

Equation 2-1

Where the symbols represent parameters as follows,

M_{dt}	is the maximum allowable distribution revenue per unit distributed in year *t*.
RPI_{t-1}	is the average of the annual inflation rates in July to December of the previous year.
D_t	is the quantity of units distributed in year *t*.
C_t	is the number of customers in year *t*.
AL_t and L_t	are the allowed and actual distribution losses.

K_t is the correction factor for under- or over-recovery of revenue in previous years.

X_d is the distribution X factor as set by the regulator.

P_{ut} and P_{mt} are factors representing allowances for non-distribution business areas.

P_{0i} is the base price for customer type *i*.

P_{Lt} is the base price for losses.

$_t$ and $_{t-1}$ are the subscripts denoting the year.

The price control formula for distribution and the revenue which it controls is one of two major influences on distribution profitability. The level of costs incurred by the distribution company is the other major factor influencing profitability. Incidentally the regulator has influence over expenditure through approvals for expenditure plans.

OFGEM controls the total regulated revenue (effectively the product of M_{dt} and D_t) through the setting of a number of base prices and factors (P_{ut} , P_{mt} , P_{0i} and P_{Lt}) and the distribution price control factor, X_d . Table 2-1 shows the range of X factors for the fourteen mainland UK distribution companies from the year 1995 to 2000. The general level of reductions in distribution revenues can be clearly seen with each of the distribution companies requiring to reduce their regulated revenue by 11% to 17% in 1995/96, 10% to 13% in 1996/97 and by 3% in each year thereafter.

Financial Year	X factor (range for individual RECs)
1995/96	- 11 to - 17 %
1996/97	- 10 to - 13 %
1997/98	- 3 %
1998/99	- 3 %
1999/2000	- 3 %

Table 2-1: X factors for UK distribution companies from 1995 to 2000.

There is continuous pressure on the distribution companies to reduce the costs of operating and investing in the distribution networks. The topic of distributed generation will be discussed at greater length later in this chapter but a number of important issues are raised from the price control formula in consideration of distributed generation. For example, if there is a substantial shift to on-site generation, where a consumer generates some or all of their own electrical energy requirements, then the number of units of energy transported through the network will reduce. This will result in reduced regulated revenue according to the price control formula. If distributed generation results in further reductions in losses in the distribution network then there may be a premium for the distribution company through the losses term in the price control formula.

The effects of electricity industry restructuring on distribution planning are discussed by Van Geert (Van Geert, 1997). Distribution utility relations with customers will evolve with the distribution company becoming more accountable to the ever increasing customer expectations for a high quality supply. The ageing of distribution assets works against the need for ever increasing quality of supply and overcoming the problems associated with the age profile of distribution assets is viewed as one of the major challenges for distribution planners. Van Geert also predicts that uncertainty is likely to grow as restructuring continues and while distribution companies are used to operating in an environment of uncertainty, the levels and diversity of uncertainty will be unprecedented. Against this backdrop Van Geert discusses the growth of distributed generation. These themes of restructuring, distribution planning, uncertainty, network performance and distributed generation will be evident throughout this thesis.

In the recent distribution price control review (Office of Gas and Electricity Markets, 1999), the electricity regulator introduced some comparison of performance between distribution companies and provided rewards for the better performing companies and penalties for the poorer performing companies. The rewards and penalties were provided through raising and lowering the X factor for each company according to their performance in a number of categories. More recently, the electricity regulator (under the banner of the Information and Incentives Project) has been assessing the possibility of making much closer and more consistent links between allowed revenue and a number of measures of performance including comparison to other utility companies operating in similar circumstances. The purpose of a 'yardstick' approach to regulation is to not only provide incentives for financial efficiency, as exist with the present price control formula arrangement, but to provide incentives for better performance.

In summary, after several of years of changing distribution structure and regulation, one would have to note that the consequences of failing to achieve certain standards of financial and physical performance from distribution activities are growing more serious. The pace of change and the level of uncertainty within electricity distribution seem to be increasing. Distributed generation may be just another difficult issue to deal with within already very tight budgets or it may provide opportunities to perform well with the right strategies in place.

2.3 Environmental Concerns and Legislation

The effects of emissions from industrial related activities on the natural environment have become much more apparent in recent years. The harmful effects of acidic gases on flora and fauna followed by the effects on local air quality and respiratory health of certain other gaseous and particulate emissions followed by the effects of greenhouse gases on the global climate have come to light in recent years. These three effects are mainly continental, regional and global in scope respectively. The side effects of man's industrious developments are becoming clearer as the body of scientific evidence grows to show the detrimental effects of industrialisation.

Electricity generation is a major contributor to the production of emissions affecting air quality, acid rain and greenhouse gases. The advances in the understanding of the mechanisms of damage done through emissions from industrial activities has been accompanied by a growing body of environmentally related regulation and legislation in many countries. The measures adopted include the control of oxides of nitrogen through combustion adaptations and the control of oxides of sulphur through scrubbing of fuels and filtering of power plant emissions. These are in effect 'micro' measures to control the harmful effects of electricity generation.

At a higher 'macro' level, national governments and international trade groups have put policies in place to encourage the development of power generation technologies which will be less harmful to the regional, national, international and global environment. Key advances under these programmes have been the advances in Dry Low Nox (DLN) to reduce the production of oxides of nitrogen through high temperature combustion in air as found in gas turbines and the raft of environmentally oriented policies relating to climate change. The UK Climate Change programme includes measures to enable the UK to meet carbon emissions targets (the major greenhouse gas) which have been set within the Kyoto framework. Reductions in carbon emissions are to be realised through renewable technologies and the more efficient use of energy in combined heat and power schemes. A major portion of the target for carbon emission reductions in the UK has come from the use of natural gas instead of coal as the predominant power generation fuel. Natural gas produces far better carbon emission performance than coal due to its basic molecular composition and structure.

The UK government has set various targets for renewable and new energy technologies to address the need for carbon emission reductions. A target of 10% of UK electricity (in terms of energy) to be produced from renewable sources by the year 2010 is one of the major targets underpinning the policies to encourage renewable generation development. One further target for combined heat and power generation is to have 10GW (electric) installed capacity also by the year 2010. The current total installed capacity of CHP is somewhere around 4GW while the total energy produced from renewables at present is less than 2%.

A proportion of the growth in installed capacity in renewables and CHP will be in smaller units sizes and connected to the distribution networks as distributed generation. It is evident, therefore, that environmental concerns and accompanying legislation have produced an important stimulus to the continuing growth of distributed generation.

2.4 Distributed Generation

The previous sections have discussed the changes in electricity industry structure, the creation of a more competitive environment, the effect and pressures from regulation and the effects of a growing awareness of man's effect on the environment and the legislation and government policy that it has spawned. Each of these areas of major change in the electricity industry has contributed to an environment which stimulates the growth of distributed generation.

Restructuring has provided the framework of unbundled and regulated distribution companies with an obligation to offer fair and transparent terms of access to the distribution network for generation developers. Where before 1983 and the Energy Act there was no access for independent generators to the electricity network, after 1983 access to the electricity network was partially enabled. However, the terms of purchase for independent generation export were so poor that few independent generation schemes were initiated in this period. The Electricity Act of 1989 and the subsequent restructuring of the electricity industry, begun in 1990, provided the impetus for the development of new independent generation schemes. The liberalisation of access to natural gas as a generation fuel coincided with restructuring in 1990 and provided the ideal inexpensive fuel for independent generators to challenge the dominance of nuclear and coal fired generation owned by the dominant generators PowerGen, National Power and Nuclear Electric. Thus the restructuring process has provided an environment for the growth of distributed generation.

Competition has facilitated the entry of many new players to the electricity industry and both generation developers and new unbundled supply companies have used distributed generation as an opportunity to build their position. Distributed generation can be viewed as an energy trading option (see section 5.5.1.1) to support a supply business in a particular area of the country while it can also be viewed as a way of larger generators building a portfolio of generation in a different area within the market. International expansion of generation portfolios has also been a part of this strategy of diversification for the larger generating companies.

Regulation has also played its part in the growth of distributed generation. Regional Electricity Companies or RECs (the combined distribution and supply businesses which existed until 1998) while constrained in the direct ownership of distributed generation in their own franchise area sought means of expanding their non-regulated revenues. Distributed generation was one way of achieving such non-regulated business expansion. Also, the electricity regulator has looked on distributed generation as a means of providing a greater level of competition and has taken some small steps to pointing out the benefits of smaller scale generation (Thomas, 1996) to the point of offering easements to the stringent connection requirements to enable some smaller schemes to proceed.

The environmental benefits of some renewable generation technologies are relatively obvious and have been described in section 2.3. Several government policies are in place to promote the development of more renewable generation (Department of Trade and Industry, 1998). Renewable generation units are usually small in size and connected to the distribution network and thus contribute to the present portfolio and future prospects for distributed generation.

Two subsections below provide further evidence to suggest that continued growth in distributed generation is likely. Section 2.4.1 discusses the status and prospects for many distributed generation technologies, some of which are believed to offer high prospect now and in the future. Section 2.4.2 discusses some of the roles that distributed generation can fulfil. The diversity of functionality of distributed generation is one more reason for speculating that they will grow in numbers and in importance in the coming years.

2.4.1 Distributed Generation Technology

On of the key growth drivers for distributed generation has been the development of generation technology at small scale. The relatively inexpensive nature of small generation units of some types along with a perceived exhaustion of the economies of scale of larger (mainly steam based) units has renewed the focus on generating units in smaller packages. This section simply lays down the broad front over which generation technologies are developing from research concept all the way through to mature economic options for electricity generation.

General definitions of distributed generation (and 'embedded' or 'dispersed' generation) are presented in section 3.2. These definitions made no attempt to prescribe any generation technology or energy source to the general term 'distributed generation'. Likewise, the role or mission of distributed generation (2.4.2) does not influence its categorisation under the general heading 'distributed generation'. This section discusses the wide variety of existing generation technologies and also emerging or developmental technologies that may be referred to distributed generation.

The UK Government Department of Trade and Industry (DTI) regularly survey the state of 'new and renewable energy' for the purposes of developing government support programmes for technology development and exploitation in the UK (Department of Trade and Industry, 1999).

Existing distributed generation technologies which display mature technology characteristics include:

- diesel
- gas turbine
- small scale oil and coal

Newer technologies that are either undergoing extensive development or are already in commercial operation in smaller scale units and in small numbers include:

- active solar
- agricultural and forestry waste combustion
- energy crops (biomass)
- fuel cell
- hydro power
- landfill gas
- municipal solid waste combustion
- passive solar
- photovoltaic
- tidal stream
- wave power
- wind power (onshore and offshore)

Other technologies which the DTI believe are unlikely to be deployed in the UK at any meaningful scale in the imminent future include:

- large hydro
- solar thermal
- tidal barrage
- geothermal aquifers
- geothermal hot dry rock
- photoconversion
- ocean thermal
- hydrogen energy carrier

The lists of distributed generation technologies presented above illustrate the diversity of energy sources and methods of conversion for electricity production.

The potential changes in the mix of generation connected to future power systems are vast. Not only is it likely that there will be greater numbers of generating units connected to power systems but these generators will be based on a far wider range of energy sources and will also present greater diversity in electrical characteristics.

The underlying energy sources will present new degrees of uncertainty (and predictability) in availability, from hourly fluctuating energy sources such as wind and waves to daily fluctuating sources such as solar and tidal and seasonally fluctuating sources such as biomass (and again solar and wind). The electrical characteristics of these generating units will vary from synchronous generating units (as used with gas turbines) to induction generators commonly used with wind turbines and other smaller technologies, and dc-ac conversion in such energy sources as fuel cells and photovoltaic units.

As noted, the characteristics of different generation mixes could be highly variable and likely to result in additional complexity in many of the activities undertaken by distribution network operators. This additional complexity is due to the effects of distributed generation from planning and design through operational planning and maintenance to scheduling and control of generation and even on to electromagnetic phenomena and the requirements for system protection. Each of these areas is discussed in more detail in chapter 3.

The effects of different generation technologies on the power system are highly variable and, in part, dependent on the generation technology utilised. So as well as being a key driver for distributed generation in general, generation technology is also one of the key factors influencing the effect on the electrical system.

2.4.2 Roles and Missions of Distributed Generation

The attractiveness of distributed generation has many facets depending on ownership of the generation, intended function or mission or some unique feature of the technology which can be exploited. The subsections below describe the main roles or missions of distributed generation in the UK electricity market.

2.4.2.1 Merchant Power

One mission for distributed generation is merchant power production for trading in the national electricity market. In this case, the generation developer attains project feasibility on the basis of the revenues accruing from the sale of energy alone. Typically natural gas fired engines or turbines are the most attractive technologies in this mission.

Vertically integrated utilities often find investment in modular technologies in smaller packages attractive from the point of view of not committing to large generation projects with the accompanying capital requirement when the load in any area is simply incrementing each year. Investment in smaller technologies can be made to match the annual load increase while simultaneously yielding other distributed generation benefits such as network support or reduced electrical losses. The issue of smaller modular technologies is discussed in relation to investment risk in section 3.3.1.5.

2.4.2.2 Renewables

The legislation aimed at promoting development of more environmentally benign generation technology has produced a major stimulus for renewable generation, as discussed in section 2.3. The chief mechanism for promoting renewables has been the Non Fossil Fuel Obligation (NFFO) programme under which a levy is collected for all electricity supplied from fossil fuel generation with the funds raised subsequently used to support renewable generation schemes. A report on the fifth round of the NFFO programme (Department of Trade and Industry, 1998) shows the rates guaranteed for producers of renewable power and the reductions achieved through the preceding four rounds of NFFO. By June 1998 nearly 500MW of additional renewable generation had begun generating under the NFFO schemes. As noted, each successive round of NFFO contracts under the five schemes produced a reduction in the guaranteed prices contracted with generation developers showing that the technologies were maturing with some technologies nearing competitiveness without subsidy.

It could be said that many distributed generation projects have the objective of exploiting favourable guaranteed prices for renewable generation through government schemes. In addition, a premium for 'green' electricity has emerged in electricity retail. Electricity suppliers have marketed schemes to support renewable generation development through premiums of up to 10% added to customers' electricity tariffs. The additional revenue generated is channelled into renewable generation development. This adds a further incentive to renewables developers to exploit the favourable public image of renewable generation.

2.4.2.3 Peaking plant

Industrial customers, and especially those who are intensive energy users, often utilise load management opportunities to manage their exposure to the wholesale electricity price or as part of an agreement with their supplier. It is becoming increasingly common to find on-site generation as an integral part of on-site energy management strategy. The use of peaking plant to reduce the grid import (or opportunistically export) energy at peak price periods is alternatively termed peak lopping or peak shaving (Hodgkinson, 1998).

The most transparent means of remuneration for peak reduction comes to the energy retailer who is subject to lower transmission use of system charges through a reduced annual peak demand on the transmission system. The transmission use of system charges are levied in accordance with geographical location of load demand and the magnitude of peak demand placed on the grid supply point groups in that area (averaged over three peak periods each separated by more than ten days). The charges for transmission use of system can be very steep with demand charged at £16.39 per kW peak load in 1998/99 in one charging zone (National Grid Company plc, 1998). Distributed generation offers an energy retailer the opportunity to supply energy to customers in a particular area while reducing exposure to transmission use of system charges.

The effects of peak reduction on the distribution company are discussed in section 3.3.1.2.

2.4.2.4 Combined Heat and Power (CHP)

Combined Heat and Power (CHP) has become the most common form of on-site power generation in Britain and the number of units continues to grow in line with governmental targets (Department of the Environment (UK), 1996). The many benefits of combined heat and power, particularly where based on gas turbine technology, are well known;

- Reduced energy purchase costs for facility owner
- High utilisation of fuel energy content
- Reduced polluting emissions per unit of electricity
- Flexibility of operation

In summary the benefits of combined heat and power arise from the favourable economics of gas turbine technology, an on-site requirement for heat and steam, and the reduced environmental impact of energy production. There are, however, a number of risks with CHP schemes including those arising from fuel input and electricity output prices (Burdon, 1994).

Many combined heat and power units are relatively small in capacity and are thus connected to distribution networks. They are the most prevalent type of distributed power generation in the UK at present.

2.4.2.5 Network alternative or network support

Distributed generation can be installed by a distribution utility specifically to support the network (subject to there being no restrictions on ownership of generation within its own distribution network). An extensive research programme has been undertaken by the Pacific Gas and Electric Company (PG&E) to assess the prospects and value of distributed generation in this role (Wenger and Hoff, 1995). The specific intention of the demonstration photovoltaic plant built at Kerman was to understand the interaction of the generating unit with the power network and to quantify the grid-support benefits.

The areas of grid-support identified are:

- Reliability enhancement
- Loss savings
- Feeder conductor upgrade deferral
- Substation transformer replacement and maintenance deferral
- Transmission capacity deferral

A number of other benefits have been included in this evaluation including emissions abatement, transmission connected peak lopping generation costs and energy savings at transmission connected generating plant. The total value of all these benefits has been calculated in the range $295 to $425 per kilowatt installed. The grid support benefit value alone (bulleted list above) is estimated at $80 to $155 per kilowatt installed. The drive to install distributed generation to support the electrical network is not very strong at present but has enormous potential in future years and may become one of the key drivers of distributed generation.

2.4.2.6 Standby generation

One traditional role for small-scale distribution level generation has been the provision of standby or backup generation for critical loads such as financial centres, public buildings and hospitals. This class of generators has normally remained idle until the utility supply to the site fails at which point they generally operate isolated from the utility system. The main objective for the generation is to provide higher levels of supply security.

However, the high electricity prices at peak load periods have persuaded some owners of emergency generation (with the encouragement of some supply companies) to operate in parallel with the utility network and export power when financially beneficial. Standby generation can also provide reserve and other ancillary services (O'Kane et al, 1999) to the power system given appropriate contractual terms with the distribution and transmission system operators. Thus, the traditional boundary of standby and utility connected generation has blurred slightly although the equipment requirements for parallel and non-parallel operation remain distinct.

2.5 Review of Chapter 2

This chapter has introduced only a selection of the changes in the electricity supply industry in the UK for the purposes of setting the background for the recent growth and potential for more growth in distributed generation. The combined forces of restructuring, competition, regulation, environmental concerns and generation technology development have created an environment for further growth in the numbers and diversity of distributed generation connected to the distribution networks of the UK distribution companies.

Many views could be taken of the distributed generation field such as the generation developer perspective or the central government legislator and policy developer. One of the most interesting viewpoints from which to study distributed generation is from the natural monopoly distribution company. Being barred from having direct ownership of distributed generation within their own network and being obliged to offer open access to independent generation developers to the same network creates a unique set of problems for distribution network operators. Distributed generation produces a high level of uncertainty for distribution network operators as the distribution network and business must be planned for shifting future needs but where capital investments generally have very long lives. The contrast is clear between the long term planning problem for distribution companies to very short lead-time generation projects sited at the developer's preference and operating to a uncontrolled schedule. The planning problems for distribution network operators are already numerous but the problems look as if they will only increase as greater numbers of distributed generating units appear in distribution networks.

The United Kingdom electricity market place is taken as the focus for the arguments and techniques developed in this thesis. The electricity distribution function is performed by private companies who have the franchise (by licence) to distribute electricity in a geographical zone. Due to the natural monopoly characteristics of electricity distribution, the private distribution companies are regulated by a state instituted Regulator. To ensure fair and open access to the distribution networks, the distribution companies are neither allowed to be the final supplier of electricity to consumers or to be the providers of electricity into the network as generation owners. Distributed generation is independently owned and operated within the regulated distribution systems. However, many of the arguments and methods presented in this thesis can be generalised to other national electricity markets and also to other planning problems than distributed generation.

2.6 Chapter 2 References

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Chapter 3

DISTRIBUTED GENERATION

3.1 Summary of Chapter 3

This chapter identifies, categorises and discusses the plethora of issues relating to distributed generation. It becomes evident that the sheer volume of issues, added to their complexity, makes rational quantitative assessment of the impact of distributed generation on distribution networks and businesses a difficult task indeed. The presentation of distributed generation issues is followed (section 3.4) by brief comments and queries regarding how the issues can be analysed and how the structuring of the issue set can assist this process.

3.2 Distributed Generation Definitions

Distributed generation has received much attention in the literature in the latter 1990s. Three different terms for distributed generation have found popular appeal in this period. Within these three terms, a plethora of different definitions for distributed generation have appeared.

'Distributed generation' is the term stemming from the United States of America and finding usage world-wide. Distributed generation is variously defined as small (typical capacity of 1 to 25MW) and located in areas of high load growth or where transmission capacity is constrained (Booras et al, 1996). An alternative definition of distributed generation is *'the integrated or stand-alone use of small, modular electric generation close to the point of consumption'* (Arthur D. Little, 1999).

'Dispersed generation' is the European term for small scale generation (*'from a few kilowatts to dozens of megawatts'*) located close to consumption centres and connected to distribution networks (Hadjsaid et al, 1999). Some definitions take a more bullish approach to location and note that dispersed generation is located as near as possible to the loads (Desbrosses et al, 1997). A central planning approach to small generation is inferred in the latter definition.

'Embedded generation' is the term used almost exclusively in the United Kingdom. 'Embedded' describes the location of the generation within distribution networks. The term 'embedded' reflects the structure of the electricity industry in England and Wales. The Central Electricity Generating Board (CEGB) had control over transmission-connected generation and the transmission network itself. All non-transmission-connected generation was thus 'embedded' in the distribution networks, from the CEGB perspective. Although the ownership of the components of the electricity supply system has changed, from a transmission and central generation perspective distribution system connected generation is still embedded. Embedded generation is therefore defined as generation connected at 132kV or below (Thomas, 1996). Other definitions of embedded generation have been proposed such as small and medium sized generators operating in parallel with distribution systems (Checksfield and Redfern, 1995). However, generation connected at 132kV in the UK can be very large with power stations of a few hundred megawatts not atypical.

Another less frequently used term for distributed generation is 'decentralised generation' which simply notes that the generation is not controlled centrally and maybe cannot be controlled in the way that transmission-connected generation can.

In essence, the three definitions for distributed, dispersed or embedded generation refer to the same concept. The term 'distributed generation' (or the shorthand DG) will be used throughout this thesis and will imply:

> ***Smaller-scale (less than about 50MW) electricity generation connected to the lower voltage electricity distribution networks at a point close to load demand centres.***

3.3 Distributed Generation Issues

The connection and operation of distributed generation produces a large number of issues for generation developers, distribution network operators, electricity regulators, government and ultimately, also, transmission system operators.

The identification and understanding of the issues involved with distributed generation are viewed as the starting point of the analysis and planning process. It will become evident later (section 5.4.2) that logical categorisation and inter-linking of the issues is a facilitator for the design of an analytical framework for distributed generation. The following categories have been identified:

- Energy Market Characteristics
- Government and Regulatory Policy
- Generator Financial and Economic Characteristics
- Distribution Network Characteristics

- Generator Electrical Characteristics
- Distribution Network Performance
- Distribution Utility Finances

The core issues relating to distributed generation within each of these categories are discussed in the following subsections. In-depth research of the issues related to distributed generation have been an essential part of understanding that planning for distributed generation will be a complex matter. The formation of this comprehensive set of issues comes from careful study of literature, attendance at industry events focused on distributed generation and, importantly, from using knowledge engineering techniques with industry experts (Ault et al, 2000).

The development of the distributed generation issues contained in the subsections below read like a reference book. To provide an overview of the issues Figure 3-1 to Figure 3-7 illustrate a hierarchy of the issues based on the seven areas bullet-listed above.

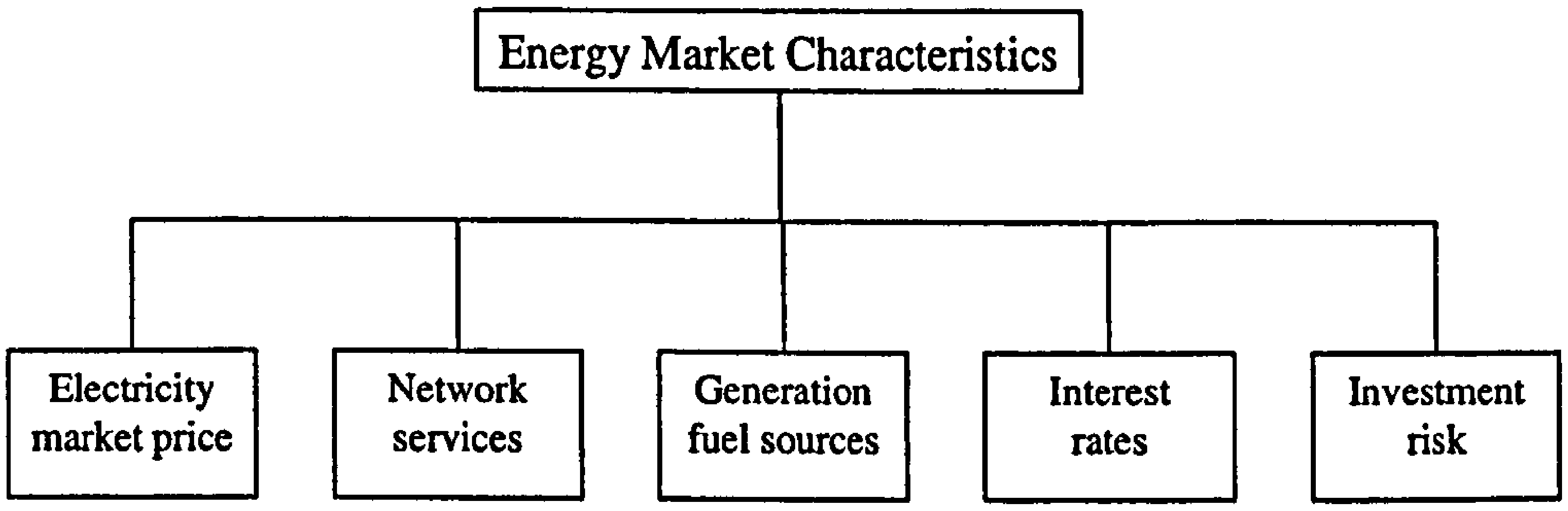

Figure 3-1: Distributed generation issues - Energy market characteristics.

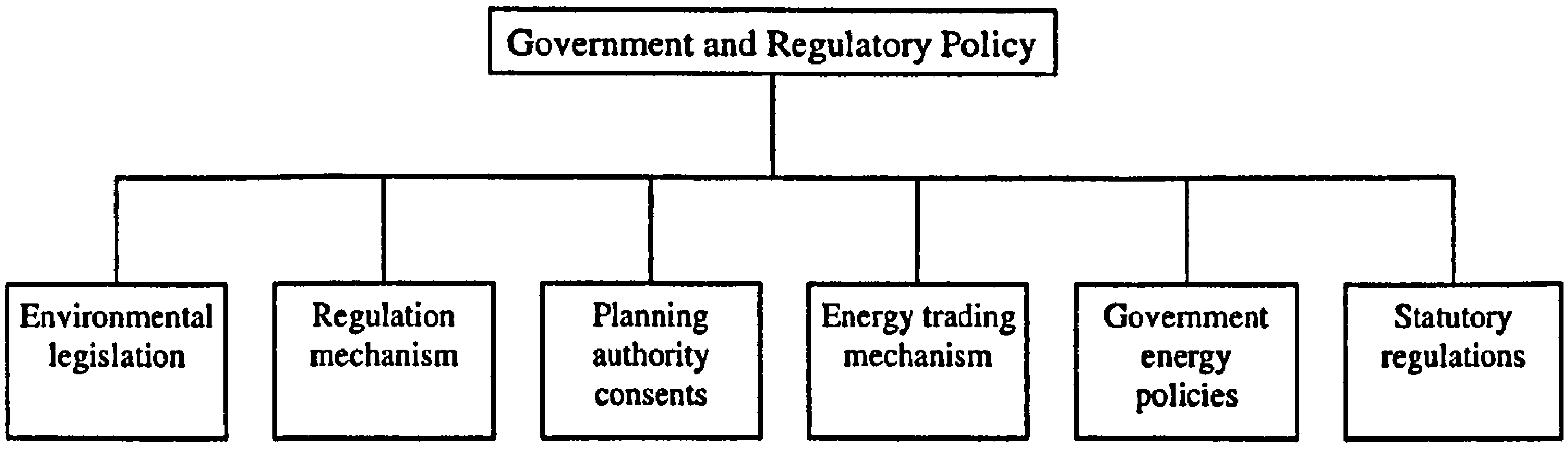

Figure 3-2: Distributed generation issues - Government and Regulatory policy.

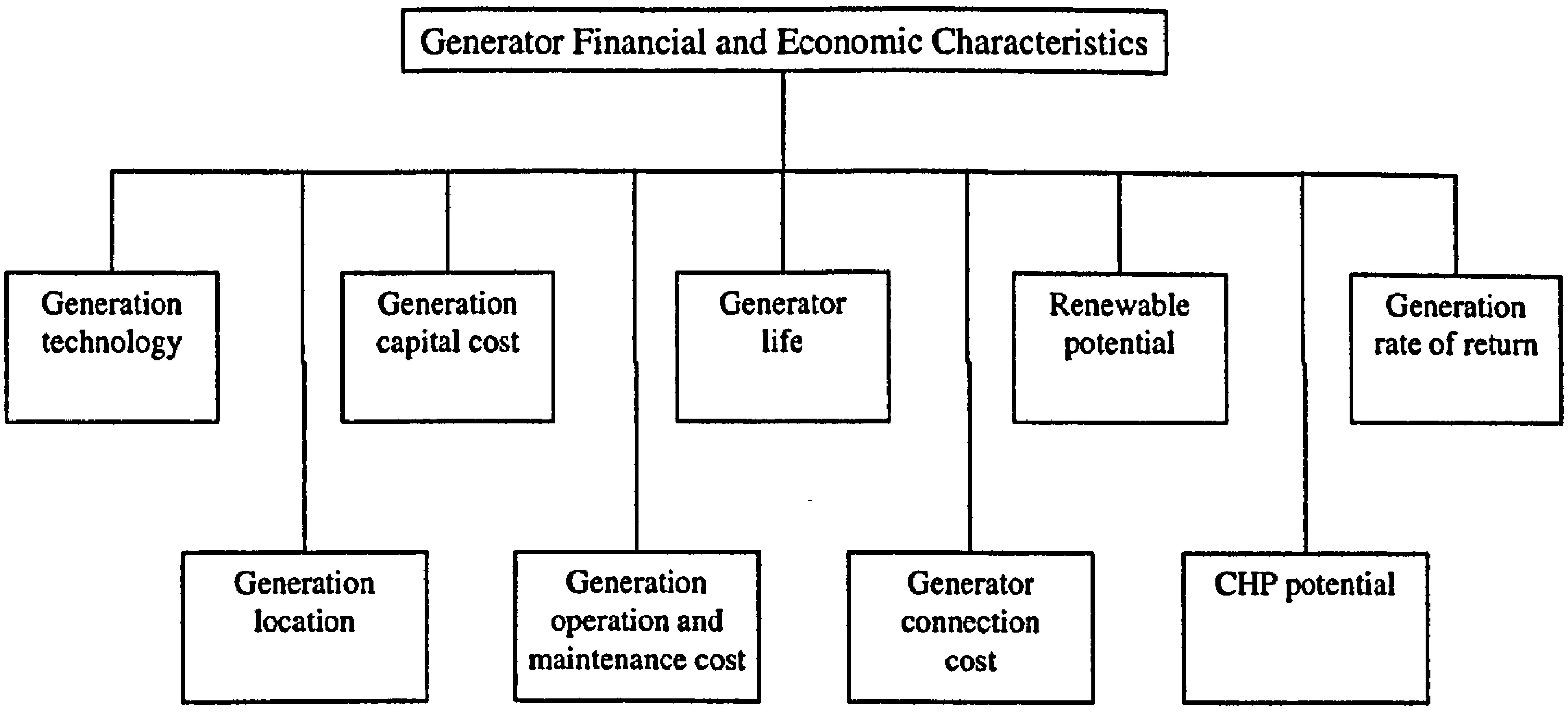

Figure 3-3: Distributed generation issues - Generator financial and economic characteristics.

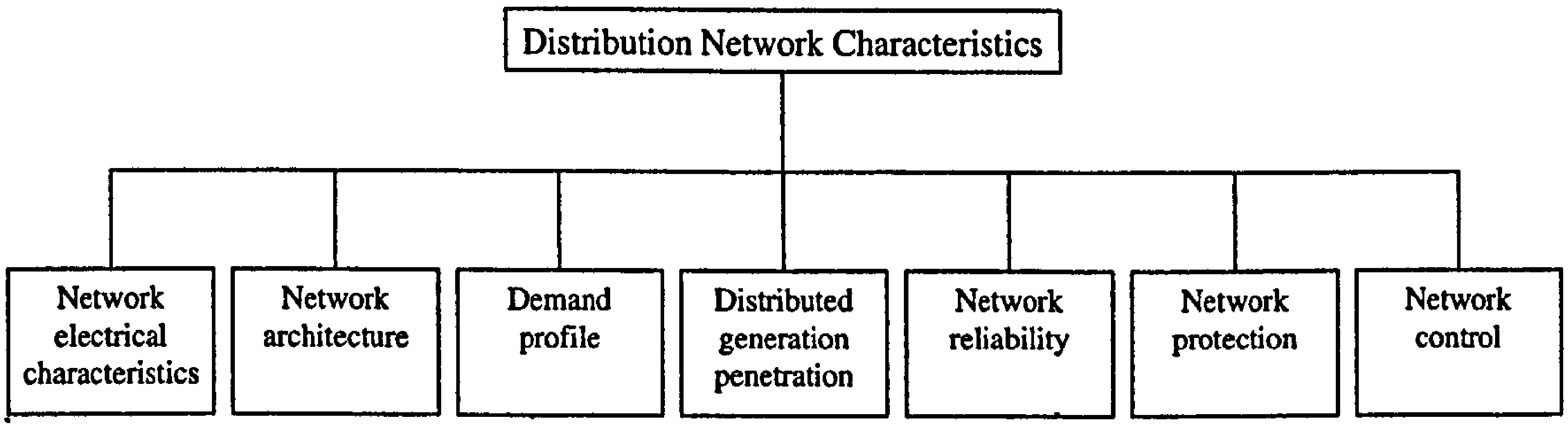

Figure 3-4: Distributed generation issues - Distribution network characteristics.

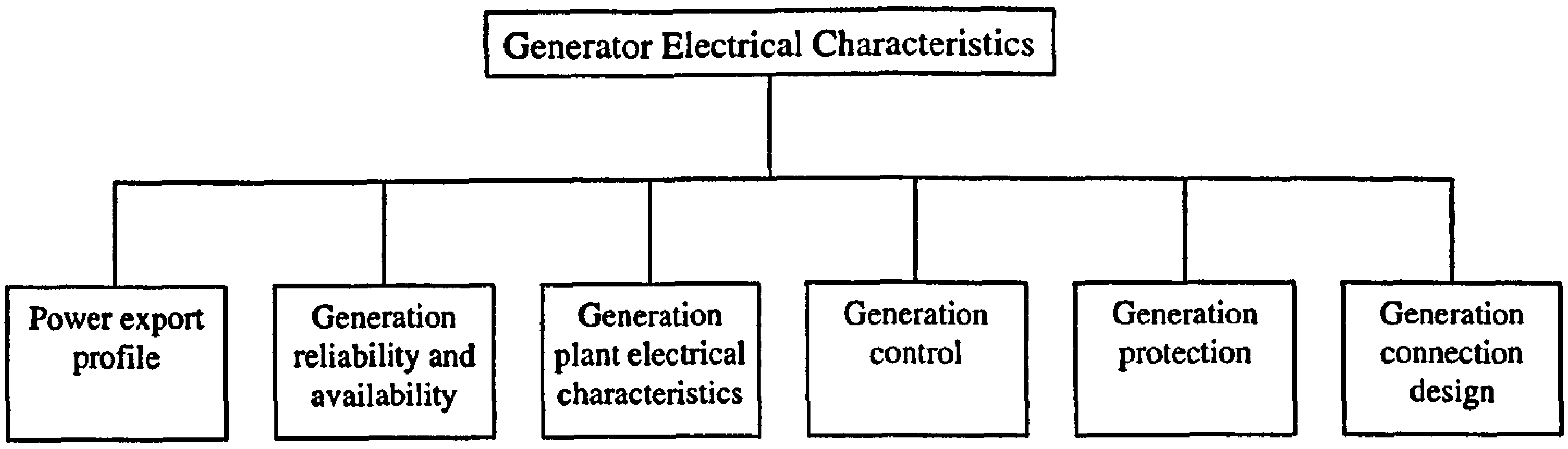

Figure 3-5: Distributed generation issues - Generator electrical characteristics.

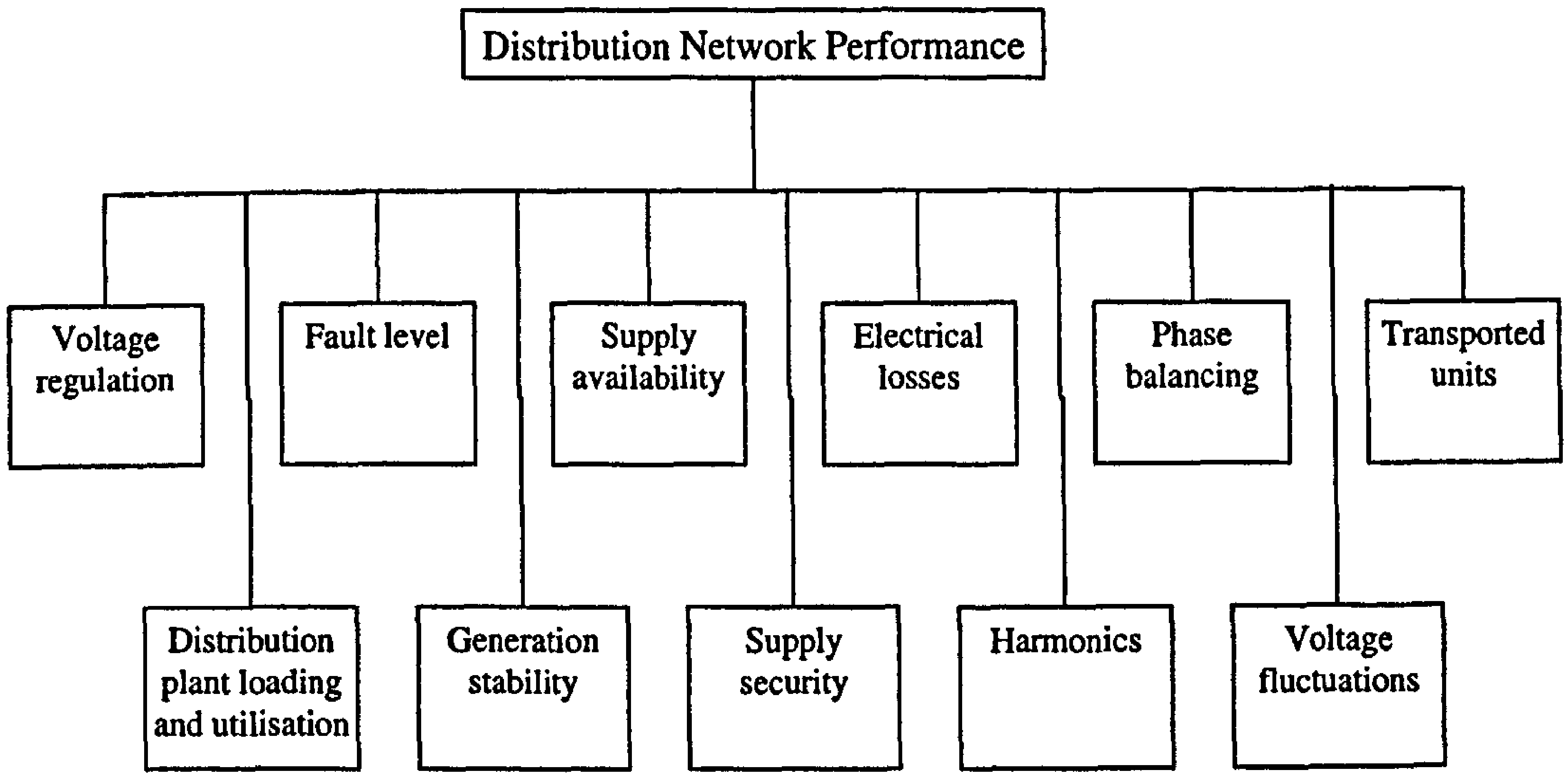

Figure 3-6: Distributed generation issues - Distribution network performance.

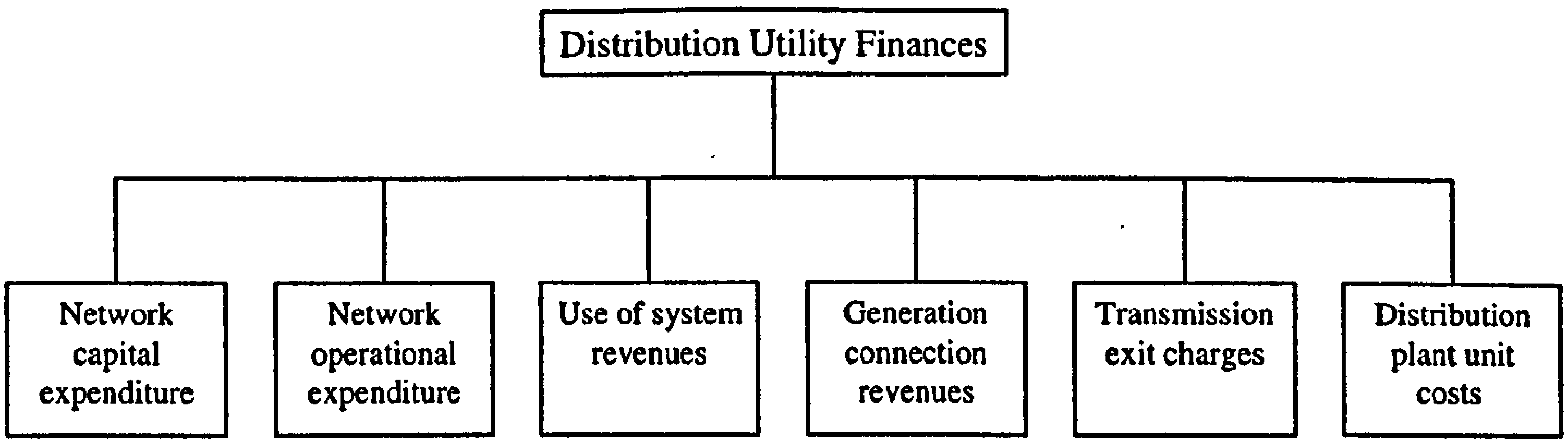

Figure 3-7: Distributed generation issues - Distribution utility finances.

The structured issue set is used in the design of a distributed generation strategic analysis framework and individual analytical modules in section 5.4.

3.3.1 Energy Market Characteristics

3.3.1.1 Electricity market price

The price a distributed generator receives for export to the power system depends on the contracts or agreements in place between the generator and the buyer. The buyer may be an electricity supply company or a customer on the same site as the generator. In either case, the price for generation is reflective of the electricity price on the spot market, either wholly or partially.

Section 3.3.2.4 describes the operation of the Electricity Pool and some other factors affecting price for smaller generating units.

The prices for electricity in the UK market are subject to substantial fluctuations that are dependent, in part, on load changes and available generation. The market price for electricity is also dependent on the bidding strategies of generation companies. The combination of these factors has produced values of Pool Selling Price (PSP) of 0 £/MWh (zero) to over 1000 £/MWh in the ten year history of the Electricity Pool.

The Electricity Pool prices fluctuate by hour of the day, by month or season and also by year. Figure 3-8 illustrates the changes in Pool Selling Price through two days. The day with the higher peak price is 19 November 1997 while the day with the flatter profile and lower prices is 27 October 1996.

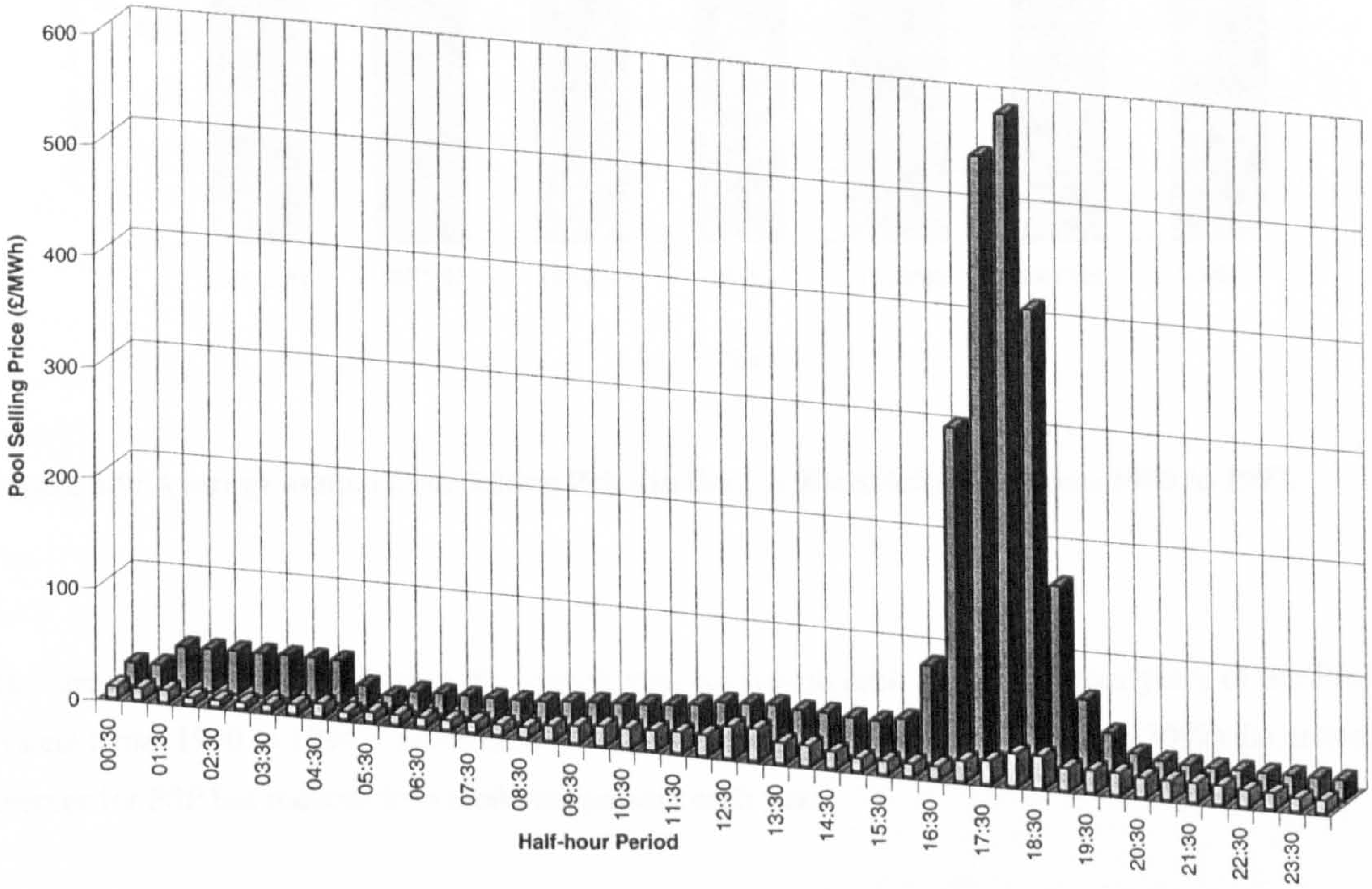

Figure 3-8: Daily Pool Selling Price profile for days with maximum and minimum Pool Selling Price value in the years 1996 and 1997.

It is evident from Figure 3-8 that the spot price of electricity on the open market varies in each half hour period and from day to day. The two days illustrated (27 October 1996 and 19 November 1997) are the periods with lowest and highest values for Pool Selling Price throughout the years 1996 and 1997. The lowest value of PSP recorded on 27 October 1996 was 6.44 £/MWh while the highest value of PSP recorded during the period was 586.81 £/MWh (on 19 November 1997).

The general trend in Pool Selling Price over the first seven years of Pool operation can be seen in Figure 3-9.

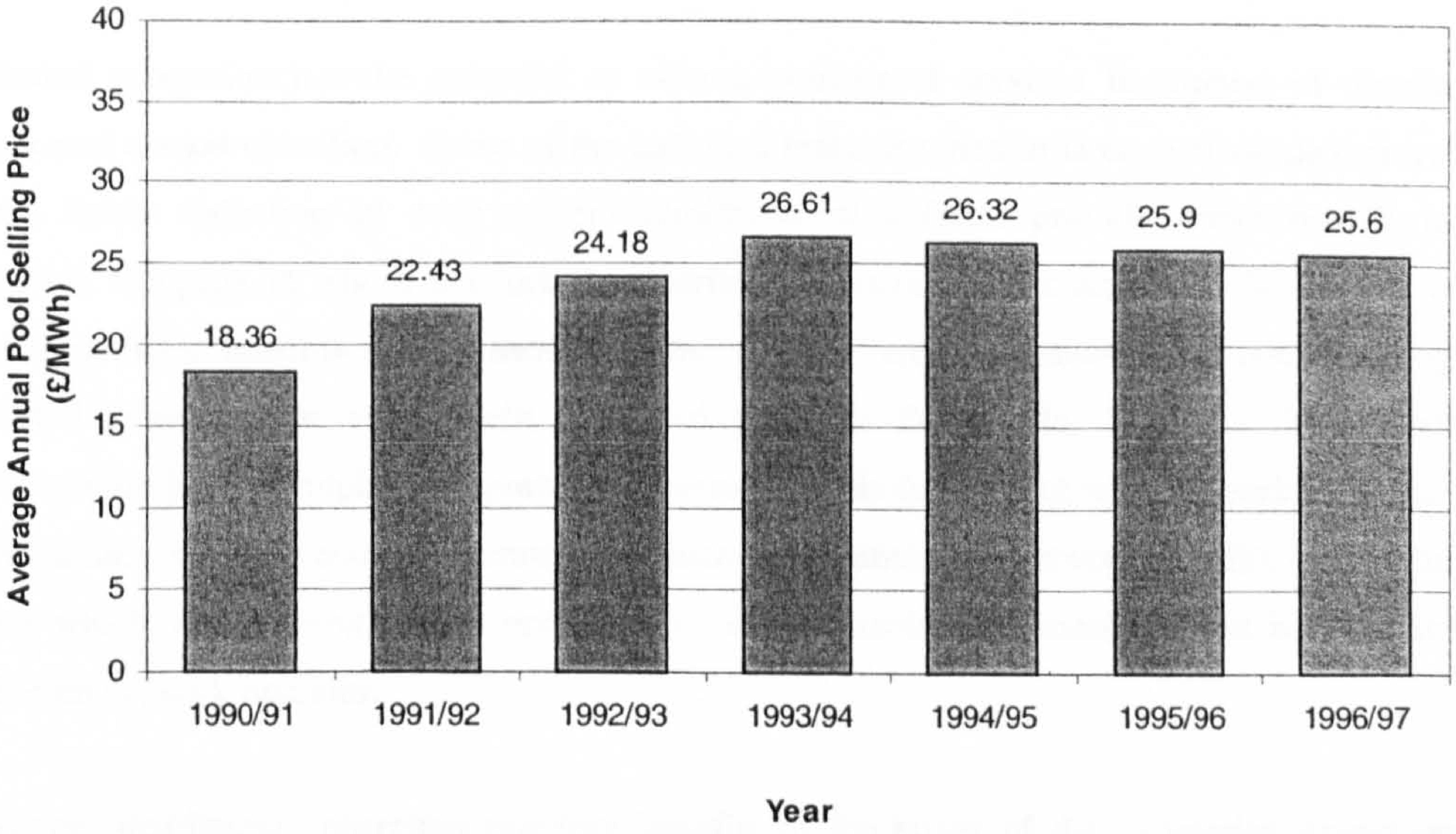

Figure 3-9: Average annual Pool Selling Price in the UK Electricity Pool from 1990 to 1997.

The annual average PSP was seen to increase year-on-year in each of the first four years of the Pool system (from 1990 to 1994). Since then (as seen in 1994 to 1997 and continuing to 1999) the annual average for PSP has reduced by a moderate amount each year.

The implications of the fluctuations and trends in the general price for electricity on the open market are substantial uncertainty for distributed generation owners and operators. In the planning phase it is very difficult to gauge the level of revenue from a distributed generation project over a ten to fifteen year period. In day to day operations, it is difficult to foresee when the price for exports may drop lower than running costs for the generating unit. These difficulties are compounded by the fact that in the current structure of the electricity market in the UK there is little participation by distributed generators in the price discovery process. As such, distributed generators are price takers rather than price makers.

In summary, distributed generation feasibility study and operation strategy development must cover a wide spectrum of possible outcomes for electricity price.

3.3.1.2 Network services

Distributed generation has the potential to offer a number of services in support of distribution network and market operation. Some of the technical features noted in later sections such as voltage support, losses reduction or even system reinforcement deferral provide direct benefit to the distribution company to whose network the distributed generation is connected. While few of the potential network benefits are realised at present, there are mechanisms for compensating the distributed generator for any benefit identified (Scottish Power plc, 1997a)*. Some industry participants are keen to implement more transparent methods for dealing with network services. The identification, evaluation and remuneration for distributed generation network benefits would, thus, be enabled which would bring higher revenues for some distributed generators and benefits for the distribution network operator.

In addition, distributed generation provides benefits to the buyer of the generation export energy beyond the potentially lower purchase price. For example, the annual charges levied by the National Grid Company (NGC) on generation and load in the UK market are dependent on the annual peak capacity averaged over the three highest peaks (known as the 'triad'). Thus, for demand, a charge is made on an electricity supply company in direct correlation with the peak demand in a particular zone of operation. Distributed generation offers the opportunity to reduce the annual peak demand for a supply company through distributed generation operation at peak demand periods. A substantial benefit arises from the reduction in peak demand and the 'triad benefit' can be traded separately from the energy output.

Other potential areas of distributed generation benefit may arise in reactive power provision and climate change certificates (the 'green' benefits of renewables may become a tradable commodity). It can be envisaged that the revenue streams for distributed generators could become quite complex with income not only from energy sale but also from a number of network and market services.

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* The Scottish Power plc Statement of Charges for Use of the Distribution System (Scottish Power plc, 1997) states: *'Where a licensed generator connected to Scottish Power's distribution system can be demonstrated to contribute system benefits then these benefits as quantified, will be used as an offset against the charges to be made'*. Thus, in theory, benefits can be realised by distributed generation operators. In reality there are few cases of benefit payments of this nature in GB.

3.3.1.3 Generation fuel sources

Important factors for the competitiveness of some distributed generation technologies are the short- and long-term prices for fuel. While many of the renewable technologies exploit 'free' fuel sources, other generation technologies are dependent on prevailing fuel prices on the open market. Natural gas currently constitutes the most important fuel for distributed generation with many combined heat and power, combined cycle and simple cycle gas turbine plants in operation in the UK and elsewhere.

The deregulation of the gas market and the legislation to liberate natural gas supplies for use in power generation in 1990 provided an additional stimulus for distributed generation contributing to its growth throughout the 1990s. Many believe that natural gas will continue to provide cheap fuel for electricity generation for many years but this assumption is dangerous (in light of the experiences with oil prices in the early 1970s). Recently, the market price for natural gas in the UK has doubled as a result of the operation of an interconnecting gas pipeline to continental Europe. The gas and electricity market regulator has refused to intervene citing that this is a result of market forces (Office of Gas and Electricity Markets, 2000a).

The status of fuel supplies for renewable technologies is a much less national scale issue. Many waste incineration, biomass, landfill gas and agricultural waste projects have been proposed in the UK with a relatively small number progressing to operation. The fuel sources for these schemes are organised more locally and the owner of the fuel source is often also the recipient of the generating plant when operational.

The issues surrounding fuel for generation relate not only to price but also to security and chemical content. Security is a problem issue for natural gas supplies where to secure inexpensive contract prices, the operators of natural gas fired generation enter interruptible contracts. There is a fear that this situation may result in supply interruptions at peak gas system loads in the near future (Burdon, 2000). Much debate has focused on the fact that while sustainable, the biomass, landfill gas, and waste incineration schemes are far from clean in terms of emissions. The chemical content therefore has consequences for auxiliary plant requirements and ultimately the cost of the plant.

3.3.1.4 Interest rates

The attractiveness of investments depends, in part, on the level of interest rates set by the relevant central bank (The Bank of England in the UK). When interest rates are low, cash deposits look less attractive due to lower savings rates while project investments look more attractive since the level of interest payable on a capital loan are lower. Conversely, when interest rates are high, cash deposits look more attractive while project investments look less attractive. In this way, the level of interest rates influences the rate of distributed generation project development in the same way as other investments.

Section 3.3.3.9 outlines the mechanisms for financial and economic evaluation of distributed generation schemes. The choice of interest (or discount) rate used in such calculations is closely linked to the general level of interest rates and therefore the projected levels of returns from distributed generation projects are affected by the general level of interest rates. A higher interest rate makes future project benefits appear less significant while a lower interest rate make future project benefits more significant.

3.3.1.5 Investment risk

The modular nature of a distributed generating project investment due to smaller unit sizes is one advantage often cited for distributed generation. This modularity provides flexibility which is of value to power generation developers. Flexibility has three main advantages (Chapman and Ward, 1996):

1. It enables a greater set of options to be exploited in the future (through not committing too much capital to one project and thus leaving capital to invest on other projects in future)
2. It enables a quicker change of direction in the future should conditions turn adverse (since smaller investments have less 'inertia')
3. It enables a less expensive change of direction in the future (since it is easier to walk away from a small poor investment than a large poor investment)

A staged approach to modular generation investments is a good strategy for reducing the risk of investment since commitment to a small generation plant still leaves open a large number of future investment options which can be moved to a low cost and in a short time. Diversity of energy source can be built more easily with smaller units. Such diversity could also lead to reduced investment risk.

Investment risk impacts on generation project financial feasibility calculations through the discount rate (section 3.3.3.9) utilised in calculations (Khatib, 1997). Where an investment is deemed 'risky', a higher rate of return is required and thus a higher discount rate is used. In power generation terms, a risky investment might be to develop an Independent Power Producer (IPP) project in a developing country with a history of political turbulence. A safer or 'less risky' investment might be a project in monopoly transmission assets in a country with rate of return regulation in which case a known and reasonable return on investment is guaranteed.

Distributed generation investment risk may be reduced through the flexibility of modular generating units as previously discussed. While investment risk may increase due to the uncertain trading conditions for distributed power services and the relative novelty of widespread distributed generation as a concept which precludes a mature market at this time. Thus financial feasibility calculations may be subject to a higher degree of uncertainty due to the additional choices of parameter values for required rates of return on investments.

3.3.2 Government and Regulatory Policy

3.3.2.1 Environmental legislation

Sections 2.3 and 2.4.2.2 have outlined the government schemes for supporting renewables in the UK electricity market. The results of the schemes have been generally positive although the barriers to renewables development are sometimes higher than the incentives to cross the barriers (e.g. planning permission constitutes a major barrier to development). The legislative framework on environmental measures not only affects the support schemes for environmentally friendly technologies such as renewable generation and combined heat and power but also the emissions control measures required by more traditional technologies. Tightening of emissions targets clearly has consequences for the costs and complexity of some fossil fuel based generation technologies. In short, government environmental policy has a major influence on the relative economics of different generation technologies and affects the development of the distributed generation technology mix.

3.3.2.2 Regulation mechanism

The office of Electricity and Gas Markets (OFGEM) utilise a price cap approach to regulate the performance of the monopoly electricity companies in the UK. The average allowable charges for use of the distribution system are set through analysis of operating costs, reasonable capital investment in the networks and a reasonable rate of return on assets (Office of Electricity Regulation, 1994). In theory, each unit of expenditure is carefully assessed by the distribution companies since the operating and capital budgets of the distribution utilities are tightly constrained by OFGEM. As a result, the expenditure of the distribution companies in the UK is focused on key performance indictors (KPI) which are set by OFGEM.

The key performance indicators for distribution include supply availability, supply security, supply quality (frequency and voltage) and performance for worst served customers (Office of Electricity Regulation, 1997; Office of Electricity Regulation, 1998a; Office of Gas and Electricity Markets, 2000b). The allowed revenue of each distribution company is set according to performance against each of these key performance indicators and also through parameters in the price control formula which reflect the distribution company performance in such areas as electrical losses. Due to the links between performance and revenue, the distribution companies tend to focus only on those areas where there are clear and direct benefits. It is felt that there are few incentives for distribution infrastructure expenditure specifically for distributed generation as there are no direct incentives for distributed generation at present. Notably, even with the increases in numbers of distributed generators experienced in the UK, there was no mention of distributed generation in the distribution price control review for the years 2000 to 2005 (Office of Electricity Regulation, 1998b; Office of Gas and Electricity Markets, 1999).

3.3.2.3 Planning authority consents

One of the major factors in generation project feasibility is the granting of local planning authority planning consents. The jocular references to NIMBY (*not in my back yard*) and BANANA (*build absolutely nothing anywhere near anyone*) have very serious implications in the initial stages of generation project planning. Many generation projects have not been able to cross the seemingly insurmountable obstacles of local public opposition to new projects. The reasons cited for such opposition to generation developments include the deterioration of local air quality, the visual intrusion of a power station and the effects on bird flight paths for wind farms (Department of Trade and Industry, 1998).

A recent policy consultation document by the Department of Trade and Industry (DTI) outlines planning consent issues as one of four main strands to government policy on new and renewable energy sources (Department of Trade and Industry, 2000). Under the proposed policy to encourage the construction of many new renewable generators, local authorities will aim to meet targets for renewable generation within their planning area. The local planning bodies will thus have an obligation to find ways of facilitating renewable energy in a manner which is least obtrusive or damaging to local amenity.

3.3.2.4 Energy trading mechanism

The Electricity Pool was established in 1990 as the main channel for electricity trading in England and Wales. The Electricity Pool operates as a spot market with generating units placing bids one day prior to operation (Clarke, 1997). Bids are placed for 48 half hour periods running from 05:00 hours the following day.

Generating plant is dispatched in merit order with the cheapest available plant dispatched in each half hour period to meet the load demand (subject to start-up and shut down costs and transmission system constraints). The wholesale price of electricity (Pool Selling Price) follows demand profile (in general) with more expensive generation required when higher loads are forecast. Pool Selling Price (PSP) also depends on constraints in the transmission system, the accuracy of load forecasting, generation availability and the cost of ancillary services such as reactive power, reserve and response.

The success of the Electricity Pool has been mixed. Initially doubts centred on the level of competition between a relatively small number of generators (Redmond, 1994). More recently doubts have escalated over the ability of the Electricity Pool to provide true competition and the accompanying downward pressure on wholesale electricity prices (Office of Electricity Regulation, 1998c). In particular, the Pool is susceptible to price spikes (Office of Electricity Regulation, 1999) which are a function of the cost characteristics of available generation but are also highly dependent on bidding strategies from a small number of influential generators. As distributed generators are effectively price takers from the wholesale market the mechanism for price setting is of great importance to smaller generators.

These suspicions about the effectiveness of the Electricity Pool have led to the commissioning of a new electricity market in England and Wales which is due to come on-line in November 2000. The New Electricity Trading Arrangements (NETA) will be based on bilateral trades between generators and electricity suppliers with a short-term bilateral market to allow participants to tune their contract positions and a balancing market to ensure that supply and demand are balanced. Penalties for imbalance provide incentives for generators and suppliers to act as committed through electricity contracts.

Smaller scale distributed generators (declared net capacity less than 100MW and maximum export less than 50MW) have always had the option to form bilateral contracts with an electricity supplier external to the Electricity Pool mechanism. The contracts between distributed generator and electricity supplier are often based on Pool Selling Price (PSP) or Pool Purchase Price (PPP: one of the intermediate prices in the determination of PSP). The new electricity trading arrangements will radically alter the structure and may affect the level of prices available to smaller generators. The new trading arrangements provide penalties for energy imbalance which could undermine the ability of generators with highly variable outputs to trade effectively. The electricity trading mechanism can be seen to have a major effect on distributed generation economics.

The resulting market spot prices for electricity are discussed in section 3.3.1.1.

3.3.2.5 Government energy policies

The government has a key role in stimulating the distributed generation market through their policies. Some government policy is specifically directed at distributed generation related issues while other influences on distributed generation occur as by-products of policies directed at other issues.

An important point to note is that, despite calls from certain quarters, there is no direct unified energy policy in the UK. Rather, a raft of policies exists to create a general framework for the energy industry at large:

- competition in the electricity market
- energy industries structure
- regulation
- environmental controls

With these policies in place the government has tended to adopt a hands off approach to the electricity (or wider energy) industry, preferring to leave matters to market forces. One notable exception (and there are others) to this hands off approach was an intervention in 1997 to limit the number of approvals for natural gas fired generation (so called Section 36 consents). This measure was intended to slow the 'dash for gas' which had endangered the security benefits from a diverse generation mix.

Few specific policies benefit distributed generation in general but the Non-Fossil Fuel Obligation (NFFO) and, more recently, new measures to stimulate the market for renewable energy provide a framework of support for renewable generation. The NFFO programme (Department of Trade and Industry, 1998) re-circulated a levy on fossil fuel generation sources into a support mechanism for renewable generation whereby contracts were placed for the development of specific competitively bid renewable projects. The operators of renewable generation receive a guaranteed unit price for exported energy at an agreed rate for a period of eight or fifteen years after which the generators enter the open competitive market. The new measures outlined by the UK government (Department of Trade and Industry, 2000) include:

- Obligation on supply companies to purchase 10% of energy from renewable sources or buy out the obligation at a fixed price with the proceeds being distributed by OFGEM.
- Exemption from the climate change levy for renewable sources of energy (as outlined below for CHP schemes).
- Support programme for new and renewable energy technology research, development and demonstration.
- Setting of regional planning targets to ensure every region in the country contributes to the adoption of cleaner and more sustainable sources of energy (see section 3.3.2.3).

The governments enthusiasm for combined heat and power (CHP) generation has also recently led to a policy (Department of the Environment, 2000) to exempt high quality CHP schemes from paying the Climate Change Levy (CCL) which is effectively a tax on carbon emitting sources of electricity. This measure is likely to make high quality (one of the measures of which is higher fuel utilisation) CHP schemes more attractive to developers.

While no specific measures exist for distributed generation in general, there are some policies applicable to specific types of distributed generation such as CHP or renewables. Further policies and legislation may appear in the future as the importance of distributed generation grows.

3.3.2.6 Statutory regulations

A high number of statutory regulations apply to distributed generation. Many of these regulations have provided the foundation for the safe, secure and relatively high quality supply of electricity for many years. The regulatory environment for distributed generation ranges from the all embracing regulations such as the Energy Act (1983) and the Electricity Act (1989) which set the framework for the electricity supply industry to the detailed specifications and recommendations covering specific aspects of distributed generation such as G59/1, the recommendation for the connection of distributed generation units to distribution networks.

G59/1 (Electricity Association, 1990) has been noted and is a critical regulation for distributed generators and distribution companies (along with the accompanying protection guidelines in ETR 113 (Electricity Association, 1995). The Distribution Code (The Public Electricity Suppliers of England & Wales, 1990) also provides a very specific set of guidelines for the relationship and interactions between distributed generators and distribution companies in planning and operational matters.

Many other regulations are already or are fast becoming important for distributed generators in terms of their effects on the electricity network. G5/3 specifies the limitations for harmonic distortion which will become increasingly important for power converter interfaced generation units. P2/5 specifies the security of supply standards required in planning electricity networks in the UK. P2/5 has major implications for generators and distribution companies alike which are discussed more fully in sections 3.3.6.6 (supply security) and 3.3.7.1 (network capital expenditure).

Rogers (Rogers, 1998) discusses many of the electricity regulations and their implications for the connection and operation of distributed generating units. For smaller generators, the regulations can appear to stifle the freedom of their enterprise and that, while creating a framework for the effective management of electricity networks, can be complex and restricting. There is a general feeling within the electricity industry that some of the regulations require to be updated to reflect the new requirements of distributed generation. To this end the new regulation G75 (Electricity Association, 1996) was introduced in 1996 to cover the growing prevalence of small generators in distribution networks which had capacities or outputs greater than those covered in the equivalent standard for very small units, G59/1.

G59/1 is the crucial standard for distributed generation developers while P2/5 is the crucial requirement for distribution planners. These standards (and their implications) are discussed in sections 3.3.5.6 and 3.3.6.6 respectively.

3.3.3 Generator Financial and Economic Characteristics

3.3.3.1 Generation technology

Section 2.4.1 discussed the diversity of generation technologies and outlined some of the potential effects of the different technologies on the planning and operation of the power distribution network. In addition to the effects on the distribution network, and of key importance to the generation developer, are the economic characteristics of each generation technology. In turn, the economic characteristics of generation technologies will influence the development of actual generation projects which will give rise to a set of influences on the utility network and business operation. It can be seen, therefore, that the distributed generation technology mix clearly has influence on the distribution network and business.

3.3.3.2 Generation location

The site chosen for new generation is a complex decision for generation developers and is based on a large number of factors such as:

- land availability, planning permission status and cost
- proximity to electrical network
- proximity to fuel source
- prospective connection and use of electrical system costs

In turn, the selection of the site has major influences on the overall impact of the generation scheme on the power system. The position of the generator connection within the power system affects the power flow, fault, dynamic and financial performance of the utility network. Some consider that, to ensure the maximisation of economic efficiency within the electricity system, location based charging structures must be introduced to provide differentials between those generators sited where they provide benefits to the system and those sited where they produce costs to the system (Mutale et al, 2000).

The arguments about the influences of generator location could be taken further to include economic externalities in the assessment of distributed generation schemes. Some of the externalities relating to distributed generation schemes and their location are:

- visual intrusion (particularly vociferous for wind farms)
- emissions performance (greenhouse gases, acidic gases and local air quality gases)
- local employment prospect

In summary, the location of distributed generation schemes may have significant consequences not only for the local distribution and wider power network but also for the economy and society at large.

3.3.3.3 Generation capital cost

The choice of generation technology for a distributed generation scheme will in large part be influenced by the capital cost of generation units of that technology. With such a wide variety of generation technologies on the market (see section 2.4.1) it is not unexpected that there exists a wide range of capital costs for distributed generation plant. Capital costs range from inexpensive industrial gas turbines to relatively expensive technologies such as photovoltaics and emerging technologies such as fuel cells. The capital cost of distributed generation technology plays a central role in the success of a generation project as interest must be repaid on a loan throughout the financial life of the scheme. If the interest and capital repayments are not covered by revenues then the project fails.

3.3.3.4 Generation operation and maintenance cost

In addition to the central role of capital costs to financial viability of a generation project, the ongoing operation and maintenance costs of the generating plant also have a key part to play in the success of the project. Some aspects of operation and maintenance are subject to a degree of uncertainty which produces risks for the project. For example, fuel costs (if not part of a fixed price contract) may vary substantially over the life of the project while maintenance costs can be volatile for fledgling technologies with no proven track record of reliability. The lost revenue costs of generation unit down time can be as high if not higher than the actual costs of maintenance work.

Operation and maintenance costs are a central financial element for generation projects and a major component of risk. The risk in operation and maintenance costs can be reallocated through fuel purchase contracts, operation and maintenance agreements, plant guarantees and insurance. These risk mitigating options all come at additional cost.

3.3.3.5 Generator life

Generator life has a clear and direct bearing on the financial attractiveness of a project as evaluated using the financial and economic evaluation techniques outlined in section 3.3.3.9. These techniques take, primarily, an 'accounting life' view of generation which is important for initial feasibility studies and ongoing accounting processes.

The actual plant life of a generation unit also has consequences. The operating mode, location and maintenance practices may all affect the plant life which has clear implications for the generation owner but also for the distribution or supply company who may rely on the generating unit for other services. For example, a distribution company may in the future rely on a distributed generator for security for operational support or a supply company may become reliant on the benefits gained through reduced energy purchase costs or system charges based on peak load, both of which are influenced by contracted distributed generation.

Plant life varies between different generation technologies. For example some components of gas turbines (and the same could be true for fuels cells and other technologies) are not economically replaceable when a particular condition level is reached. The life of newer technologies also presents an unknown factor since little operational experience has been gained with these units.

3.3.3.6 Generator connection cost

Connection charges to cover the work and equipment required to connect a generating unit to the distribution network are levied by the distribution company to whose network the connection is made. The generator is liable for the full costs of the work, including any reinforcement made to the system at higher voltage levels, although there is some flexibility in the way in which the costs are calculated and collected.

Normally, if the distribution company is likely to receive use of system income from a customer then the connection cost will be reduced to reflect the fact that the connection will result in an income stream over a number of future years. Generation is not liable for use of system charges for exports (in most circumstances) so would not be eligible for this so-called 'tariff support allowance' or TSA.

The connection costs of distributed generation can be prohibitively high for small generation schemes since each item of work and equipment is charged for including administrative and connection design works (Scottish Power plc, 1997b). The major factor in the level of the connection costs tends to relate to specific characteristics of the local network around the connection point. If, after analysis of the connection, the generator appears to require upgrading of network capability then the costs of these upgrades will be added to the costs of the equipment required simply make the connection to the specified connection point in the network. Clearly if the generation scheme is distant from any existing network then the costs of electric circuitry to make the connection to the network will be large owing to the length of circuit required.

Section 3.3.7.4 deals with the issue of connection costs from the distribution company perspective (i.e. revenues).

3.3.3.7 Renewable potential

While the general economics of particular renewable generation technologies operating in a particular mode may suggest the development of many projects based on the technology, the regional potential for the technology will be highly influential in determining the actual numbers of generating units installed. For example, while the current economics for wind generation are generally favourable in the UK, wind generation projects are most often developed in rural areas. The regional potential for renewable generation can work at a number of levels. The renewable potential in an area depends on a complex interaction between the technically possible, the economically desirable and the socially acceptable. For example, a very good physical location for the wind turbines may exist with high average wind levels over the year but the combination of the economics of connecting the wind farm to the electricity network and the social cost of disturbance of a culturally important area with visual intrusion and noise (manifested in the local planning process. See section 3.3.2.3) may render the wind generation scheme infeasible.

3.3.3.8 CHP potential

In a similar manner to the arguments for renewable generation potential in section 3.3.3.7, the potential of CHP within a region, or the country as a whole, depends on a complex interaction of technical, economic and social aspects of generation projects. The main factors affecting CHP potential include such issues as domestic, commercial and industrial units where CHP would be advantageous, the ability and willingness of site owners to invest in on-site CHP generation and local authority drive to develop municipal heating schemes based on CHP. In some areas the issues of exhaust gas pollutants and noise may introduce a social factor while the economics of connecting to the electricity network are less important than for renewables since customers considering CHP would normally be connected to the power system with sufficient capacity to meet the on-site load.

CHP has been mainly developed at industrial, larger commercial and some public service sites. For the moment, the economics of CHP indicate that CHP is most effective where there is an existing high heat and power load density such as manufacturing and process factories, large office developments and hospitals.

3.3.3.9 Generation rate of return

Several methods exist for evaluating and comparing the rate of return from an investment in power generation (and other projects of a similar nature). Chief among such methods and those which include a time dynamic (discounting) approach to money are (Khatib, 1997):

- net present value (NPV)
- benefit to cost ratio
- internal rate of return (IRR)

Discounting methods aim to provide a measure, in a base year (normally at the start if a project) of the relative value of the project over its life. These methods include all costs and benefits likely to arise from the project through its life.

The net present value of one future year (year n) of an investment is calculated by discounting the net benefit (benefit minus costs) in that year to the present (or base year) through the following formula (Equation 3-1):

$$NPV = \frac{(B_n - C_n)}{(1+r)^n}$$

Equation 3-1

Where,

NPV	is the net present value
B_n	is the benefit from the investment in year *n*
C_n	is the cost of the investment in year *n*
r	is the interest (or discount) rate
n	is the year in question.

The net present value (NPV) of a project is simply the sum of the net present value for each year in the life of the project. The use of NPV enables projects with different life spans, costs and benefits to be compared in the present by a single monetary value.

The benefit to cost ratio is similar to the net present value calculation but a ratio is taken between the whole stream of benefits discounted to the base year and the whole stream of costs similarly discounted to the base year as shown in Equation 3-2:

$$\frac{B}{C} = \frac{\sum_n B/(1+r)^n}{\sum_n C/(1+r)^n}$$

Equation 3-2

The benefit to cost ratio also enables a direct comparison between the benefits of a project and its costs. Clearly only projects with B/C > 1 could be considered and the higher the B/C ratio, the greater the total return.

Internal rate of return (IRR) is calculated through an iterative process to determine the interest rate (*r*) which sets the net present value of the benefits equal to the net present value of the costs. Equation 3-3 illustrates this formulation:

$$\sum_{n}\left[C_n/(1+r)^n\right]=\sum_{n}\left[B_n/(1+r)^n\right]$$

Equation 3-3

If the resulting interest rate is higher than a predefined level then the project is deemed to be worthwhile. The internal rate of return is a widely used method which enables a number of projects to be compared with each other on even terms. The projects with higher internal rates of return being the most attractive on financial or economic terms.

A general picture of the attractiveness of different distributed generation technologies operating in different modes and maybe in different geographical locations can be compared with any of these methods of evaluating return on investment. Such analysis could provide some indication of the likely distributed generation mix in future years through ranking the generation technology types by return on investment.

3.3.4 Distribution Network Characteristics

3.3.4.1 Network electrical characteristics

The electrical characteristics of the existing distribution network (and any subsequent developments in the network) will have a major influence on the impact of distributed generation on the network. The network electrical characteristics of most importance for the evaluation of distributed generation are (Bird, 1994):

- load electrical and dynamic characteristics
- electrical and dynamic characteristics of other generation
- circuit ratings and electrical parameters
- switchgear normal and fault ratings
- transformer ratings, electrical parameters and tap-changer controls
- earthing arrangements

The effects of these issues are generally studied through the following power system analysis techniques:

- Power flow analysis
- Fault analysis
- Dynamic analysis
- Motor starting and re-acceleration analysis
- Load shedding analysis
- Harmonic analysis
- Contingency analysis

The electrical characteristics of the distribution system along with the higher level system architecture (section 3.3.4.2) and the distributed generator characteristics define how the distribution system and the generator will perform when linked together. There are potentially major implications from the interaction of generator and network for future system designs in each of the areas in the first list above. The effects of distributed generation on system performance are discussed in section 3.3.6.

3.3.4.2 Network architecture

Network architecture is closely related to network electrical characteristics but refers to the higher level design of the distribution network. The connectivity, voltage levels, standard substation layout, circuit configurations and control arrangements all contribute to the overall performance of the distribution network. Many of these factors are firmly influenced by historical factors such as electrification programmes and their timing, local equipment manufacturers, demographics and geographical features of the region.

Some network architectures are more amenable to distributed generation than others. For example, interconnected (or meshed) arrangements of circuits tend to have different voltage, fault, loss and stability characteristics from radial circuits each of which will be affected in different ways by distributed generation. A major issue for distribution companies is the selection of the most appropriate network architectures for the future. Distributed generation will be one factor in the selection of the best network architecture but not the only consideration. Cost and the various measures of distribution performance will remain key factors for distribution network designers.

3.3.4.3 Demand profile

The demand profile within load groups has a number of influences on the impact of distributed generation on the distribution network. The peak demand for a load group clearly sets the requirements for circuit capacity to provide the required level of security while the daily fluctuations in demand have effects on the temperature of conductors and the degradation of insulation. The demand profile also influences the contribution to electrical losses in the network from a particular load group according to the square law governing power losses.. Demand has a number of spatial and temporal characteristics which influence losses, voltage, asset wear and capacity requirements. Spatial characteristics refer to the exact location of load relative to the distribution system while the temporal characteristics include daily, seasonal and annual variations in each load group.

The temporal and spatial characteristics of distributed generation interact with the spatial and temporal characteristics of demand either positively or negatively. For example, the output of a distributed generating unit may reduce system loading and hence asset wear depending on the location and timing of the generation output and the location and time profile of the load.

3.3.4.4 Distributed generation penetration

One of the key issues regarding distributed generation relates to the extent of its penetration or proliferation. Many of the other issues will be significantly affected by the volume and capacity of distributed generation in the distribution network in general but also in particular areas of the network.

The penetration of distributed generation and the mix of generation appearing will be affected by the relative economics of different generation technologies and the level of the barriers to distributed generation development. A UK government report on distributed generation technologies expands on the issue of barriers to distributed generation growth. The barriers to growth come from a number of sources and can be grouped as follows (Department of Trade and Industry, 1999):

- Social and environmental
- Technical
- Economic
- Political, institutional and legislative

Social and environmental barriers include lack of awareness on the part of the generation developer of local concerns and local planning authority preferences and processes. Equally, the local community and local government can show a lack of awareness of the benefits of renewable distributed generation technologies.

Technical barriers can be specific features of the generation technology such as costly impact on the distribution network or low load factor. Many technical barriers manifest themselves as economic barriers. These two examples cited as technical barriers have a direct bearing on the economic attractiveness of a generation technology or project.

Political, institutional and legislative barriers include lack of government led education on the benefits of renewable and other distributed generation technologies, lack of common technical standards and conflicting legislation such as electricity market reform which reduces the revenues that already marginally feasible generation schemes receive.

It can be seen that there are many barriers to higher penetrations of distributed generation in general and renewable distributed generation in particular.

3.3.4.5 Network reliability

The reliability of series, parallel and mesh connected distribution network components dictates the overall reliability of customer supply on which distributed generation has an effect (see sections 3.3.6.5 and 3.3.6.6). In addition, the prospects for electricity trading by distributed generation units is affected by the reliability of the distribution network which stands between the generator and the customer. If a generating unit is connected to its customer via relatively unreliable network components then it will not be in a position to deliver its contracted volume from time to time. The new electricity trading arrangements (section 3.3.2.4) for the UK electricity market will penalise market participants whose contracted production or consumption volume does not match actual volume. The prices paid for so-called balancing units to enable a match of contract and actual volume are expected to be highly variable and often very high when the generating plant margin is low. Thus, the reliability of the distribution network will play a more important role in the profitability of distributed generation than previously which has led to a debate in the industry over who should face this liability, the distribution company or the generator. Distribution companies are clearly reluctant to accept new liabilities for the performance of their network when the regulatory measures already in place can be financially detrimental.

3.3.4.6 Network protection

In addition to altering the direction and magnitude of real and reactive power flows, distributed generation also changes the characteristics of fault current flows. Such changes in the nature of fault currents in distribution networks have major implications for time-graded directional over-current (DOC) protection which is predominant in distribution networks. The operating time of DOC protection units is sensitive to fault current magnitude which may in future be highly variable as a result of the profile of connected distributed generators in the locality of the protection unit.

Protection grading systems employed in distribution networks rely on the assumption of uni-directional fault current flow. This assumption no longer holds true in distribution networks with distributed generation.

The implication of the effects of distributed generation on network protection range from generation stability to protection re-design. The clearance times of standard distribution protection systems may be too long to prevent generation instability (Edwards et al, 1998). It is likely that, for the reasons outlined, that network protection settings will at least require to be reviewed at each new distributed generator connection. It has been suggested that distribution protection systems of the future will resemble those currently found in transmission networks (Rogers, 1996). Fast-acting unit protection for each circuit would reduce the need for protection redesign at each new generator connection, while improving the chances of distributed generation stability during faults due to quick fault clearance. However, such a protection scheme would be very costly for distribution networks due to the volume of network components.

3.3.4.7 Network control

Many of the distributed generation effects on the distribution network discussed in this chapter have implications for distribution network control. For example, the effect of distributed generation on voltage regulation (section 3.3.6.1) is dependent on the voltage control system in place. The opportunity to harness some benefits from distributed generation also depend on the control systems in place within the distribution network. For example, the enhancement of supply security (section 3.3.6.6) resulting from the presence of distributed generation in the distribution network may require the linking of generation and network control systems with extensions to the functionality of both.

Dugan *et al* (Dugan et al, 1984) describe some of the potential problems with distribution network control systems as a result of distributed generation and suggests a number of courses of action to rectify the situation. Options such as indicative messaging from distributed generation units to distribution control system, scram signalling to disconnect distributed generation following a major network incident and automation of feeders to which generation is connected are suggested to enhance the operability of distribution networks with distributed generation. It is noted that all suggested control system extensions will be available through the natural evolution of distribution control systems although controlling very small generating units will be problematic from a practical point of view. In essence, the authors suggest that automated control will be one of the keys to successful integration of distributed generation.

3.3.5 Generator Electrical Characteristics

3.3.5.1 Power export profile

Section 3.3.4.3 outlines the spatial and temporal characteristics of load which influence the operation of distribution systems. It was noted that the interaction of load demand and generation output profiles could affect system performance and condition characteristics either positively or negatively.

The underlying drivers of distributed generation export profiles range from the effects of the weather on wind and solar generation to the on-site requirements for combined heat and power schemes and from the hourly, daily and seasonal variations in electricity market prices to crop yields and processing for biomass schemes. Each of these factors will either dictate or influence the decisions made by generation owners regarding export to the distribution network.

3.3.5.2 Generation reliability and availability

In addition to influencing the financial return from a distributed generation project (through meeting energy export commitments), the reliability and availability of a generation scheme determine its ability to deliver network services such as security and voltage support. If a generation unit is highly reliable then it could be depended upon to reduce system peaks or support a fault weakened system on demand. Non-dispatchable generation units and those with lower availability levels (maybe due to the intermittent nature of a renewable energy resource) would not be relied upon to the same extent to provide essential network services.

Only if a generating units were relied upon to provide an essential network service would its reliability affect the performance of the network. The benefits from distributed generation in such areas as electrical loss reduction or reduced load stressing of assets are incidental in nature. Definitive delivery of the benefit in a given time period is not critical to real time control of the distribution system. Generation reliability and availability is not important for exploiting the incidental benefits distributed generation.

3.3.5.3 Generation plant electrical parameters

The generation plant electrical characteristics are of prime importance to the impact of the generation on the distribution network. The electrical parameters affect the fault characteristics and the dynamic characteristics of the generation when synchronized with the distribution system. Key parameters affecting the fault and dynamic performance of a distributed generation unit are listed below (Checksfield and Redfern, 1995):

- Inertia constant
- Transient reactance
- Open circuit time constant
- Alternator resistance
- Alternator damping power
- Speed of excitation controls
- Governor time lag

The interaction of these factors (for synchronous generation) with the characteristics of the distribution network determine transient stability of the generating unit (see section 3.3.6.4). The reference cited draws attention to the fact that many of the key characteristics listed are not found to be particularly favourable for small scale distributed generation leading to poor performance in fault situations.

The characteristics of induction generators and power electronics interfaced generating units also provide challenges for effective integration into the distribution network. The steady state and dynamic reactive power requirements of induction machines could cause problems for network performance and stability while the characteristics of power electronics have the potential to distort the balanced sinusoidal waveform in the distribution system.

3.3.5.4 Generation control

Two considerations of generation control are required to fully open up this important area. The first, and more commonly considered aspect is the area of real time control of generation dynamics through the traditional channels of excitation, governor and power system stabiliser control. The section on generation stability (section 3.3.6.4) and generation plant electrical parameters (section 3.3.5.3) have outlined the requirements for stable distributed generation and the characteristics of some generating units which make stable operation a difficult objective. Some observers, of the growing number of distributed generating units in distribution networks with poor stability characteristics, have suggested that a centralised control methodology would be required to ensure stable continuous operation of generation through fault incidents. Preliminary analysis of decentralised distributed generation control has shown that, with the use of appropriate control design tools, satisfactory decentralised generation control can be achieved (Dudgeon et al, 2000). The tuning of distributed generation controllers to ensure the steady state stability of larger transmission connected generation is also a key requirement which can again be analysed and assessed with modern control methods (Edwards et al, 2000).

The second area of generation control is really a generation system control activity relating to the dispatch of generation for energy and other ancillary services plus co-ordination activities which may be required as distributed generation grows in deregulated electricity markets. This topic is discussed in section 3.3.4.7 which puts generation control in the general context of distribution network control.

3.3.5.5 Generation protection

The requirements for protection for generation connected to the distribution networks in the UK are set out in Engineering Technical Report No. 113: 'Notes of guidance for the protection of embedded generating plant up to 5MW for operation in parallel with Public Electricity Suppliers' Distribution Systems' (Electricity Association, 1995). These recommendations are used to assist distribution network operators and distributed generation developers to meet the requirements for protection placed on distributed generation plant within the connection standard G59/1 (Electricity Association, 1990).

For high voltage connected distributed generating plant there are requirements to provide the following protection functionality:

- Under/Over Voltage
- Under/Over Frequency
- Overcurrent
- Earth Fault
- Reverse Power

- Neutral Voltage Displacement (for generator earthing arrangements where earth leakage current is considered a risk)
- Loss of Mains

Three interesting matters arise from the protection requirements on distributed generators. Firstly, the extent of protection functionality proves to be expensive for very small generation schemes. Secondly, the assumption in ETR 113 is that the protection requirements are valid only for a small total national output from distributed generation. This assumption may rapidly become invalid if the penetration of distributed generation rises according to some expectations.

The third aspect relates to the provision of loss of mains protection. This protection function is necessary to prevent cases of load becoming disconnected from the remainder of the system with the load being met from one or more distributed generators within the power island. There are a number of problems with the creation of such a power island (Rogers, 1996):

- Loss of system earth where the generator is operating without an earth connection
- Reduced fault level affecting network protection operation
- Possibility for out of synchronism reconnection of the power island to the remainder of system
- Higher source impedance affecting customers quality of supply
- Risk of infringing statutory voltage and frequency limits

It can be seen that loss of mains detection and subsequent tripping of distributed generation is desirable. The most common means of providing loss of mains detection is the use of a rate of change of frequency relay (ROCOF). The relay detects when a generator has been islanded with a load by assuming that the generation output will not match the load and as such there will be a change in system frequency (Shrimpton and Sheard, 1998). The extent (or rate) of change of system frequency is detected by the relay and tripping action is initiated.

The most suitable sensitivity for the relay is a matter of debate. If most islanding events are to be detected the relay must be sensitive to a wide range of frequency changes. However, if the relay is too sensitive, nuisance generator tripping may occur as a result of some frequency altering event other than distributed generation islanding.

There are reported cases in the UK of large transmission connected generator trips and England-France DC interconnector trips causing a change of system frequency which subsequently causes tripping of multiple distributed generation units. There is clearly a security of supply concern with multiple tripping resulting from such events. If distributed generation becomes more prevalent, then multiple unit nuisance tripping may exacerbate an already problematic incident by adding to the capacity of generation (or interconnection) disconnected from the system.

An alternative loss of mains protection to ROCOF which finds application in distributed generation schemes is the reactive export error detection (REED) relay. In this case the reactive power output form a synchronous generating unit is measured and islanding events identified by changes in reactive power export.

Research into alternative means of loss of mains protection has received a concerted effort in recent years. Methods investigated include a power based algorithm (Redfern et al, 1994; Redfern et al, 1997), system impedance measurement (O'Kane et al, 1999), elliptical trajectory technique (Salman, 1997) and voltage collapse method for induction generators (O'Kane et al, 1999).

3.3.5.6 Generation connection design

Some aspects of distributed generation connection design are a matter of preference for the generation developer while some are stipulated by the distribution utility receiving the generation connection. All distributed generation in the UK must follow the recommendations set out in the Electricity Association document G59/1 (Electricity Association, 1990). G59/1 includes the consideration of earthing, connection arrangements and synchronizing amongst many others.

The design of the connection has a bearing on the impact of the generator on the network and the network on the generator. The cost of the connection to the distribution network can be a major cost in developing a distributed generation project (see section 3.3.3.6) and the connection design must be conducted with care to minimise costs but ensure satisfactory performance and compliance with regulations.

3.3.6 Distribution Network Performance

3.3.6.1 Voltage regulation

The effects of distributed generation on voltage control in distribution networks can be quite pronounced. The injection of real and reactive power from distributed generation into the lower voltage networks can result in a voltage rise which in extreme situations can take the voltage outwith statutory limits. The problem is greater in 11kV networks in the UK where there is normally no voltage control equipment between the 11kV network and the customer supply points at 240V. The 11kV/400V transformer ratios are either fixed or manually changed which results in all voltage changes in the 11kV network being experienced directly by customers.

The extent of the impact of distributed generator operation on voltage levels is influenced to a large degree by the size, electrical characteristics, operating regime, network loading conditions and location of the generation units concerned (Thomas and Welsh, 1996). The alteration of real and reactive power flows in the distribution networks due to distributed generation also impinges on the operation of Automatic Voltage Control (AVC) systems linked chiefly to primary 33/11kV transformation. The AVC systems control the voltage at the local 11kV busbars to ensure the voltage drop is acceptable from the busbars to the 11kV/400V transformation points and on to the customer load points. The injection of real and reactive power alters the pattern of power flows and injections which ultimately affects the voltage profile in the network. The use of Line Drop Compounding (LDC) adjusts the 11kV busbar voltage to account for the expected voltage drop of a measured load current or reactive power flow (depending on the exact nature of the LDC scheme). The alteration of power flows and the potential for reversed power flow through primary transformers causes problems for voltage control based on such methods (Rogers, 1996).

There are also potential benefits for voltage control from the presence of distributed generation in distribution networks. Where load growth has resulted in high voltage drops at peak network loading periods, there is potential for distributed generation to positively contribute to voltage control through the controlled injection of real and reactive power (Salman, 1996). The co-ordination of such an arrangement between utility and independent generation operator requires careful consideration and the onerous requirements on distribution companies under their licences to maintain performance of the distribution network may result in a reluctance to contract out essential network performance functions.

3.3.6.2 Distribution plant loading and utilisation

Loading and utilisation of distribution assets are key influences on their need for reinforcement, repair or replacement. As the loading level on particular distribution assets increases, the need for reinforcement arises. While there is some flexibility in replacement timing (due to the fact that plant can be moderately overloaded from time to time with no ill effect), at some point reinforcement will be required. Distributed generation can have beneficial and detrimental effects on plant loading levels depending on the characteristics of the distribution assets and the generation scheme. The effects of distributed generation reducing peak load levels and thus deferring required reinforcement work are discussed in sections 3.3.6.6 and 3.3.7.1.

Irrespective of the effect of distributed generation on peak load (and whether the distribution company would be willing to rely on the generation to be available at peak load times) the very fact that distributed generation is often located close to loads means that the higher tiers of the distribution network are not so heavily utilised. It could be argued that investment in distribution plant which is no longer utilised at expected levels is a case of asset stranding. The under-utilised assets still provide top-up and back-up supplies while distributed generation has taken on the role of routine energy supply. The implications for use of distribution system charges are relatively complex and present a different set of requirements than those for which the present charging structures were designed.

The pattern of plant utilisation is also important, with cyclical patterns of load being replaced by potentially more steady flows of power from distributed generation units. Many distribution plant ratings are based on the assumption that the asset will not be loaded to maximum capacity continuously throughout the day. Distribution ratings for plant tend to be higher than a level at which the plant could be continuously operated based on this assumption of cyclic loads. With distributed generation potentially giving rise to more steady power flows through distribution plant, the issue of plant ratings could become problematic. Higher utilisation levels suggest greater maintenance requirements while lower utilisation levels suggest lower maintenance requirements.

Changes to peak and profiled utilisation of distribution assets in the era of distributed generation present a new set of requirements for distribution plant. The impact on plant safety, maintenance and reinforcement requirements have far reaching effects for distribution companies.

3.3.6.3 Fault level

The fault level (or short circuit) contribution from distributed generation can be quite significant depending on the capacity and electrical characteristics of the generator. Fault level contribution from distributed generation becomes a major issue where distribution network components (mainly switchgear) operate close to their fault level limit without any generation in operation. Many distribution network operators choose to operate their networks near to fault level limits for the purposes of improving power quality (which arises from higher fault level).

Generator connections which raise fault level through the limits of existing plant results in potentially costly switchgear upgrades. The cost of any such upgrade normally falls on the generation developer in the UK at present. The alternatives to upgrading switchgear are not normally satisfactory. The insertion of series reactors in the connection can lead to stability and voltage regulation problems while the disconnection of a distribution infeed circuit to lower the fault level has a negative effect on supply security (Fairey and Redfern, 1996).

3.3.6.4 Generation stability

Transient stability relates to the ability of generating units and the power system to remain in synchronism following large disturbances such as faults or generator tripping (Stevenson, 1982). Smaller generators are particularly susceptible to transient instability due to low inertia of the rotating plant and high transient reactance of the generator itself (Checksfield and Redfern, 1995). These characteristics, and others to a lesser extent, result in the rapid instability and subsequent disconnection of distributed generators following system disturbances. The relative instability of smaller generators causes concerns for system security in cases where a larger proportion of the load is met by distributed generation.

The other aspect of stability which could be problematic for smaller distributed generators is small signal or steady-state stability. The coupling of machines and control systems can be excited by seemingly innocuous events but the results can be as serious for system security and performance as the results of transient instability. However, recent studies focusing on distributed generation small signal stability show that there is a low level of coupling between distributed generators (Edwards et al, 2000). The effects of distributed generation dynamics on transmission connected generation and transmission connected generation dynamics on distributed generation have yet to be fully investigated.

3.3.6.5 Supply availability

One of the key performance measures adopted by the electricity regulator is supply availability (Office of Gas and Electricity Markets, 2000b). In the regulatory year 1998/99 most of the UK distribution companies produced between fifty and one hundred minutes off-supply for the average customer. The trend in customer minutes lost has been downwards since 1990.

The financial welfare of the distribution companies requires them to produce specific standards of performance from the distribution network. In the recent distribution price control review (Office of Gas and Electricity Markets, 1999) the distribution companies were awarded the right to collect a greater or lesser revenue based on the bench-marked performance of their distribution network. Quality of supply (including supply availability) was one measure used to adjust the companies allowed regulated revenue.

Any impact on supply availability from distributed generation would be carefully considered by the distribution companies. The additional complexity of distribution networks with distributed generation could mean that control could be lost in parts of the network during emergency situations. It is also feasible, if unlikely, that generation faults could result not only in generator disconnection but also customer disconnection.

On the positive side, the use of mobile generation to support the network during maintenance is already routine among distribution companies. Distributed generation could fulfil a similar role while also reducing the average minutes of customer disconnection through enhanced security (See 3.3.6.6).

3.3.6.6 Supply security

There are two main effects from distributed generation on supply security both positive and negative.

In section 3.3.6.4 it was noted that smaller generators have particular problems with stability due to their own characteristics and the characteristics of the distribution network to which they are connected. While the generating units are protected from the effects of instability there are potential problems for the rest of the power network. Events in the transmission system may also result in distributed generator tripping due to the characteristics of typical loss of mains protection units (section 3.3.5.5). If distributed generation disconnects from the power system due to instability caused by a system fault or due to inappropriate action of the loss of mains protection, the end result could be very serious. The loss of distributed generation capacity at a time when the system might be already suffering from the loss of a larger generation unit (which brought about the frequency dip causing the nuisance operation of the loss of mains protection) could exacerbate the problem. When distributed generation constitutes a much greater proportion of the system capacity, the disconnection of a large proportion of this capacity could result in tumbling system frequency and ultimately complete system de-energisation. Thus, distributed generation, or more correctly the means of connecting and protecting distributed generation, may have negative consequences for security of supply.

Positive effects for security of supply may also result from distributed generation. If a distributed generating unit is located on the customer side of a substation then the generator capacity will provide additional security to the customer supply. This seemingly simple concept is complicated by a number of factors including the generating unit availability, characteristics of the electricity network and the standards for security of supply. The engineering recommendation on security of supply for the UK is P2/5 (The Electricity Council System Design and Development Committee, 1978). It is widely believed that strict adherence to this standard (and its predecessors) has provided UK consumers with very high supply security levels. Adapting P2/5 to enable the security contribution from distributed generation to be used in distribution network planning calculations is currently a controversial topic (Driver, 2000). The problems with reliance on independent distributed generation for security are numerous but the appeal of deferring upgrades to the distribution network is obvious.

Distributed generation is independent and as such is operated for the benefit of the owners. It is difficult to imagine that ensuring the operation of the generating unit when required for security purposes will be a priority unless supported with commercial incentives. The short, medium and long term availability (for security support) of distributed generation cannot be guaranteed under existing industry frameworks. The financial benefit of deferring a single circuit upgrade for one year can be immense and for this reason overcoming the barriers to releasing the security contribution from distributed generation is likely to continue to receive considerable attention in the future.

3.3.6.7 Electrical losses

Two main issues arise from consideration of the impact of distributed generation on electrical losses in distribution networks. The first aspect is the actual physical change in losses as a result of the operation of distributed generation and the second aspect is the pricing mechanism for these losses.

Losses are incurred as power flows through the transmission system from large centralised generating stations to Grid Supply Points (GSP), where the distribution system interfaces with the transmission system, and on through each of the distribution voltage levels to consumption points. Distributed generation provides power closer (in many cases) to the point of consumption and therefore reduces the need for some quantity of power to flow through the higher voltage networks. In theory this reduces the electrical losses in transport (Thomas, 1996).

A number of factors make the issue of losses more complex in reality. Some distributed generation is not particularly close to consumption points, as in the case of rurally sited wind farms, and power flows through very long distribution circuits to load centres. The losses incurred in doing so can be greater than if the demand at the load centre were supplied through the transmission network. Another factor is the coincidence of the distributed generator output with the local load demand. When the load level in the neighbouring network is high it is likely that distributed generation will alleviate the peak power flows and this will inevitably reduce losses. When the local load demand is low, the excess power from generation units may flow long distances to other load centres and in so doing increase losses. In some cases the power flow may be completely reversed with sections of distribution network 'exporting' power to higher voltage distribution networks or even into the transmission system.

These spatial and temporal aspects of electrical losses have been studied with regard to the second main issue regarding electrical losses: the allocation of losses to particular system users (Mutale et al, 2000). To allocate and thus to charge for losses in the distribution network in a transparent and fair manner promotes greater economic efficiency. A defensive approach towards the issue of distributed generation impact on losses is sometimes evident in the distribution sector in the UK. Distribution companies are sometimes unwilling to concede that there are benefits in loss reduction since some distributed generation schemes are poorly sited and contribute to an increase in losses. The implementation of temporally and spatially variable loss allocation factors and charges would provide incentives for right location and operation of distributed generation.

3.3.6.8 Harmonics

Harmonic distortion of the sinusoidal waveform has become a major issue in recent years due to the vastly increasing numbers of non-linear loads and other power electronics based applications such as power conditioners for distributed generation. Many more distributed generation units are expected to require power conditioning units in the future for the DC-to-AC conversion of power output from photovoltaics and fuel cells to the AC-to-AC conversion of high frequency power output from micro gas turbines. The effects of the additional harmonic voltage and current propagation into the system from distributed generation could be problematic. There is evidence of interference with protective relay operation from harmonic currents (Longrigg, 1992) while concerns over general power quality levels would also be heightened.

3.3.6.9 Phase balancing

The operation of very small generating units connected to single phase supplies could create phase balancing problems within distribution networks. Loads are generally divided between the three phases of the distribution system to create a balance of load across the three phases at each substation. There are periods in any day when loading deviates from a completely balanced state but the diversity of loads connected to any substation keep the phases relatively well balanced over time. Large unbalances between the phases could raise a number of electro-magnetic inefficiencies throughout the system and is generally undesirable.

Diversity in loads has been thoroughly analysed and is relatively well understood. The issues with extensive single phase generation may follow some of the same generalities as single phase loads but it is likely that generation will possess some unique factors also. The extent of this problem and its effects require careful consideration by distribution utilities.

3.3.6.10 Voltage transients, variations and fluctuations

Voltage transients, variations and fluctuations can result from the operation of distributed generation within distribution networks. The terminology is complex in this area and the definitions listed in Table 3-1 have been extracted from a power quality text (Dugan et al, 1996).

Phenomena	Description
TRANSIENTS:	Undesirable and momentary power system variations.
Impulsive transient	A sudden, non-power frequency change in the steady-state condition of voltage, current, or both, that is unidirectional in polarity.
Oscillatory transient	A sudden, non-power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values.
LONG-DURATION VOLTAGE VARIATIONS:	Voltage variations in excess of 1 minute.
Overvoltage	An increase in the rms ac voltage greater than 110 percent at the power frequency for a duration longer than 1 minute.
Undervoltage	A decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 minute.
Sustained interruptions	The supply voltage has been at zero for a period of time in excess of 1 minute.
SHORT-DURATION VOLTAGE VARIATIONS:	Instantaneous (0.5 cycle to 30 cycles), Momentary (30 cycles to 3 seconds) or Temporary (3 seconds to 1 minute) variations to supply voltage.
Interruption	The supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1minute.
Dip	A reduction to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 minute.
Swell	An increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 minute.
VOLTAGE FLUCTUATION:	Systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed 0.9 to 1.1 pu.

Table 3-1: Definitions of voltage transients, variations and fluctuations.

The mechanisms through which transient voltage conditions could arise from distributed generation are not immediately evident. The synchronising, disconnecting and tripping of distributed generation units are likely to create short duration voltage variations while long term voltage variations could arise from interference from distributed generation excitation systems with distribution voltage control schemes (see section 3.3.6.1). Voltage fluctuations could arise from energy sources such as wind and wave generation where the periodic effects of wave impact and tower shadowing (when the wind turbine blade passes the tower) cause momentary voltage variations.

The gains in power quality made by the UK distribution companies in recent years could be undermined in a future where distributed generation proliferates to high levels.

3.3.6.11 Transported units

As a physical effect, the number of units transported through the distribution network will influence the wear on the system components, many of which are sensitive to utilisation levels (see section 3.3.6.2). The volume of energy flowing in the network in any year will contribute to the general level of wear on the distribution system. Distributed generation is likely to reduce the annual utilisation in some parts of the network while increasing the utilisation in other parts of the network. This shifting profile of utilisation has implications for the condition of the network assets in the longer term.

There is also a financial implication from the number of transported units in the distribution system. The distribution price control formula was outlined in section 2.2.1 (Equation 2-1). The regulated aggregate revenue allowed by each distribution company in each year is partially dependent on the number of units (kWh) transported through the distribution network in any year compared to the previous year. The use of on-site generation is likely to erode the volume of electrical energy flowing through the network in any year and, therefore, the revenue allowed will drop. This is naturally of great concern to distribution companies and taken to the extreme of many thousands of very small distributed generation units installed in domestic and commercial premises would completely undermine the financial model which the distribution companies currently rely on to obtain revenue growth.

3.3.7 Distribution Utility Finances

3.3.7.1 Network capital expenditure

Capital expenditure in distribution networks is normally regarded as expenditure on network assets which have long lives. The accounting definition of capital expenditure refers to discreet items which can be said to exist after one year. It is the long life of some distribution assets which makes them hard to plan for with the high level of uncertainty in the electricity supply industry. The performance of the capital investments to produce performance improvements in the distribution network is another area of great uncertainty for distribution companies.

Distributed generation raises the level of capital expenditure uncertainty if it is considered that investments in the distribution network can be left redundant through alterations to network requirements from distributed generation. Load uncertainty has always brought this level of uncertainty through unanticipated changes in network requirements. For example, a network reinforcement made to prepare for anticipated load growth which does not materialise results in stranded assets. So, from one point of view, distribution investments have always been made with reference to some level of risk and distributed generation could simply be seen as another area of uncertainty to cope with. From another viewpoint it could be said that distributed generation in relatively large discreet lumps raises the level of uncertainty in distribution planning at a time when distribution capital budgets are being increasingly constrained by the electricity regulator.

Distributed generation also brings the opportunity for some reduction in capital investment. In certain circumstances distributed generation may provide a service or performance benefit which would normally be required through traditional investments in distribution plant. The distribution company could save some capital expense if these opportunities could be identified and exploited. On the other hand, the requirement to control and manage the distribution network with increasing levels of distributed generation may, at some point, require investment in new systems which may come from the capital expenditure budget. The overall effect of distributed generation on capital expenditure is not clear at present.

3.3.7.2 Network operational expenditure

Operational expenditure relates to the expense of operating the network and running the distribution business. The expenditure cannot be identified after the end of a financial year since the costs relate to such items as personnel, transport and repairs which cannot be valued as assets. The effects of distributed generation on operational expenditure could be potentially significant. The administrative and technical effort required to plan and operate a distribution system of greater complexity will produce costs either in personnel or new computer systems to streamline the work.

It is also possible that distributed generation cold change the repair and maintenance requirements of the distribution system through altered network utilisation patterns which may lead to lower levels of stress on the system in some cases but higher loading levels in other cases. The effects of distributed generation on capital expenditure (section 3.3.7.1) are said to be unclear and this is also true for operational expenditure.

3.3.7.3 Use of system revenues

Distribution use of system revenues are regulated under the price control mechanism described in section 2.2.1. The aggregate use of system revenues allowed in any year depend on a number of parameters set by the electricity regulator including the X factor and base prices plus factors for numbers of connected customers, volume of distributed units and losses. The effect of the volume of transported units on regulated use of system revenues is described in section 3.3.6.11. The effect of losses on regulated use of system revenues is noted section 3.3.6.7. Distributed generation could affect transported units and losses and thus impact the level of regulated revenue.

Total revenue is obviously important to distribution companies and the influences of distributed generation on use of system revenue is an area that needs to be investigated by distribution companies to produce effective strategies for managing this distributed generation impact on the distribution business.

3.3.7.4 Generation connection revenues

Section 3.3.3.6 discusses the issue of connection costs from the generator viewpoint while this section tackles the issue of charges for connection from the distribution company viewpoint.

The term 'deep' connection charge is used for cases where the distribution company makes full recovery of all costs associated with the connection while 'shallow' connection charges cover only a fraction of the cost of the connection. A distribution company is within its rights to charge the generator for the full cost of the connection but may charge only a fraction of the full connection cost because the reinforcement required by the generator will provide benefits for other system users.

The connection construction process is a competitive activity under the current UK regulatory environment. This is to say that a generator could seek an approved third party to construct the connection according to the distribution company specification. The generator may choose this course of action if the price quoted for the connection by the distribution company was beleived to be too high.

Under normal circumstances the distribution company will not make any additional profit from generator connections other than some allowed margin on the equipment and works required for the connection. The costs of connections are normally fully covered by charges made to the distributed generator and as such enter into the distribution finances as an expense and as revenue. Problems could arise in the timing of the expenditure and the receipt of the revenue.

3.3.7.5 Transmission exit charges

Distribution companies in the restructured UK electricity industry pay National Grid Company (NGC) charges to cover the assets required at grid supply points (GSP). The charges are made annually for a very specific set of assets and their ongoing maintenance. The more GSPs a distribution company has or the more extensive or sophisticated the equipment, the greater are the transmission exit charges. At present the distribution company simply passes the transmission exit charges through to users of the distribution system without alteration such that the transmission exit charges do not come within the scope of the distribution price control mechanism.

Some distribution companies think it likely at some point in the future that incentives will be provided for them to manage the level of the transmission exit charges. At present, there are no incentives for the distribution companies to control the level of transmission exit charges. If incentives are introduced then there may be some benefit to distribution companies with significant levels of distributed generation present in their network since the assets involved in each transmission exit point or the number of transmission exit points could be limited due to reduced loading on the GSPs through more significant load take from distributed generation. The issue of transmission exit charges is one which might arise for distribution companies at some point in the future.

3.3.7.6 Distribution plant unit costs

The cost of distribution plant has a major effect on either the extent of capital work a distribution company can undertake for a fixed regulated capital expenditure budget in any year or regulatory period or how much capital expenditure the distribution company seeks in the regulatory review. Either way, the costs of a range of plant items has a major bearing on the distribution company. In addition to the effect on the distribution company, plant unit costs also affect the cost of generation connections to the distribution network which the generation developer must meet (see section 3.3.3.6). As part of the five yearly regulatory review preparations, distribution companies prepare a number of budget scenarios, with the aid of asset management software, which includes the preparation of a comprehensive set of distribution plant unit costs.

If distributed generation causes some change in expenditure on reinforcement, replacement or other works, then the rate of the increase or decrease in expenditure will be related to the distribution plant unit costs.

3.4 Analysing the Distributed Generation Issue Set

The preceding sections have illustrated the volume and complexity of the issues relating to distributed generation. The distributed generation issue set cuts across financial, economic, regulatory, government policy and technical power system disciplines. A number of questions arise for those wishing to take a broad strategic view of distributed generation.

- How can these issues be assessed in a structured manner?
- How can the relationships between the issues be identified?
- What tools and techniques can be utilised to analyse distributed generation in each of the disciplines?

This thesis is built on the need to structure the distributed generation issue set, to understand the relationships between issues and set out a strategic analysis framework to facilitate the analysis of the implications of distributed generation. These ideas and the three questions raised in this section are developed in chapter 5.

3.5 Review of Chapter 3

This chapter has defined distributed generation as generally smaller scale generation connected to the lower voltage levels of power systems (i.e. distribution systems) near load points. A multiplicity of issues relating to distributed generation have been discussed showing the complexity of this relatively new development in electricity systems and the need for clear quantitative analysis of the issues.

The volume, complexity and diversity of the issues point to structured analytical frameworks to provide broad understanding of the implications of growth in distributed generation. The generalities of the constitution of such analytical frameworks will be discussed in chapter 4 while the specification of such an analytical framework for distributed generation is developed in chapter 5. The implementation of the framework is defined in chapter 6 with results from the use of the strategic analysis framework presented in chapter 7.

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Chapter 4

DISTRIBUTION SYSTEM PLANNING

4.1 Summary of Chapter 4

This chapter puts planning techniques for distributed generation into the context of the wider activities of power system planning (section 4.2). The general processes of distribution system planning are also explored (section 4.3) to highlight that planning for generation connected to the distribution system is a new area which receives little attention in established distribution system planning methodology.

A set of general characteristics of modern power system planning methods is established in section 4.4. These characteristics form the design foundation of the distributed generation strategic analysis framework which is specified, implemented and demonstrated in chapter 5, chapter 6 and chapter 7 respectively. The use of scenario based techniques to deal with future uncertainties in power system planning is noted in several places in this chapter. The production of scenarios of distributed generation is one of the key techniques taken forward and implemented within the distributed generation strategic analysis framework proposed in this thesis.

Finally, a review of published material relating to distributed generation planning is presented (section 4.5). This review shows that, while distributed generation planning has received some attention in the literature, most applications of planning methods for distributed generation assume that the generation ownership and operation is an option for the distribution company. This is not the case in the UK where distribution companies are explicitly prohibited from owning generation. Any distributed generation appearing in the distribution networks of the regulated distribution companies is therefore independent. There is therefore great scope for investigating methods for planning for distributed generation from the viewpoint of the privately owned regulated distribution companies.

4.2 Power System Planning Concepts

4.2.1 Energy System Planning

The highest level of planning applicable to power systems is planning conducted at a national government level. The general approach to state energy system planning and how it relates to power system planning is illustrated in Figure 4-1 (Wang and McDonald, 1994).

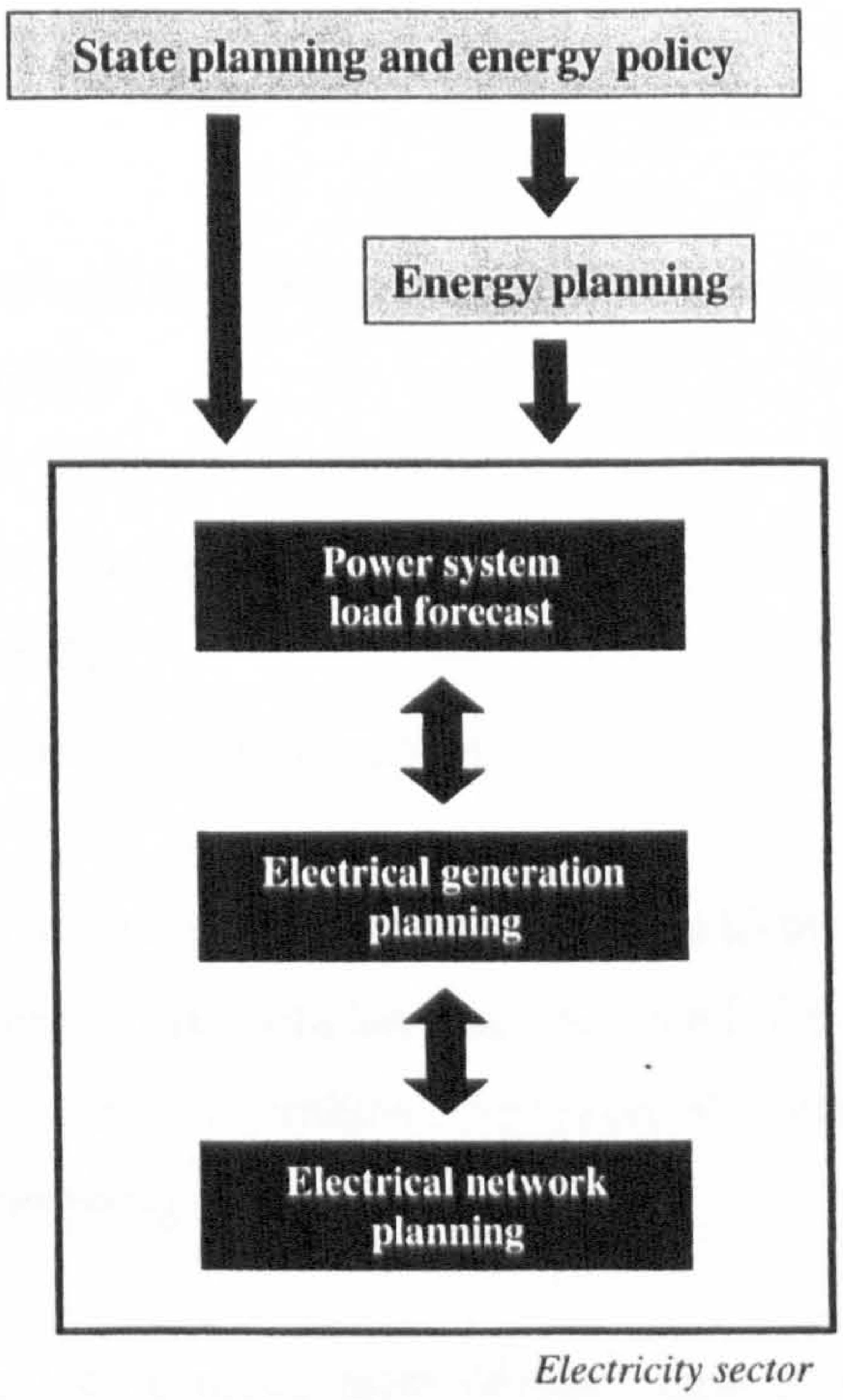

Figure 4-1: State policy impacts on energy system and power system planning.

A national government may legislate on matters which directly affect power system planning or may indirectly influence power system planning through legislation for the whole energy sector. For example, measures affecting the permitting system for the construction of new overhead lines affects power system planning directly while lifting restrictions on the use of natural gas for power generation affects the whole energy sector.

Within the electricity sector, three main planning activities have been identified:

- Load forecasting
- Generation planning
- Electrical network planning

A brief description of each of these areas sets the context for analysis of distribution planning which can be viewed as a specific area of electrical network planning.

4.2.2 Load forecasting

Three general groups of load forecasting techniques are commonly cited (Wang and McDonald, 1994; Lakervi and Holmes, 1995):

- Extrapolation (or time series) methods
- Simulation methods
- Econometric (or multivariate) analysis

Extrapolation methods use various techniques to project historical load growth levels to the future. In its simplest form a basic extrapolation may be valid for two to three years. More complex extrapolation methods such as logarithmic, regressive and moving average techniques can be applied to longer term load forecasting with satisfactory results.

Simulation techniques take a much more detailed view of a particular load area and analyse the composition of load and the likely load growth in each of the customers or customer groups identified. This type of spatial analysis and forecasting of load is particularly common in distribution where the areas involved are likely to be smaller and more manageable from an analytical viewpoint.

Econometric (or multivariate) analysis of loads correlates load growth to a number of more general variables such as national economic growth or inflation and is therefore most applicable to national or regional load forecasting.

4.2.3 Generation planning

Generation planning is the process of making decisions to invest in new generation capacity and retire old generation capacity based on minimising the cost of the whole generation system. Timing, location, capacity and technology of the generating units are the main decisions to be made in most generation expansion planning problems. Production cost simulation techniques are used to quantify the total generation system cost for a particular year to meet the expected energy demands placed in the system. Production simulation is combined with various optimisation techniques whose objective is to minimise total system cost (capital and operational) given a set of constraints such as plant maintenance, reserve margin and generation system reliability. The main uncertainty in the generation expansion planning problem has tended to be the level of load growth for which to plan. This made generation expansion planning particularly difficult in the past since generating station lead times for coal and nuclear plant (the two main options) were in the region of five to ten years when load forecasts tended to become much less certain.

Various sophisticated techniques have emerged to optimise the generation plan given the uncertainties of load growth plus other uncertainties relating to fuel costs and plant capital costs. The list of techniques applied to the optimisation of generation plant mix is extensive and includes dynamic programming, fuzzy logic, genetic algorithms and multiple criteria decision making.

Restructuring of the ESI has removed the need for such generation expansion planning techniques in the UK since no generation company in a competitive wholesale market structure has the responsibility to optimise the whole system and provide services such as reserve margin. Generation investment decisions are based purely on financial criteria within the independent private generation companies.

4.2.4 Electrical network planning

Electrical network planning is essentially about providing a power network with the capacity to transport electrical energy from generating units to consumers premises with the least cost while meeting certain performance standards such as voltage level and security. The formulation of the problem in network planning is essentially the same as for generation planning – where to build new circuits, what type of circuits to build and when to build them.

Network planning methods can be broadly separated into two main areas:

- Heuristic methods
- Optimisation methods

Heuristic analysis is based on the intuition and experience of a system planner or an artificially intelligent system as a proxy for the system planner. A proposed extension to the electrical network is simulated to test for adequate steady state, contingency and dynamic performance using appropriate tools. The mathematical optimisation methods seek to establish an ideal electricity network which meets all forecast future needs for power while meeting a least cost criteria. The optimisation techniques used for network planning tend to be different from those used in generation planning due to the formulation of the network objective function (which often includes a square term for losses) and the possibilities for solutions with multiple combinations of circuits and nodes. To address the issue of whole system optimisation (see section 4.4.1), combined network and generation planning techniques have also been proposed.

Network expansion planning has changed since the advent of electricity industry restructuring with its independent generating companies and profit or price regulation of natural monopoly transmission and distribution companies. The core analysis tools and techniques have remained the same but the planning and decision making objectives have changed. While least cost planning is clearly a sensible philosophy it is not the main objective of modern utilities where the overriding criteria is 'most profit' which sometimes requires a different approach from a strict least cost solution. For example, regulatory incentives to enhance power quality and supply security sometimes require heavy investments to improve performance and claim the incentive payments available within the regulatory mechanism.

4.2.5 Deficiencies with traditional planning techniques

Traditional power system planning techniques have a number of serious deficiencies which planners are now addressing to an extent. Berrie (Berrie, 1992) notes that in the late 1980s, a number of 'serious defects in the traditional methods of planning' were identified:

- Inaccuracies in load forecasting, cost, construction time and plant availability.
- Over- and under-planting resulting from traditional planning techniques.
- Pricing developed from least cost plans failing to give appropriate economic signals.
- Sub-optimal plant mixes resulting from traditional planning techniques.
- Traditional planning failure due to sudden changes in the industry.
- Separation of long-term planning activities from ownership and accountability for system operation.
- Co-generation and auto-generation not owned by the utility.
- Least cost plans rarely resulting in least cost system operation and investment.
- Consumer reaction being excluded from the planning process.
- Limited crossover with other energy sector planning activities.
- Loss of faith by decision-makers in computer based planning software.
- Inability of planning techniques to deal with uncertainty despite elaborate sensitivity analysis and risk analysis features.
- Lack of capability of traditional planning techniques for entrepreneurial planning.
- Failure to take account of and make use of the private sector in electricity supply.

The deficiencies with traditional techniques stem from a number of core facts which are implied with the list of deficiencies noted above. One strand of the problem with traditional planning techniques results from the attempt to generate an optimal plan for what is essentially an uncertain future. The uncertainties appear as inaccuracies in forecast data or failures to appreciate a substantial change in direction of the industry or society as a whole. The inability to deal with a highly uncertain future leads to poor decisions and sub-optimal developments to the power system. Sub-optimal plans take many forms but essentially arise from poor allocation of resources through either under or over-investing, poor timing of investments or investments in the wrong technology or in the wring location. This topic is discussed further below in section 4.4.4.

Another general area of planning deficiency is the inability to deal adequately with restructuring of the electricity supply industry. As discussed in chapter 2 (section 2.2), the electricity supply industry has undergone and continues to undergo substantial changes in structure and ownership. With responsibilities changing and private investors keen to exploit new opportunities, the role of the central planner has diminished (or even disappeared).

The power system planning activity can be further undermined by the lack of importance granted to external influences (externalities) on and from the electricity industry. The lack of incorporation of consumer and environmental issues in the planning process are examples of issues not wholly addressed by traditional planning methods which may result in further deviation from a true least cost plan. Plans may be least cost in strict financial terms for the utility company concerned but may be far from least costs in the wider economic sense.

The final area of deficiency in planning noted by Berrie is private investments in auto-generation. In a more general context this is the topic of independent distributed generation which will be tackled in this thesis.

Chapter 2 outlined the changes in the structure of the electricity supply industry which have created a more dynamic sector with a range of new opportunities. Distributed generation is one such area of opportunity. The list of perceived shortcomings in planning methodology presents another area where opportunity for innovation exists in abundance. This thesis is built on these two ideas: the opportunity for vast growth in distributed generation, and; the need for modern planning approaches to deal effectively with distributed generation.

4.2.6 Desired features of modern planning methodologies

To emphasis the new requirements of planning techniques in the modern day electricity industry Berrie (Berrie, 1992) lists the following desired features of modern power system planning:

- Selection of development programmes which are most robust
- Flexibility in development programmes.
- Scenario planning (rather than deterministic planning).
- Treatment of decisions as individual events (based on current knowledge) in the longer and ongoing process of planning.
- Bringing demand side more fully into the planning process.
- Use of interactive, computerised, graphic displayed, computer models of planning alternatives for use by decision-makers.
- Treatment of planning as a product of the market and pricing (not vice versa).
- Use of theories of games, war and catastrophes in electricity planning.
- Obtain multiple-objective solutions rather than single least-cost solutions.
- Treatment of utility capital and operational costs in financial terms (not only in economic terms as in the past).

- Treatment of demand management projects and conservation as alternatives to generation expansion.
- Treatment of annual return on assets as the meaningful parameter for the utility.
- Prices to trend towards the fully competitive.
- Use of short-run marginal costs rather than long-run.
- Assumption that dynamic real time pricing will gradually take over from prescribed pricing.
- Explicit treatment of co-generation and auto-generation in the planning process.

As with the previous list of deficiencies in power system planning (section 4.2.5), Berrie brings great insight to the requirements of power system planning in the current age of greater pace of change and greater level of uncertainty in the electricity industry. The general philosophies in this list of modern power system planning techniques will be developed in section 4.4.

4.3 Distribution Planning

Traditionally, the three main activities in distribution planning have been (Willis et al, 1987):

- load forecasting
- substation location and sizing
- feeder routing and design

The engineering factors of most importance in conducting these three network planning tasks are (Khator and Leung, 1997):

- Kirchoff's current law
- Kirchoff's voltage law
- Concave variable cost in feeders
- Radiality of feeders
- Voltage drop on feeders
- Substation normal capacity

- Substation distribution capacity
- Substation emergency capacity
- Feeder emergency capacity

In addition to dealing with the complexities of the distribution network from an engineering viewpoint, the costs and benefits of various courses of action must also be evaluated.

In recent years, standard distribution network expansion planning has been extended to include other aspects of 'asset management' such as investments based on condition monitoring assessments and careful targeting of investments to leverage better performance from the distribution network. In addition more focus has been centred on planning automation and control schemes to enhance network performance. The general area of asset management has brought much closer integration of technical analysis and business needs and has tended to utilise sophisticated information technology techniques and draws on planning and operational databases as sources of analytical input. The techniques used by distribution network asset managers compare much more favourably with the requirements of modern planning techniques outlined by Berrie than traditional distribution expansion planning techniques (section 4.2.6).

In addition to advances in the treatment of the business needs of distribution businesses, distribution system expansion planning techniques have evolved to include heuristic based approaches to represent the fact that distribution system development consists of rather more than simply minimising the costs of investment and losses and requires a high level of expert judgement. Interactive simulation based approaches enable the distribution system planner to interact with the planning programme and, through the use of expert systems and multiple criteria decision making approaches, result in more comprehensive analysis and better plans (El-hami, 1995). Advances in the core methodologies and techniques for distribution planning are advancing but are still some way from the vision for modern planning methodologies set out by Berrie (section 4.2.6).

The three areas of distribution planning noted at the outset are expanded in the following three subsections (4.3.1, 4.3.2 and 4.3.3).

4.3.1 Distribution load forecasting methods

Load forecasting is concerned with predicting the capacity and volume of electricity demand in one or more specified periods in the future. To enable the following two distribution planning activities (substation location and sizing and feeder routing and design) to be conducted effectively, the location of future load growth requires careful assessment.

Section 4.2.2 discussed three general groups of load forecasting methods. Econometric or multivariate load forecasting is unlikely to provide sufficient resolution for distribution planning purposes. Time series and simulation methods tend to be the most common approaches to distribution load forecasting.

4.3.2 Substation location and sizing

When the load forecast has been prepared, the most suitable location for substations to service the loads can be determined. This activity must take account of existing substations such that consideration is given to capacity additions to existing substations as well as to the construction of new substations.

Traditionally, the substation location and feeder routing problems in distribution expansion planning have been tackled with optimisation techniques. The optimisation methods are chosen to best deal with the formulation of costs of substation and feeder capacity and include linear programming, dynamic programming, integer programming and quadratic programming. Techniques for non-linear problems which better represent the distribution expansion planning problem of location and size of substations and length, route and capacity of circuits, include genetic algorithms, simulated annealing and artificial neural networks (Ferreira et al, 1999).

4.3.3 Feeder routing and design

When the nature and location of future load requirements and the best locations and capacity of substations have been determined, the layout and design of the distribution feeder system can be addressed. This involves decisions regarding the use of different types of overhead and underground circuits, along with switching arrangements.

The techniques proposed for feeder routing and design have been discussed in section 4.3.2 above. The treatment of uncertainties has led to the proposal of risk based techniques in recent years although it is not clear to what extent these techniques are used in practice.

4.3.4 The distribution system expansion plan

The sequence of three major activities outlined in sections 4.3.1, 4.3.2 and 4.3.3 constitute the process of distribution expansion planning. Expansion planning produces an evolution in network designs through a number of years to a horizon year at some point in the future. The expansion plan covers the type, rating and location of primary network components such as cables, lines, transformers and switchgear. Therefore, the distribution expansion plan focuses mainly on load related reinforcements of the system and it has been shown in the preceding subsections and in the literature (Gonen and Ramirez-Rosado, 1986) that many problem formulations and techniques can be applied to various aspects of the distribution expansion planning problem.

The detailed design of primary plant along with ancillary components for communications and control will be conducted prior to installation. Installation may be planned for many years from the inception of the plan. Further planning activities in the intervening years may result in alterations to the scope or timing of planned extensions to the system due to changes in the assumed requirements of the system in future years.

This 'traditional' view of distribution expansion planning does not include any notion of other system developments to address the increasingly important areas of power quality, information systems for asset management and control, or environmental programmes. Distributed generation is becoming one of the most important system developments likely to affect the performance of distribution plans.

4.4 General Requirements in Power System Planning

Many contributors in the field of power system planning have outlined a desirable features of power system planning techniques. In the consideration of a new strategic analysis framework, as outlined in this thesis, it is crucially important to assess and then build on these aspects of planning best practice. While the focus of this section remains on distribution planning, the generalities for power system planning and other planning fields will become evident.

Desired planning methodology characteristics have been grouped according to their relationship to the whole planning activity. The groups chosen for this discussion of the requirements of modern power system planning techniques are:

- Planning activity scope
- Planning framework structure
- Planning process
- Future focus of planning activity
- Planning decision process
- Planning information recording

There is some degree of overlap between these areas such as the desirability for the decision process to incorporate the uncertainties identified in the necessary future focus of planning activities.

It should be noted that the use of computer technology for power system planning activities is assumed throughout this chapter, and indeed throughout this thesis. The complexity and magnitude of power system planning activities are not just aided by modern information technology but could be said to be dependent on high specification hardware and software.

4.4.1 Planning activity scope

There are three main areas relating to the scope of planning activities which should guide the construction of new planning techniques and methodologies:

- criteria, issues or attributes to be considered
- options or alternatives to be considered
- scope of power system to be considered

In recent years, there has been a major shift in planning and strategy formation activities towards multiple criteria, multiple attribute or multiple objective techniques (Mollaghasemi and Pet-Edwards, 1997). The manner in which decisions are made is the focus of section 4.4.5 and will not be treated thoroughly here. The important point to note is that good planning techniques deal with as many relevant issues as practicably possible. Andrews also discusses the idea that, in order to incorporate all the possible issues and preferences in a planning problem, all stakeholders in the result of the planning process should participate in the planning process itself (Andrews, 1990). In this manner, planning becomes an open process with contributions from many interest groups which may include consumer representatives, local planning authorities, environmental concern bodies and others for power system planning activities.

The concept of dealing with all or as many issues as possible is an integral part of the multiple criteria planning concept. Burke, Merril, Schweppe *et al* (Burke et al, 1988) relay some of the core concepts in multiple criteria planning such as options, uncertainties and attributes. The focus of their paper is on tradeoff and risk analysis methods in multiple objective planning.

The basic multiple objective planning process involves following the steps outlined in Figure 4-2.

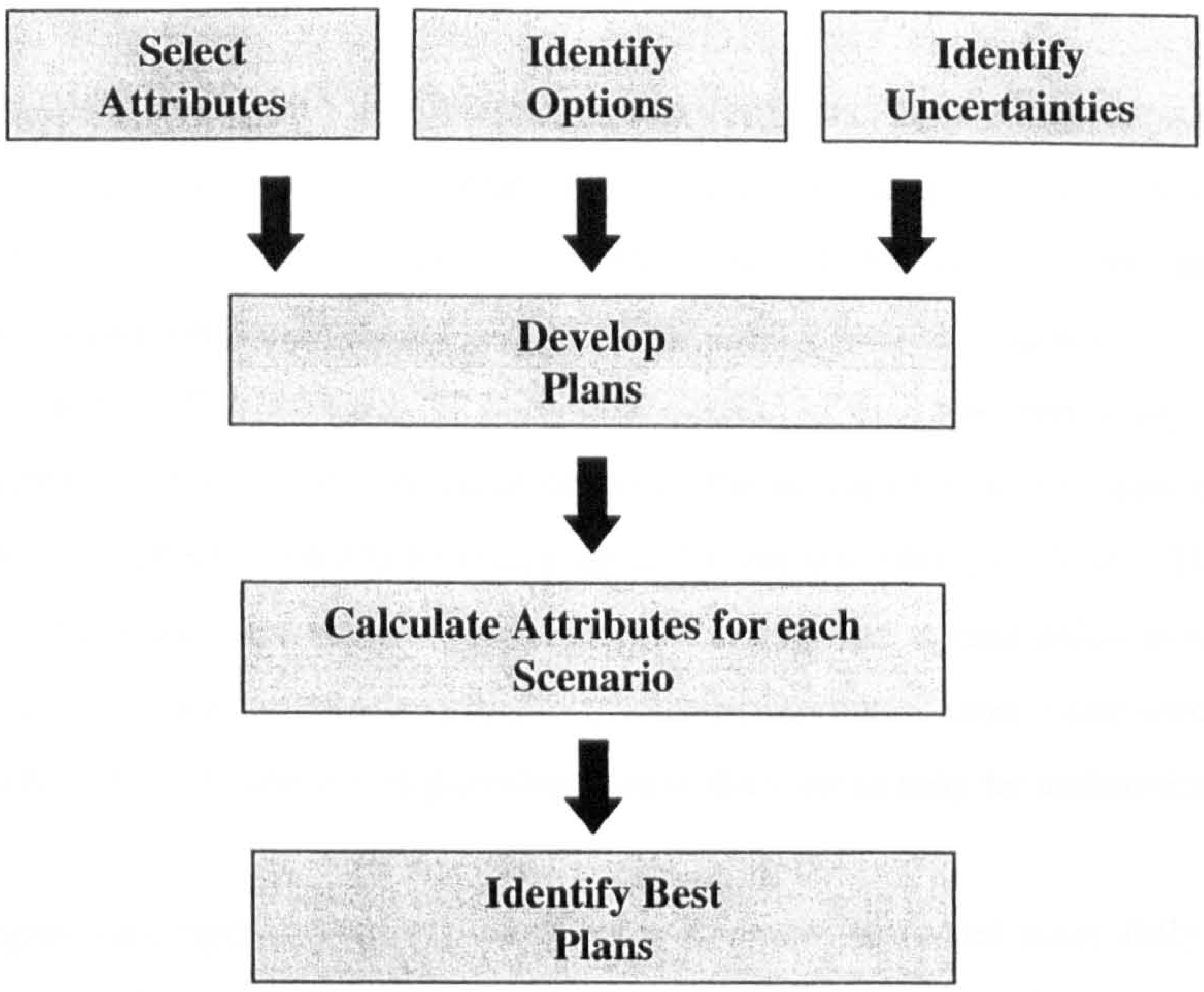

Figure 4-2: General multiple objective planning process.

It can be seen that the issues of importance as represented by attributes are clearly identified in the first step of the process along with any uncertainties to be dealt with and the possible options for the decision-maker. The next step is the development of a range of plans from individual options. Unlikely planning options often perform well across a diverse set of attributes and also against an uncertain future. It is therefore desirable to produce a wide range of planning options to maximise the chances of identifying a high performance plan.

The proposed strategies (or plans) are simulated to produce results in terms of the attributes selected in the first step. It should be noted that the range of possible attributes may be far greater than the ability to simulate them in which case a reduced set of attributes is selected to best represent the underlying problem to be solved. The final step is to use some method for identification of the best plans as simulated against a set of attributes with a range of uncertainties. The techniques for the identification of best plans proposed in this paper (Burke et al, 1988) are based on the concept of trading off one plan against another across the full range of attributes. It is very unlikely that any one plan will perform best with respect to the full set of selected attributes so a sequential approach to eliminating poorer performing plans is adopted.

The specifics of tradeoff methods and other decision making methodologies are discussed further in section 4.4.5.

In addition to the wide scope of the planning exercise in terms of all the issues in the planning problem, it is equally important that planning activities seek to optimise systems rather than components within the system. Thus the optimal plan for an individual distribution plan may result in a sub-optimal plan for the system as a whole. Steiner (Steiner, 1985) discusses the importance of total system optimisation and the requirements for analytical tools which are capable of dealing with large and complex problems. The advance of computer capability has resolved many of the technical problems for planners of the last two decades (such as the issues of whole system optimisation) but has raised the expectation of solutions to emerging and more complex problems. The unbundling of electricity supply chain functions seems to act against whole system optimisation as individual private companies may make decisions which optimise system performance from their own perspective. In this way the benefits of co-ordination of planning across the system may be undermined.

A fourth area regarding scope of planning activities is time and is treated more fully in section 4.4.4. Planning, by its very nature, should deal with an appropriate time horizon. It is interesting to note that planning horizons are becoming shorter which is surprising given the additional sophistication of the tools and techniques available to planners. Mostly, this shortening of planning horizons is due to new electricity industry structures and ownership which tend to make private utilities more short-term oriented. In addition, the regular industry reviews by government appointed regulators, backed up by wide ranging powers of intervention, produce significant risks for inflexible plans beyond the next regulatory review (typically five years hence).

4.4.2 Planning framework structure

The structure of a planning framework can be crucial to the success of the planning activities undertaken within that planning framework. This section will discuss a list of key planning framework structural characteristics which can have great bearing on the quality of the planning activity:

- modular
- integrated
- automated
- data-handling

The first two features are closely linked, as are the third and fourth features. This will become evident as these features are discussed.

A modular approach to the structure of a planning framework facilitates the exploitation of the most appropriate analytical functions and applications for the planning task. Often a utility company will have licences for and operate a number of individual software application items which can be brought to bear on a planning problem. The successful integration of these functions has the potential for great benefit in planning outcomes. A recent article described the harnessing of information from a number of analytical applications for the purposes of power system planning (Rajnpreht and Bray, 1998). The article describes the integration of several power system models:

- power system simulator
- electricity market model
- load forecasting
- electromagnetic transients
- harmonic analysis
- eigenvalue analysis

The foundation for this modular approach is a common database of power system and operational information. The article suggests that power system planning results are enhanced with the inclusion of multiple analytical functions.

A modular approach to planning frameworks leads to requirements for successful integration of the modules, the second feature of planning framework structure.

Mukerji *et al* (Mukerji et al, 1994) provide a description of an early integrated framework for power system planning. Their planning framework consists of a graphical user interface combined with data-handling facilities which together drive a number of analytical modules:

- production costing
- load flow
- optimal power flow
- stability

The core power system analysis functions are integrated with artificial intelligence and optimisation techniques to yield a power system planning framework to produce enhanced results from a set of analytical resources. In essence, the adoption of a modular approach, with its many benefits, requires that the analytical modules be integrated successfully.

The third feature of planning frameworks is that they be automated. It hardly seems necessary to describe the benefits of automation with the usual increases in productivity that normally accrue to automated processes. Automation of power system planning activities can take several forms. Two main aspects of automation seem to appear in the literature: batch processing and solution generation. Both of these features replicate the steps normally taken by a planning engineer in the planning process. Batch processing enables the execution of multiple analytical activities with minimal input from the planning engineer while automated solution generation produces many feasible solutions to a given problem for further investigation by the evaluation modules.

A further important aspect of automation of the planning process is the replication of decisions and judgements made by the planning engineer. Mukerji *et al* (Mukerji et al, 1994) describe the use of knowledge based artificial intelligence techniques to produce rules to enable focus on the best solutions to a transmission planning problem. In addition, numerical optimisation is often used to evaluate an 'exact' best solution to a planning problem (according to the objective function) thus replicating and enhancing evaluations which the planning engineer may have previously made.

The fourth important feature of a planning framework is the ability to handle large volumes of data from diverse analytical applications and databases. This point is clearly noted by Rajnpreht and Bray in their article on an integrated generation and transmission planning framework for the Australian power market (Rajnpreht and Bray, 1998). Four key elements of the data handling requirements of the planning framework are noted:

- data repository for all application data requirements
- data communication between applications
- transfer of operational data into planning framework
- data models for input to applications

With increasingly more emphasis on databases within utilities it is certain that data handling and the integration of utility databases into planning frameworks will continue to attract much attention in the future.

4.4.3 Planning process

Several aspects of the planning process itself are seen to be important in the literature. This section discusses the following features of the planning process:

- productivity enhancement
- flexibility to planning resource availability
- provision of robust solutions where planning resources are scarce
- provision of insight
- openness to stakeholders
- appropriate use of simulation and optimisation techniques

In a paper of its time, Northcote-Green and Ayre (Northcote-Green and Ayre, 1985) discussed many of the then emerging computerised distribution planning techniques and their benefits for system planners. Of key importance, at a time when computing power was not high, the amount of data to be handled in planning activities often proved to be restrictive. A focus on time taken to perform planning activities or, in other terms, the productivity of planners was an important consideration with computer techniques inevitably increasing productivity. With the astounding advances in computing power it may be surprising to find that the issue of productivity remains. Power utilities have increasingly smaller human resources available to perform increasingly complex planning activities. The issue of enhancing the productivity of system planners through appropriate computer tools and techniques is just as important now as then. Northcote-Green and Ayre present a planning performance index which is defined as follows:

$$\text{Planning Performance Index} = \frac{\text{Quality of Result of Planning Process}}{\text{Time taken to perform Planning Process}}$$

Equation 4-1

The relative performance of a planning activity is a function of the time taken and the quality of the result. The time taken to conduct a computerised planning study is, in turn, a function of the data entry requirements and the complexity of the analytical techniques utilised to process the data. Planning engineer time is now an equally (if not more) important resource than computer simulation time. In the restructured electricity industry computer time, human resource time, data requirements and availability of analytical resources are all under pressure from utility efficiency drives. As a result of the need to maximise productivity there must be a tradeoff between the quality of the planning result and the expenditure of resources in conducting the planning activity. In general the more resources allocated to the planning activity the higher quality the result that will emerge.

Flexible planning processes enable a planner to select the level of resources to be allocated to a planning activity in the knowledge that the end result may be compromised by committing less resources but that a reasonable result can be obtained nonetheless. Flexibility can be built into planning processes through open and modular approaches to the planning framework where analytical modules and databases can be integrated into the planning framework as necessary or as dictated by the resources available for the activity (see modular planning frameworks: section 4.4.2).

Taylor (Taylor et al, 1997) notes that optimisation will become increasingly important for utilities operating in the post-restructuring period since quick, effective answers will be required to many problems and optimisation techniques can provide both the speed and a degree of certainty regarding the quality of the result. However there are problems with moving wholesale to optimisation as the technique of choice for planning. Optimisation can sometimes appear opaque to the planner who receives little insight into the effects of different uncertainties and strategies as the optimisation process progresses. Simulation, rather than optimisation, provides insight and also enables a planner to provide more human judgement in the planning process. Not being restricted by an objective function as with an optimisation technique also brings benefits to the planning process which may otherwise be forced down a limited number of search paths by the formulation of an objective function. There is therefore a tradeoff to be made in the extent of use of optimisation in planning activities.

Willis and Northcote-Green also provide an insight into the thorny area of testing the validity of planning methods and processes (Willis and Northcote-Green, 1985). Since issues to be planned for, by their very nature, occur in the future, it is difficult to make comparisons between competing planning methods in the present day. Willis and Northcote-Green propose that comparisons between planning methods are made using a historical data set. The optimal plan for the actual sequence of events can be defined (since it is known) and this result compared with the result from each of the proposed planning methods based on their result calculated from data available at the beginning of the historical planning period. Figure 4-3 illustrates a comparison with an optimal plan where the optimal plan is based on fully known data through out the historical period and any proposed planning method has the data available in year '-30' only.

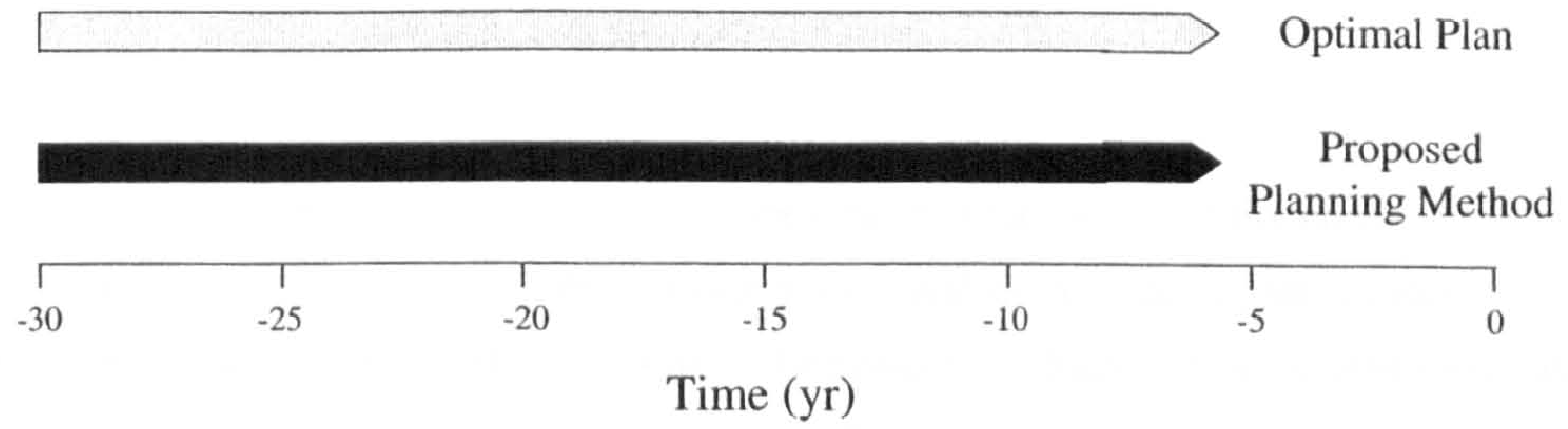

Figure 4-3: Assessment of proposed planning method by comparison with the optimal plan for a historical data set.

It is not difficult to see that assessing a planning process proposed to meet a relatively recent need could have difficulty using this method for testing. Restructuring has disturbed the traditional assumptions in the electricity industry to such an extent that using pre-restructuring data for comparisons of planning methods could be risky.

The planning process must also be robust against limitations regarding available data and the planning methods themselves. Willis *et al* (Willis et al, 1987) conducted a study of available distribution planning software and made comparisons of each individual software package and combinations of the software packages to conduct each of the three main distribution planning activities (i.e. Load Forecasting, Substation Siting and Feeder Circuit Planning). One of the key attributes studied was the robustness of the method against input data errors and omissions. Some of the planning methods were able to produce surprisingly good results despite a relatively high number of errors and omissions in the input data.

One further feature of planning methods is that they be insightful. This is to say that in using the planning tool, the characteristics of the system being planned become better understood through conducting the planning process, as do the component features of successful solutions to the planning problems (Willis et al, 1995). Interactivity (user to computer) and the use of graphical methods contribute to the insightfulness of a planning tool.

4.4.4 Future focus of planning activity

Power system planning by its very nature focuses on future needs of the power system. Necessarily, planning also takes account of the existing system and the results of past decisions. The essence of planning, however, is to make decisions in the present (or delay decisions until some later date), with currently available information, to best meet the future demands on the power system within all relevant constraints. The constraints on power system development tend to be related to technical standards, statutory obligations and financial limitations.

The first aspect of the future focus of planning to note is that decisions taken and plans made in the present have potentially large impacts on the future performance of the power system and the power utility. Decisions lead to favourable results or non-favourable results with financial significance well beyond the cost of the planning activity. Thus it can be said that planning activities leverage the future. Steiner (Steiner, 1985) notes that, along with whole system optimisation (section 4.4.1), leverage is the most important aspect of planning. Figure 4-4 illustrates the typical through life expenditure characteristic for some item of power plant. The exact proportions of costs between the different phases of the asset lifetime will depend on characteristics of the asset such as whether the asset is network or generation related. The height of the curves illustrate the rate of expenditure on the project in its various phases from planning and design through construction and operation.

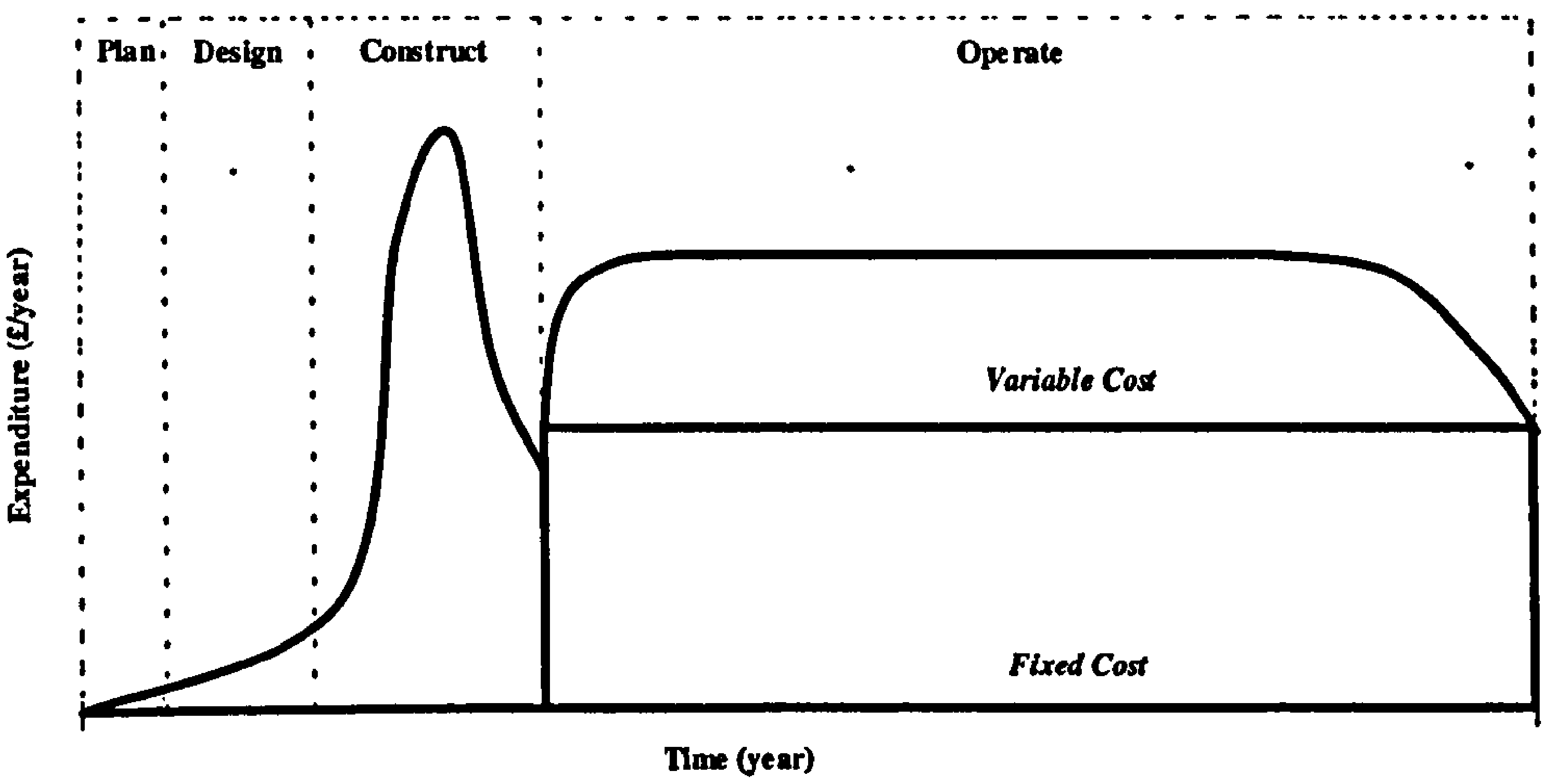

Figure 4-4: Leverage characteristics of planning activities (Steiner, 1985).

The small 'wedge' of cost (shaded in the planning phase of Figure 4-4) for planning can have significant bearing on the magnitude of the costs for the remainder of the life of the asset. For example, investment of additional resources in the planning phase could result in a saving of as little as half a percentage point in operational costs. Over a forty to fifty year life for a network asset, this seemingly small saving could be very substantial.

Similar arguments relating to leverage can be made for the design process also although it is in planning that the greatest leverage is gained. The plan must be correct for the design to be truly effective.

Planning is critical to the initial capital costs and the ongoing operating and maintenance costs of power plant, whether generation or network related. Leverage is, not so much a desirable feature of planning as, an illustration of its importance and justification for resources employed in planning activities.

The major aspect of the future focus of power system planning is uncertainty. If the future were certain or accurately predictable, then forming plans would be a much simpler matter. In a 'certain' future, there would still be conflict between objectives and preferences of all the stakeholders in a decision but the task of forming plans to meet these objectives would be more straightforward. Uncertainty makes the planning process much more difficult.

An IEEE Long Range Planning Working Group Survey (Sener and Greene, 1997) on the areas of most concern for system planners in a wide range of United States utilities found that uncertainty was the main area of concern. The highest ranking problem was general industry uncertainty relating to restructuring and competition while the second ranking problem was generation uncertainty. Generation uncertainty relates to the impact of independent generation on network focused utilities. One of the foundations to this thesis is that the uncertainties relating to independent distributed generation are causing major concern to the UK distribution utilities. Such uncertainty leads to requirements for analytical frameworks with the capability to deal with such uncertainties. Restructuring of the electricity industry has provided the platform for growth in distributed generation which is now producing substantial levels of uncertainty among the UK distribution companies. It can be seen that the two major areas of uncertainty identified by the IEEE working group are directly impacting the area of distributed generation.

Uncertainties in the electricity industry take various forms, and techniques have been produced to deal with the many forms of uncertainty. Traditionally, uncertainties have related to load (location, magnitude and timing) and the fuel costs and capital costs of generation. A CIGRE working group (37.10) under the Power System Planning and Development Study Committee was tasked with the job of reviewing techniques for planning under uncertainty (Van Geert and CIGRE Working Group 37.10, 1995). The two main techniques identified for dealing with uncertainty in power system planning are:

- Scenario method
- Decision tree analysis

The scenario method involves the creation of a set of scenarios which represent the future with particular assumptions regarding uncertainties. Various strategic options (controllable parameters) are assessed against these scenarios and values of a set of performance measures (or attributes) are generated for each combination of strategy and scenario.

Some criterion is used to evaluate these attributes and assess the best strategy across all of the scenarios deemed plausible. The criteria often utilised are:

- Mathematical expectation of outcome
- Minimise the maximum regret
- Laplace criterion
- Von Neumann-Morgenstern criterion
- Hurwicz criterion

The mathematical expectation of outcome is the sum of the individual products of the attribute value for a particular strategy and the probability of the scenario occurring. In this case, the planner or decision-maker must use judgement to assign occurrence probabilities for each scenario. The Laplace criterion is similar to the mathematical expectation but assumes that the future is so uncertain that the selection of a probability of occurrence for each scenario is banal. In this case, equal probabilities are selected for each scenario.

Minimising the maximum regret focuses attention on how much is lost by choosing a particular strategy under one scenario. The result for the strategy in each scenario is compared with the best strategy for that scenario and the difference between the strategies is termed the regret. The best strategy is that with the least regret summed across all scenarios.

The Von Neumann-Morgenstern criterion places the decision-maker in the position of either optimist or pessimist. In the role of optimist the decision maker chooses the strategy which produces the best possible result over all scenarios. In the role of pessimist, the decision-maker would assume that the worst result would occur in each strategy selected and choose the strategy with the most favourable worst result across the scenarios. The Hurwicz criterion takes the Von Neumann-Morgenstern criterion further and enables attitudes to risk between the extreme optimist and extreme pessimist. In this manner a strategy can be selected to suit the risk attitude of the organisation making the decision or, alternatively, a strategy can be selected which produces the most favourable result over the full range of attitudes from extreme pessimist to extreme optimist.

Chao (Chao et al, 1999) outlines the merits of using scenario based planning methods in the restructured electricity industry with the many new uncertainties that ESI restructuring creates. An explicit step in the power delivery planning process is a decision on whether sufficient scenarios have been examined to provide assurance regarding the result of the planning process. Tabors and Monroe (Tabors and Monroe, 1991) discuss the use of highly analytical techniques for generation planning based on the concept of scenarios. Many combinations of planning options and uncertainties are formed into scenarios which are assessed to find the best performing strategies. By adopting a combinatorial approach to the formation of scenarios, a greater likelihood of encapsulating a greater number of uncertainties is achieved. Through assessment of diverse criteria within the planning framework, tradeoff techniques can be used to identify, refine and select strategies for emissions control which are acceptable in terms of all the criteria (in this case sulphur emissions, carbon emissions, cost and net societal cost).

The second approach to dealing with uncertainty in planning is decision tree analysis. In decision tree analysis, an event tree is developed in which each potential course for the future is specifically mapped by a separate branch in the tree. By specifically creating a path for each uncertainty through time, it is possible to evaluate the effects of time separated decisions and choose the best decision in the present to maximise the chances of a good result in the future. Decision tree analysis also has the benefit of providing useful graphics of the event and decision paths which creates greater insight into the problem while also enabling focus on the most interesting paths of decisions and events.

Hirst (Hirst et al, 1993) discusses a range of techniques that planners have used to deal with uncertainty including sensitivity analysis, scenarios, portfolios and probabilistic approaches. Many of these techniques focus on the analytics of planning, while Hirst proposes that a better focus is on the decisions themselves. Simulation process are interrupted for planner input at various stages through the planning period to emulate the actions the planner may take as events unfolded. This tackles one deficiency in some planning methods whereby it is assumed that all decisions are made in the base year for a complete planning period of many years. Such interactivity with planning application software was noted as a key feature of the planning process in section 4.4.3.

Uncertainty gives rise to risks. If a decision is made against a background of uncertainty then poorly performing outcomes may result from deviations from the assumed set of future conditions. This constitutes major risk to investment return and also performance of the generation system or network. Miranda (Miranda, 1993) discusses the requirement for robust solutions to power system planning problems and concludes that modification of least cost plans to reduce risk exposure is a feasible and highly desirable aspect of planning. Miranda goes further (Miranda and Proenca, 1998) to argue that simply making a decision based on the average (or weighted average) of the possible futures could produce high exposure to risk. Again, seeking robust solutions, which may not be least cost over the average of the futures, is highly desirable.

One final aspect of the future focus of planning is the timescale for which the planning process is conducted. A planning horizon of 25 years or longer was not uncommon for generation planning in the past where large scale generation plant could take up to ten years to design, construct and commission following a planning decision. A similarly long planning horizon was adopted for transmission network expansion planning since it incorporated long life assets and is closely linked with the generation plan. Distribution planning has tended to have shorter planning horizons, despite the long life of the investment, since the variability in regional load requirements makes longer term planning more uncertain. Planning in the restructured electricity industry has become more short-term in nature due to short regulatory time lag and greater investment return demands from private shareholders and higher risk associated with restructuring. It is, now, not uncommon to assess generation projects over a 15 to 20 year time scale and to assess most network investments over a 10 to 20 year time scale. The short term focus of network investments worries many industry participants since many of the longer reach capital intensive projects are now overlooked, leading to concerns that insufficient capacity will be a major constraint for power systems in future years.

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4.4.5 Planning decision process

The preceding sections have discussed many important features of power system planning relating to the scope of the planning problem, the structure of the planning framework, the planning process itself and the future focus of planning activities. When all aspects of planning relating to these four areas have been dealt with, the focus of planning logically moves onto the fact that near the end of the planning activity a decision must be made. This section deals with aspects of decision-making.

Section 4.4.2 discussed the requirement for the inclusion of all issues in the planning process with reference to the scope of planning activities. It was argued that techniques to deal with multiple issues (or multiple criteria) are gaining in usage as well as necessity as planning problems become more complex.

Crousillat, Merril *et al* (Crousillat et al, 1993) provide some insight into the tradeoff process. If the results of simulations of several proposed plans in only two attributes are illustrated on a two dimensional graph, three distinct tradeoff patterns can be identified. Figure 4-5, Figure 4-6 and Figure 4-7 illustrate the three general tradeoff characteristics. The arrows next to the attributes axes illustrate the direction of preference for that attribute. In these cases, the lower the value of the attribute the more attractive the overall result.

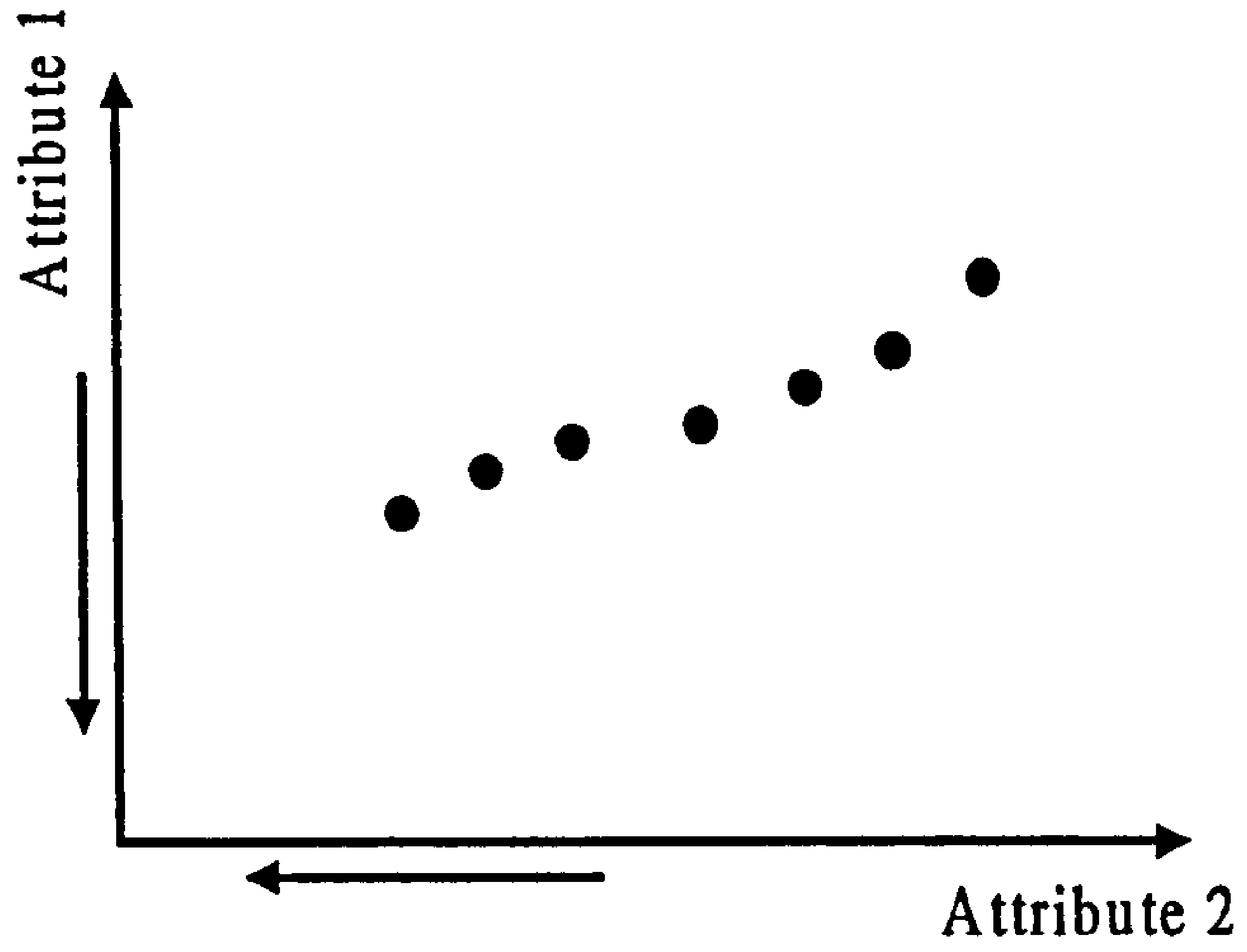

Figure 4-5: Trade off curve in two attributes for 'no conflict' case.

Figure 4-5 illustrates the trade off case where there is no conflict between attributes. Better performance in both attributes can be achieved simultaneously by selecting the plan which yields results at the lower left end of the curve assuming that low values of the attributes are preferred.

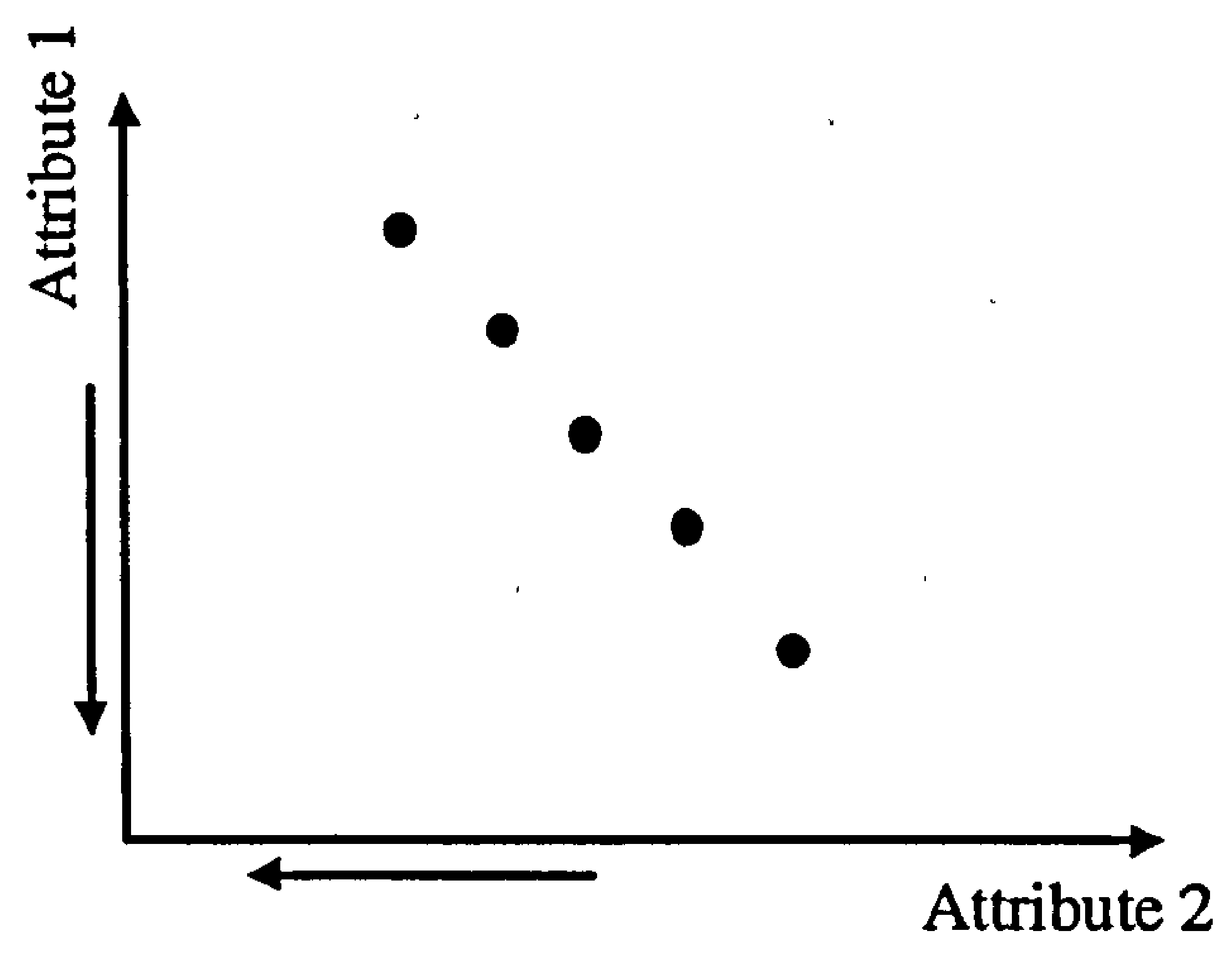

Figure 4-6: Trade off curve in two attributes for 'no attractive compromises' case.

Figure 4-6 illustrates the trade off case where a linear 'frontier' is produced. This makes the selection of one plan more difficult as there is no natural breakpoint or threshold on the curve. It is recommended that a point at one extreme end of the curve should be selected in this case. The end of the curve chosen will be dictated by the relative importance of the attribute which this selection minimises. For example, if attribute 2 is most important in Figure 4-6, then the plan at the upper left end of the curve would be chosen as it minimises the value of attribute 2.

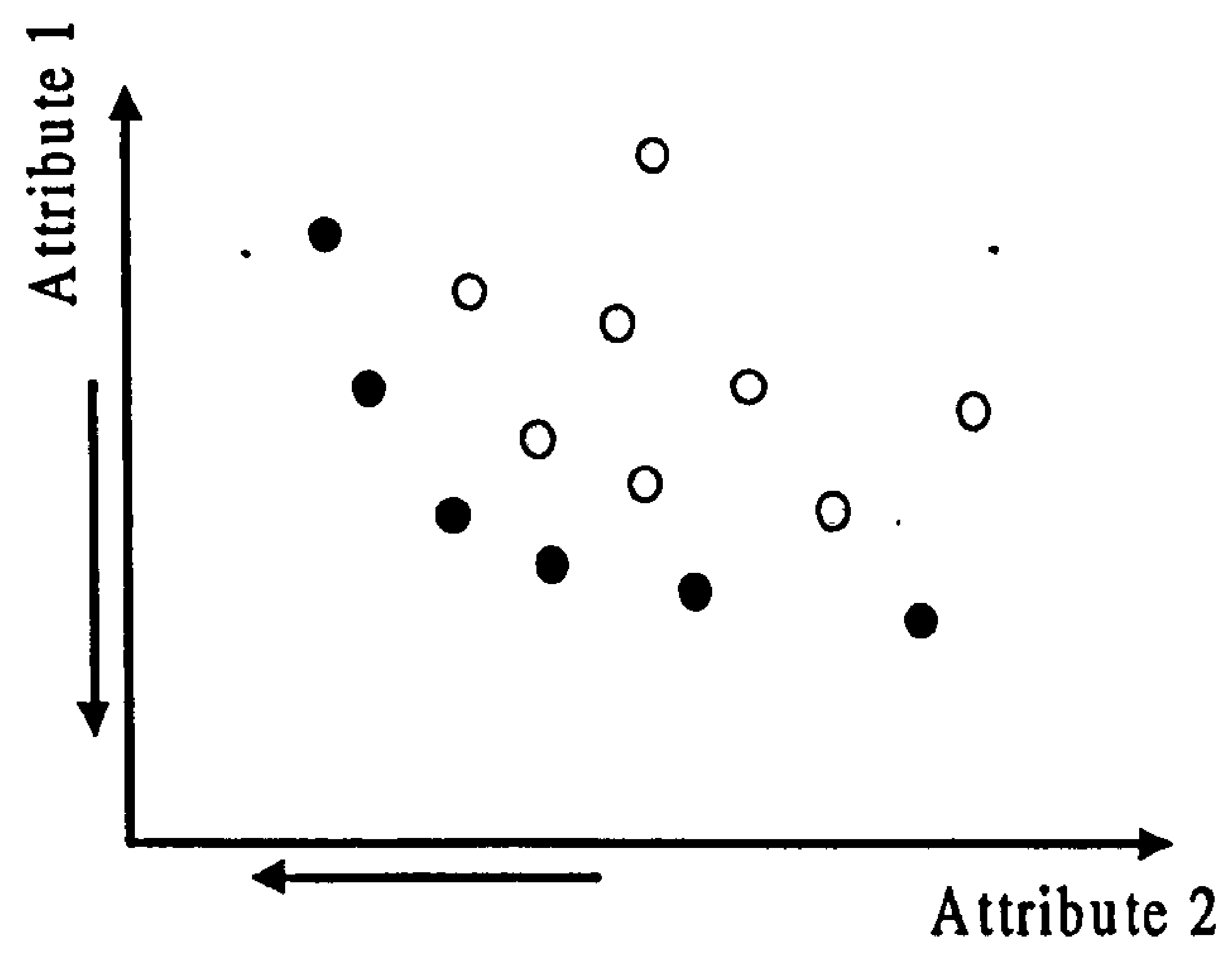

Figure 4-7: Trade off curve in two attributes for 'attractive compromises possible' case.

Figure 4-7 illustrates a case where attractive compromises are possible. While it is unfortunate that the best possible result in one attribute cannot be attained due to the importance of other attributes (and issues), compromises must be made. Selecting a plan at the knee-point of the curve is likely to provide the best opportunity for enhancing the result across the two attributes without unduly conceding performance in any single attribute. Burke et al (Burke et al, 1988) describe the process of establishing the knee-point for decisions with three or more attributes. Where three or more attributes are required to represent a decision problem the knee-point (representing non-dominated solutions where opportunities exist for tradeoff between attributes) would be represented by a surface rather than a curve.

The general points to be made from this overview of multiple criteria planning techniques are that most planning problems are characterised by both numerous issues and numerous attributes. For example, in a paper by Gauld describing a prioritisation method for allocating investment, nine criteria are identified for distribution expenditure decisions (Gauld, 1993):

1. reliability of supply
2. voltage quality
3. line clearances
4. general safety
5. bushfire hazard
6. visual impact
7. public criticism
8. plant damage
9. costs and revenues from investment

The era of the least cost plan (in financial terms) has been replaced by a more complex decision arena in which many preferences, viewpoints and issues vie for attention. Good planning methodologies must take account of all criteria. In addition, a wide range of possible plans must be assessed to enhance the chances of identifying unlikely but high performance plans.

Section 4.4.3 discussed some differences between simulation and optimisation as a feature of the planning process. Although simulation offers advantages over optimisation in terms of transparency of the planning process, sometimes optimisation techniques are the most appropriate way to aid a planning decision. Willis (Willis et al, 1995) discusses the use of optimisation based tools for distribution planning where the chief end of the process is providing distribution services at minimum cost. Formulations for the problems of distribution layout, switching points and circuit designs can be optimised using various methods to reduce the overall cost of the distribution service. Such techniques become less valuable as the number of non-monetary attributes increases and as the level of uncertainty increases. Therefore, multiple criteria techniques for power system planning problems are likely to become more widely used in future.

4.4.6 Planning information recording

One final aspect of planning frameworks is the careful recording of investigated plans, analysis results and decisions made. A number of obvious reasons for careful recording not only of models, data and analytical results but techniques used and decisions reached are listed below:

- future use of data and models
- auditability of the planning process
- reuse of solutions to specific problems
- reuse of rationale behind decisions

The reuse of models and data seem to be a logical requirement of any planning system which incorporates a simulation environment. Providing an audit trail of the planning process could be viewed as a basic requirement of an accountable corporate culture or national legislative framework.

The reuse of planning and design solutions and rationale in power system applications is discussed by Foote *et al* (Foote et al, 2000). The creation of a planning system which incorporates not only the models and techniques of previous planning activities but also the issues, criteria, general approach to the planning problem, solutions and the rationale behind decisions could enable decisions to be built on previous decisions and planning activities in every sense.

Especially in the formative years of distributed generation planning, the careful recording, within an appropriate system, of the planning and decision processes related to distributed generation could yield great benefits in the future. As planning methodologies for distributed generation develop, the decisions made in the initial years and the reasoning behind them could be of crucial importance for improved future decision making.

4.5 Distributed Generation and Planning

The preceding sections of this chapter have discussed the traditional techniques and current requirements for power system planning. In addition, an outline of the deficiencies of existing methodologies and the desired features of modern has been proposed. Until this point, the integration of distributed generation into utility planning has been noted, either by its absence in the review of traditional power system planning techniques, or as a desired feature in modern planning techniques.

This subsection describes the published work in the field of power system planning for distributed generation. It is in this field that one of the major contributions of this thesis is established.

Several perspectives of distributed generation and planning are possible in the restructured electricity supply industry. Three main aspects of distributed generation and planning are discussed below:

- Distributed generation as an additional planning option for vertically integrated distribution utilities.
- Distributed generation as an investment option for an independent generation developer.
- Distributed generation as an uncontrollable phenomenon in regulated distribution systems.

Other perspectives of distributed generation and planning exist, such as how to conduct transmission planning under a future possibility of rapidly increasing distributed generation capacity in distribution networks. There is also a high level governmental view of planning for distributed generation and how to stimulate the market for distributed generation technologies and how to support research and technological development in key distributed generation themes. However, only the three perspectives noted in the bulleted list above are developed further here.

The first perspective (and most common in the literature) is the view of distributed generation as an additional option for an integrated utility providing generation, possibly transmission, distribution and retailing of electricity to customers.

Weinberg *et al* (Weinberg et al, 1991) have presented developments to the least cost approach to utility planning. They argue that a true least cost planning approach must include all links in the electricity supply chain from power sources to consumers. The cost of service function to be minimised includes both large centralised generation and distributed generation. Thus, distributed generation becomes an additional utility option alongside network expansions, large scale generating plant investments and demand side management. Willis and Scott (Willis and Scott, 1994) describe a method of integrating distributed generation, demand side management and distribution automation into the distribution planning process. They note that the planning process becomes much more complex (requiring two to four times the effort of standard distribution planning) and that a number of additional issues must be considered at the planning stage. The additional modelling issues required in future include:

- longer planning time frames to capture the benefits of the distributed generation
- demand side management and distribution automation units
- coincidence of load, demand side management and distributed generation resource availability curves
- expanded modelling requirements for distributed generation units.

Dugan *et al* (Dugan et al, 1999) consider a planning method for distributed generation which focuses primarily on minimising capacity costs in the distribution system through the use of distributed generation. A traditional formulation of a cost function for the distribution company is utilised which includes the usual components of electrical losses costs, capacity reinforcement costs and power quality costs. The planning method takes into account the technical problems with distributed generation of voltage regulation and power islanding while the siting of new units is considered of primary importance in utility distributed generation planning studies.

Nishiya *et al* (Nishiya et al, 1995) describe an optimisation approach to the distributed generation planning problem whereby the heat and power outputs of proposed distributed generating plants are positioned in optimal locations to maximise the reduction in central generating unit fuel costs and the cost of transmission losses. The distributed generation units are sited at the best locations, first with additions being made up to the point where the costs of the next connected distributed generating unit exceed the reductions in central generation fuel costs plus transmission losses. The vertically integrated utility is implicit in this form of marginal cost and benefit assessment.

A method for maximising the potential benefits from distributed generation expansion based on a specialist form of genetic algorithms (Hereford ranch) is proposed by Kim *et al* (Kim et al, 1998). Distributed generators are sited in a network in varying numbers and capacities to reduce the overall system losses to a minimum. The focus on a single benefit (i.e. reduced losses) of distributed generation could be viewed as myopic to the multitude of other issues and the opaqueness of the techniques used reduces any insight into the characteristics of the problem. The focus on locational aspects of distributed generation planning does have some merit since there are strong locational drivers for the costs and benefits from distributed generation.

The second perspective of distributed generation in planning is the view of a generation project as one project option for an independent developer. This area has not been well developed in the literature since it is assumed that private investors in generation, or any other project type, have their own fiercely guarded criteria for assessment and decision-making regarding distributed generation. As a result, the focus from the generation developer viewpoint has been on the development of structures and processes for connecting and operating distributed generation in utility distribution networks rather than on evaluation techniques.

The third aspect of distributed generation in planning relates to the ongoing problem of a distribution company in planning the distribution network in the face of growth in independent distributed generation. In this situation, the distribution company is a regulated monopoly provider of distribution services including open access to the distribution system for third parties. This is the current state of affairs in the UK.

The resolution of the issues arising when a private generation developer proposes to establish some generation scheme in the distribution utility network is discussed by *Seitz* et al (Seitz et al, 1997). A structured and open approach to the analysis of generation connections by the distribution utility is cited as a means of overcoming some of the more contentious issues which cause discord between generation developer and distribution utility. The structured approach to analysing the impact of distributed generation is utilised to assess maximum installation limits in districts of the network which do not have a deleterious effects on current and voltage limits, protection, voltage flicker, fault level, losses, transformer tap-changer loading and reliability.

The idea of maximum distributed generation introduction limits is further developed by Kim *et al* (Kim et al, 1999) with a technique to assess the impact of distributed generation on voltage control in distribution systems. The effect of distributed generation on the voltage control system sending end reference voltage is assessed and limits are set on the allowed capacity of generation in the distribution system down-stream of the voltage control relay. The potential for distributed generation interference with voltage control operations in distribution systems is also discussed in detail by other authors (Thomson, 2000).

It is evident from contributions within the area of planning for distributed generation that the UK perspective of distributed generation has not been tackled. From the distribution utility viewpoint distributed generation is autonomous. This creates particular difficulties in planning the distribution system. It might be expected that, in some way, distributed generation could be incorporated into existing network expansion planning methods. The study of distributed generation issues presented in chapter 3 point to greater issues of more strategic importance than simply coordinating distribution expansion planning to take account of distributed generation. The incorporation of distributed generation into network expansion planning methodologies could be viewed as a tactical measure when an overall distribution utility strategy for distributed generation had been formed. The larger strategic issues related to distributed generation rotate around the effects distributed generation will have, not only on the network but, on the whole distribution business. Distributed generation has the potential to do great harm to distribution business profitability under current business structures and regulatory mechanisms. The strategic question relates to changing these structures to facilitate a positive outcome from distributed generation. A strategic planning framework to assess the higher level issues with distributed generation is developed in this thesis.

4.6 Review of Chapter 4

This chapter has discussed the generalities of power system planning with specific focus on distribution system planning.

It has been argued that restructuring of the electricity supply industry with the accompanying set of drivers for distribution companies along with increasing levels of uncertainty faced by utility companies have raised requirements for new planning methodologies.

A comprehensive discussion of power system planning requirements for the new era has been presented. It has been proposed that modern planning methodologies should:

- deal with multiple criteria
- enable consideration of multiple and diverse solutions
- provide whole system solutions
- be modular
- provide means of integrating analytical modules and interfacing with other applications
- be automated/interactive as appropriate
- provide bulk data handling facilities
- enhance planner productivity
- provide flexibility in the planning process

- be robust to limited planning resources
- provide insight to the planning problem and solutions
- make appropriate use of simulation/optimisation
- deal with uncertainty
- deal explicitly in terms of risk
- provide leverage to future activities
- be decision focused
- use appropriate time scales
- make appropriate use of graphical/mathematical decision techniques
- enable data and model reuse
- provide auditable planning records
- enable reuse of solutions
- facilitate reuse of planning rationale

The specification and implementation of a strategic analysis framework for distributed generation presented in the following chapters is based on the application of these 'best practice' characteristics of modern planning techniques.

4.7 Chapter 4 References

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Chapter 5

SPECIFICATION FOR A DISTRIBUTED GENERATION STRATEGIC ANALYSIS FRAMEWORK

5.1 Summary of Chapter 5

This chapter establishes the objectives and general high level structure of a strategic analysis framework for distributed generation based on the distributed generation issue set (chapter 3) and planning methodology best practice (as established in chapter 4). A general specification for the strategic analysis framework is illustrated through the use of influence diagrams which show how each of the distributed generation issues influences each of the four key issues for distribution companies (sections 5.2 and 5.4).

A number of options are considered for the provision of the required functionality for strategic analysis of distributed generation from the distribution utility perspective (section 5.5). The options cut across energy market, power system and utility financial domains and are by no means presented as an exhaustive list but rather as likely possibilities. The choice of analytical options for proof of the general methodology is made in chapter 6 where constraints regarding implementation of the strategic analysis framework are considered.

5.2 Objective for a Strategic Analysis Framework

The objectives in the design of a planning framework for distributed generation are to establish a structured analytical base in which information regarding the impact of distributed generation can be generated for the purposes of policy and strategy formation. The structure of the strategic analysis framework should reflect the best features of power system and strategic planning methodologies.

The quantitative information provided by the strategic analysis framework is critical to a number of distributed generation stakeholders as the distributed generation market undergoes significant growth. The primary beneficiaries of the distributed generation strategic analysis framework are the distribution utility companies who can study the penetration of distributed generation in their networks and assess the network performance effects and, importantly, the financial effects of distributed generation. The strategic analysis framework also provides the opportunity to test a variety of utility strategies for distributed generation. These strategies could encompass distribution network design and operation, commercial agreements with distributed generation owner-operators and lobbying for alternative government and regulatory mechanisms for treatment of distributed generation.

Four key logical issues relating to distributed generation have been identified from the distribution utility perspective through analysis of the issue set developed in chapter 3:

1. how much distributed generation will appear in the distribution networks?
2. what effect will the distributed generation have on the technical performance of the network?
3. what effect will the distributed generation have on the financial performance of the utility?
4. what changes in technical design or commercial practice will be effective within a distribution utility distributed generation strategy?

How each of these four main issues might be analysed is the focus of this chapter.

5.3 Basis of Structure for a Strategic Analysis Framework

The overall structure of an analytical framework for distributed generation has been the subject of recent publications.

Openshaw (Openshaw, 1998) describes the analytical framework utilised by a University of Strathclyde analytical team (including the author of this thesis) for studies of the effects of distributed generation on the Eastern Electricity network. Figure 5-1 illustrates the analytical framework proposed by the University of Strathclyde and Oxford Economic Research Associates (OXERA). The philosophy behind the model is to first characterise the existing network (*Network Characterisation & Development*) in parallel with analysing likely future penetrations of distributed generation (*Penetration Analysis*). This information is transferred to the power system analysis modules through a set of templates which define the changes in consumer and generation behaviour (*Consumer & Generator Template*). Power system analysis is conducted on the scenarios which now include distributed generation (*Network Performance* and *Quality of Supply*). The financial and operational effects of the distributed generation in the distribution network are assessed (Financial & Operational Consolidation) and any policy requirements (*Policy Implications*) for the distribution company derived from the information produced for each distributed generation scenario. The policies and strategies derived from the new information relating to distributed generation are assessed through further iterations of the analysis cycle as illustrated.

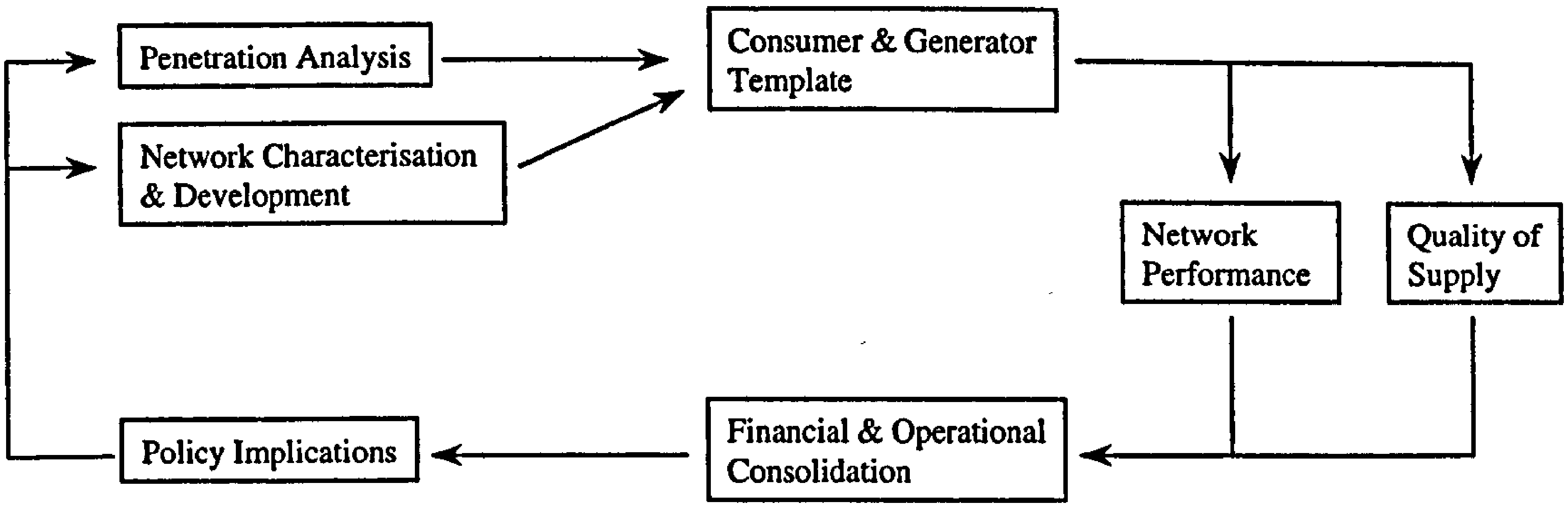


Figure 5-1: Iterative scenario analysis structure for distributed generation.

Generalities of the distributed generation analytical framework (Figure 5-1) can be drawn for further discussion. Figure 5-2 illustrates three more general analytical blocks overlaid on the previous framework:

- Energy Market Model
- Power System Model
- Utility Financial Model

The *Energy Market Model* incorporates the components of penetration analysis and consumer and generator response to distributed generation. The *Power System Model* incorporates each aspect of the effect of distributed generation scenarios on the distribution network. The *Utility Financial Model* constitutes the consolidation of the effects of distributed generation on the distribution utility. The development of distribution policy or strategy does not form a core part of these three analytical blocks but will be discussed later since it is clearly an important area.

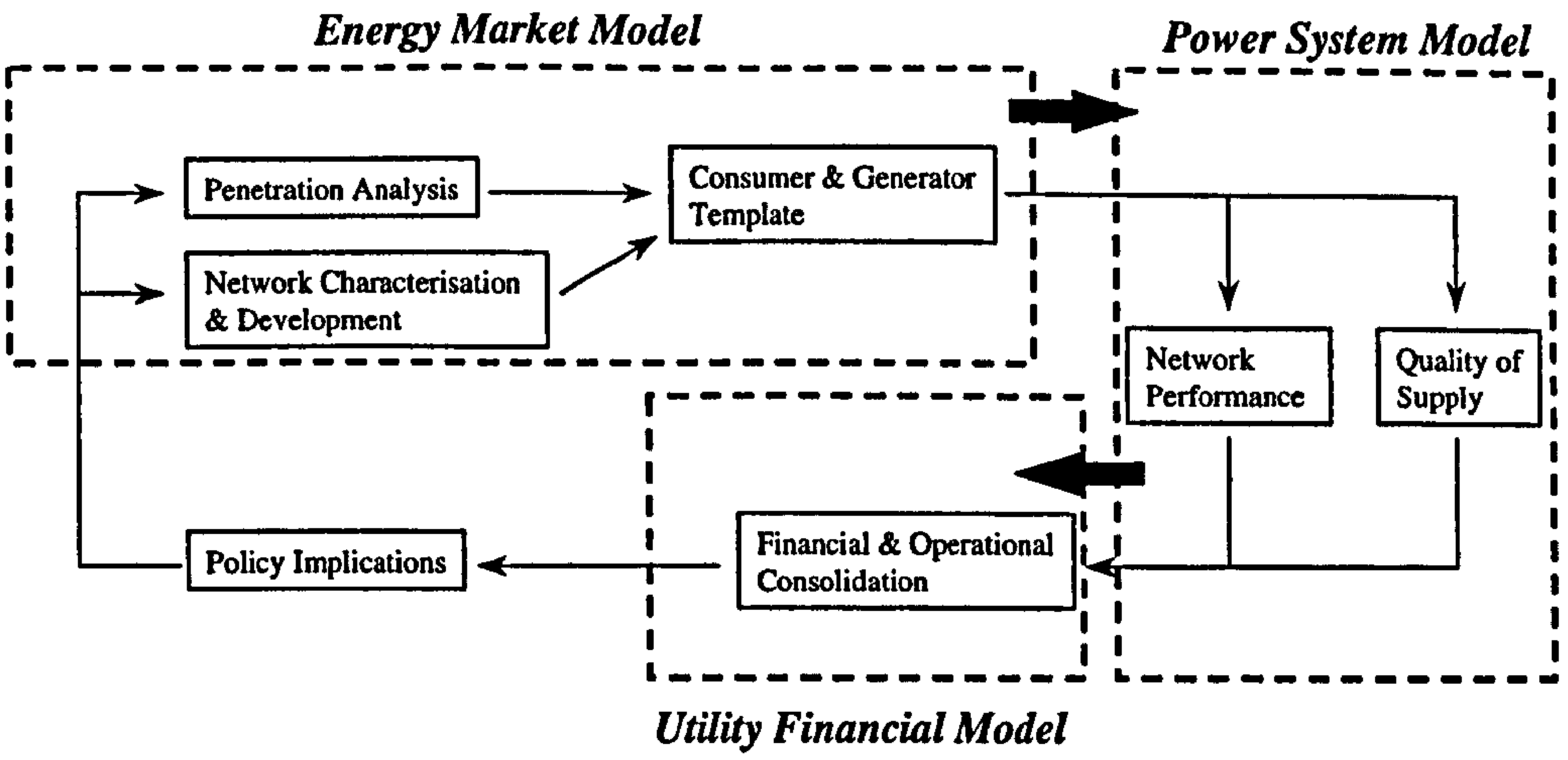


Figure 5-2: Scenario analysis structure for distributed generation illustrating three general analytical blocks.

Further justification for the proposition of the three models for the analysis of distributed generation comes from the general process of multiple attribute tradeoff analysis which can be summarised in the following steps (Andrews, 1990):

1. Identify issues and attributes relevant to decision
2. Develop scenarios of possible circumstances (along with potential strategies)
3. Model the scenarios
4. Analyse the scenarios in terms of the attributes identified previously
5. Performs tradeoffs between strategies
6. Disseminate analytical results with decision makers

These steps are illustrated in Figure 5-3 along with an overlay of the general modelling blocks proposed in this thesis.

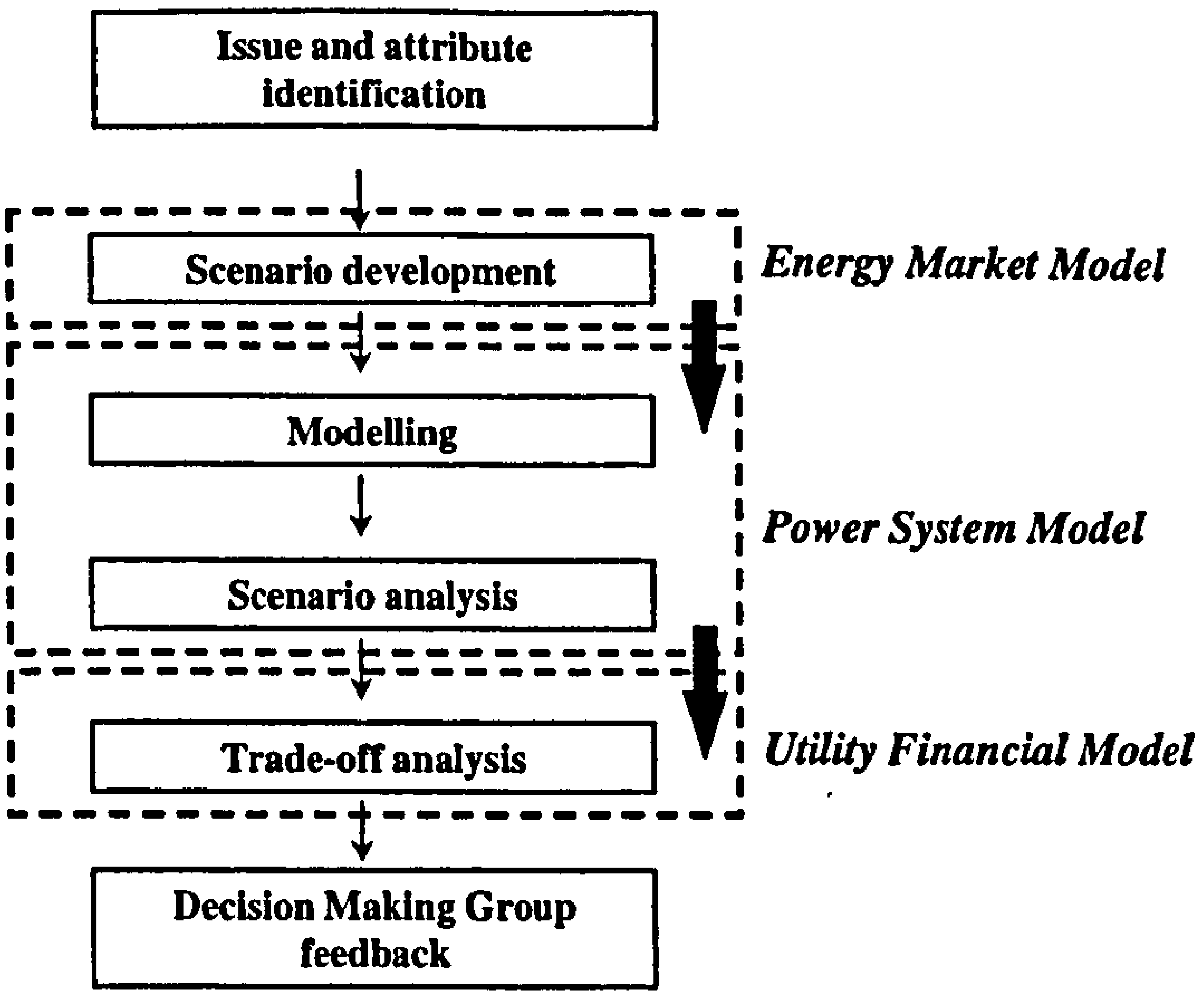


Figure 5-3: Multiple attribute tradeoff analysis framework.

The scenario development stage is akin to the process of analysing the energy market to identify plausible scenarios for distributed generation. The modelling and analysis of scenarios are the activities foreseen for the power system analysis stage while the tradeoff analysis is synonymous with the utility financial analysis module which identifies meaningful patterns and trends in the large quantities of analytical data to enable an understanding of the system to be gained.

5.4 High Level Structure for Distributed Generation Strategic Analysis Framework

The requirements for a strategic analysis framework for distributed generation will be based on the general requirements of modern power system planning methodologies (as discussed in Chapter 4) and the discussion of the plethora of issues relating to distributed generation (Chapter 3). One of the key features of a modern planning methodology noted in section 5.3 is a clear focus on all pertinent issues. The distributed generation strategic analysis framework has been designed to incorporate all distributed generation issues. An implementation of the framework may not include considerations of all issues but the specification of the framework must refer to all issues.

Three analytical blocks have been outlined (section 5.3) to address the first three of the four key distributed generation questions raised in section 5.2. The analytical blocks and the key distributed generation questions they tackle are illustrated in Figure 5-4. Also shown are the potential effects of distribution utility strategies on each of the three areas (the fourth key issue).

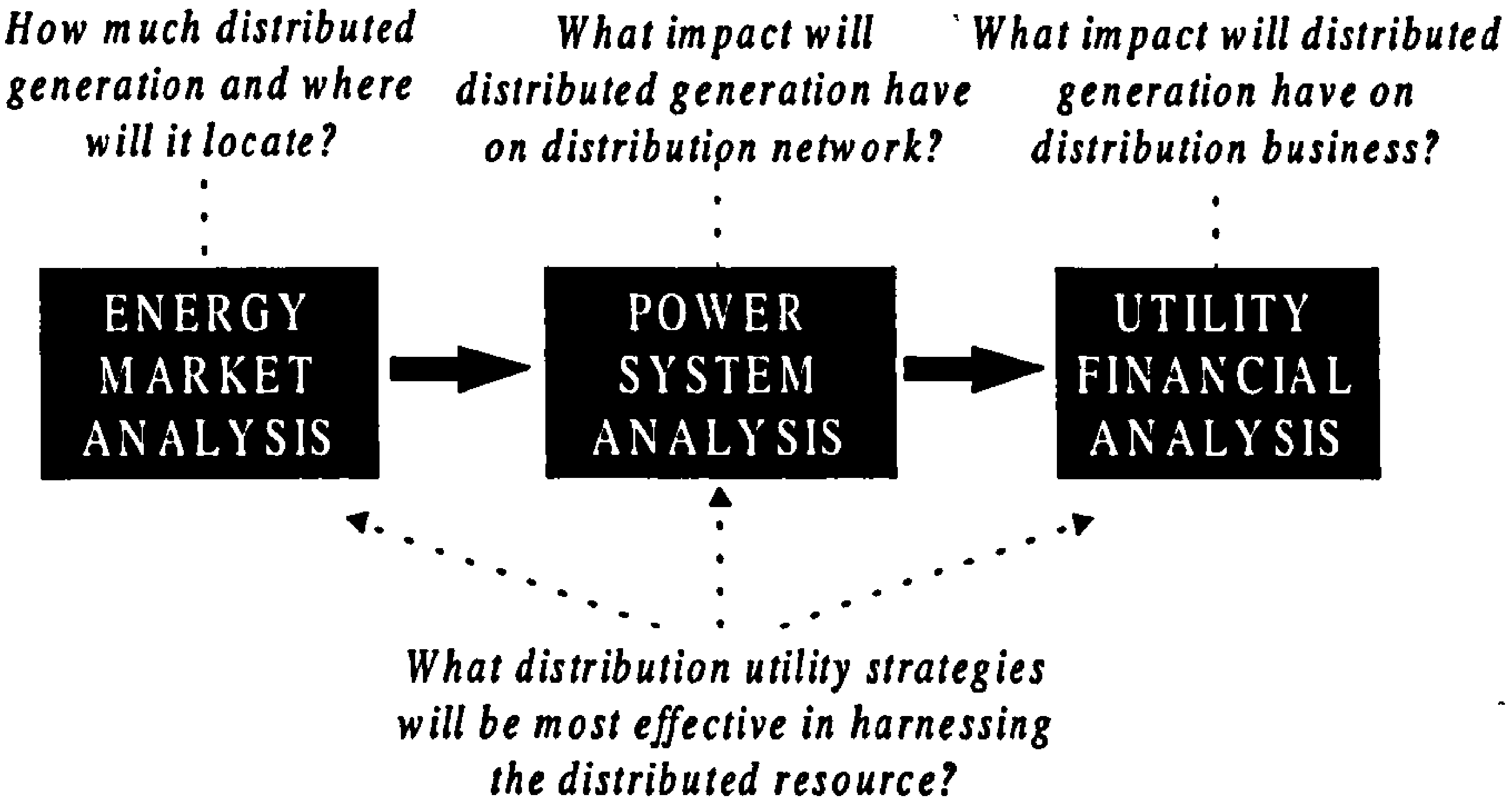


Figure 5-4: Four key distributed generation questions and high level analytical blocks.

Figure 5-2 and Figure 5-3 plus the accompanying discussion have each illustrated that the end-point of analytical activities for planning must be in strategy or policy formation and decision making. A decision must be made when it is deemed that sufficient information exists to make a good decision. The distribution utility must form strategies for distributed generation which enable it to benefit from the shift in the energy market towards smaller distributed power generation units.

5.4.1 Analytical Blocks within Strategic Analysis Framework

Having identified the four main questions which require to be addressed by a distribution utility planning framework focused on distributed generation, it is now necessary to identify where the groups of distributed generation issues, identified in chapter 3, fit into the framework (Ault and McDonald, 2000).

Figure 5-5 illustrates the data flows required within the strategic analysis framework to enable the encapsulation of all distributed generation issues within the strategic analysis framework. The three main analytical blocks (Energy Market, Power System and Utility Finance) remain at the core of the process. Data regarding all relevant issues are fed into these analysis blocks as illustrated. The data blocks reflect the structure of the issue set as developed in chapter 3.

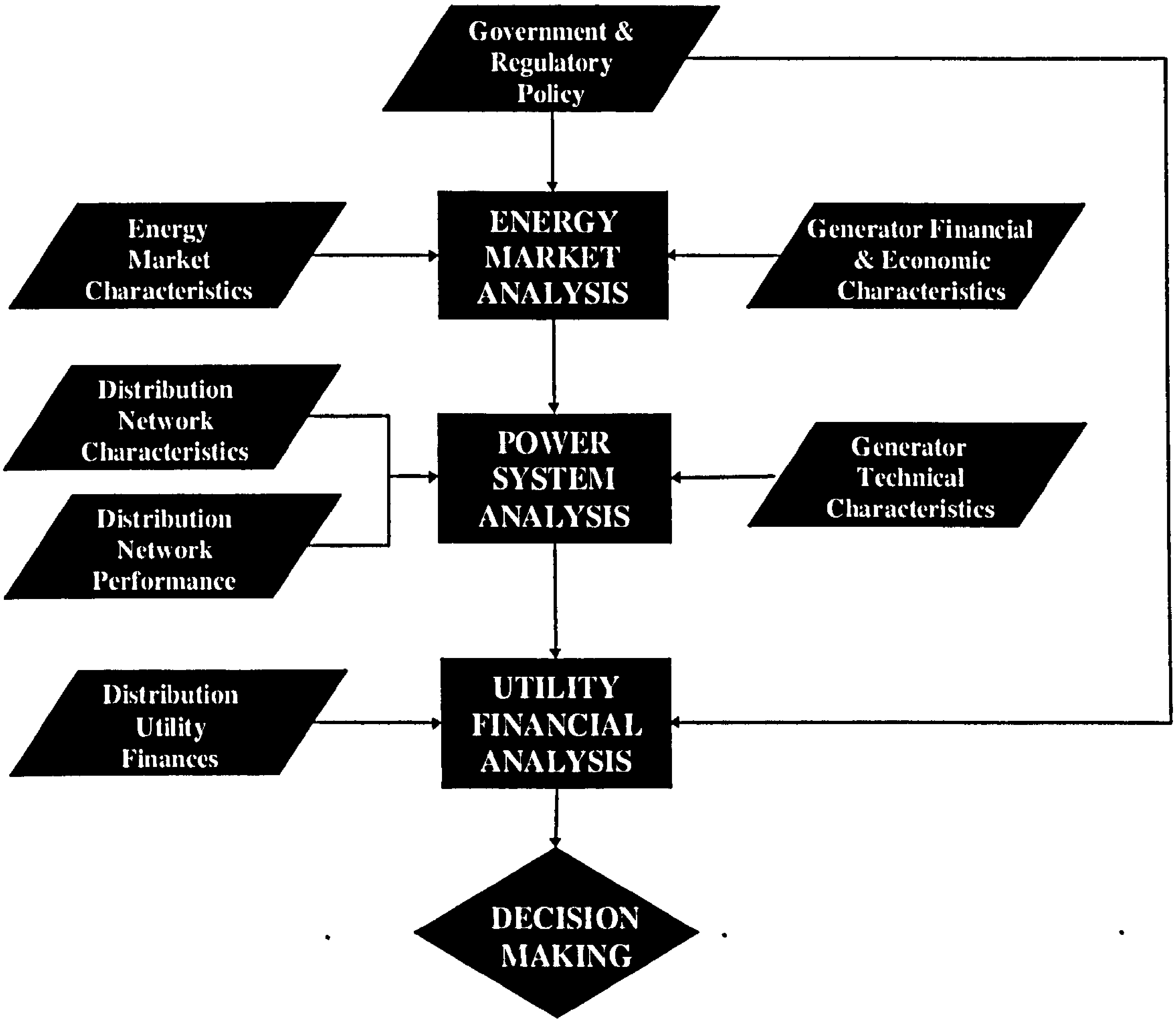


Figure 5-5: Flow diagram of strategic analysis framework

A brief outline of the scope of the data blocks is provided in the following subsections. These descriptions lead directly from the categorisation and description of issues presented in chapter 3.

5.4.1.1 Government & Regulatory Policy

This data block provides information on government and regulatory policy relating to the energy market in general and also distributed generation in particular. This includes prospective incentives and penalties, environmental legislation and the price control regulatory mechanism applied to natural monopoly distribution utilities in the UK.

5.4.1.2 Energy Market Characteristics

This data block contains all pertinent data on general economic conditions such as interest rates along with specific energy market indicators such as wholesale electricity prices.

5.4.1.3 Generator Financial & Economic Characteristics

This data block contains all distributed generation financial and economic data such as assumed cost and revenue bases for each generation technology under study.

5.4.1.4 Distribution Network Characteristics

This data block contains information relating to the physical properties of the distribution network. The level of detail required in the power system analysis module dictates the extent of the database required. Section 5.5.2 outlines the power system analysis options that dictate the scope of distribution network data required.

5.4.1.5 Distribution Network Performance

The Distribution Network Performance data block details the performance indicators for distribution networks (such as voltage losses and harmonics) along with statutory obligations relating to the planning and operation of distribution systems.

5.4.1.6 Generator Technical Characteristics

This data block describes the electrical and mechanical characteristics of each generation technology under study. The detail of the generator models is dependent on the extent of power system analysis incorporated in studies utilising the strategic analysis framework.

5.4.1.7 Distribution Utility Finances

This data block contains information on the financial characteristics of the utility such as the charging mechanisms for distributed generation connections and use of system as well as details of other network revenue and expenditure.

5.4.1.8 Utility Policy Options

Based on the prospective financial and operational implications, as evaluated in the three analytical modules, the utility may develop a number of policy options with which to take advantage of the growth in distributed generation. The effects of the policy options are fed back into the model through adjustment to the core data blocks detailed in each of the subsections above.

For example, the utility may effect a change in distribution network design (such as interconnection of previously radial circuits) or lobby for a change in the price control formula to reflect the changing cost base relating to distributed generation. These policy options would be modelled in the Distribution Network Characteristics data block and Government & Regulatory Policy data block respectively. Any utility strategies or tactics could be modelled in the data blocks illustrated in Figure 5-5.

5.4.1.9 Decision Making

A range of policy options will have an associated range of outcomes. An essential component of a strategic analysis framework is an effective means of evaluating the range of results from different strategies. Multiple criteria decision-making techniques are proposed for the selection of the best options from the range of feasible alternatives. This choice is discussed in greater depth in section 5.5.4.

5.4.2 Strategic Analysis Framework Influence Diagrams

In addition to using the groups of issues developed in chapter 3 to form a high level structure (Figure 5-5) for a distributed generation strategic analysis framework, it is possible to use the complete issue set to form influence diagrams for the first three key issues described in section 5.2.

Influence diagrams are an effective way to illustrate the interrelations between parameters or issues and serve as a means of representing complex models. Ang *et al* (Ang et al, 1999) use a probabilistic influence diagram to represent a model for the break even price of distributed generation. The probabilistic links between parameters (nodes) are used to reflect the uncertainties in distributed generation economics. The use of probabilistic links will not be used in the methodology developed in this thesis.

The influence diagrams presented below are issue based rather than parameter based and are used to support the design of a modelling framework for distributed generation rather than as a representation of a model after its design as by Ang *et al.*

Influence diagrams have been created to illustrate the complex interactions between distributed generation issues. Figure 5-6 illustrates the issues affecting distributed generation penetration.

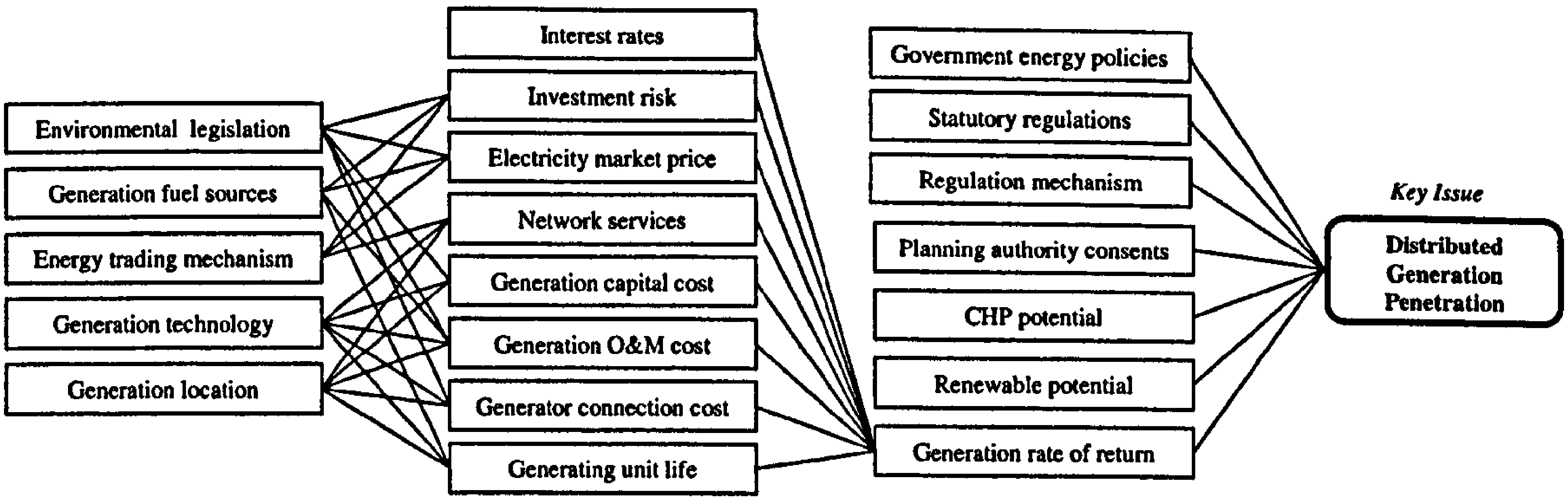


Figure 5-6: Influence diagram for distributed generation penetration

Figure 5-7 illustrates the issues affecting the impact that distributed generation may have on the distribution network.

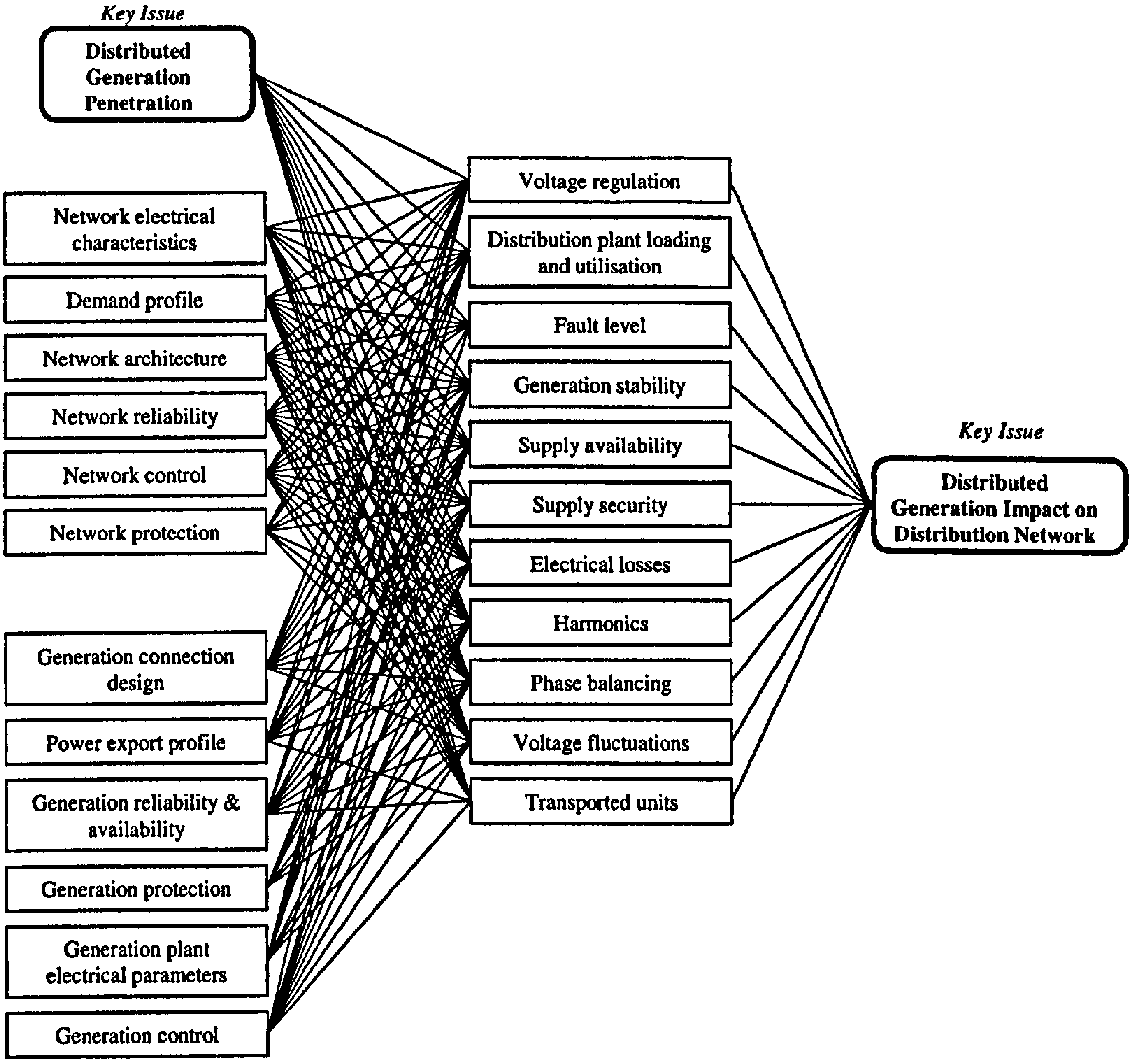


Figure 5-7: Influence diagram for distributed generation impact on distribution network

Figure 5-8 illustrates the influences on the impact that distributed generation has on the distribution business.

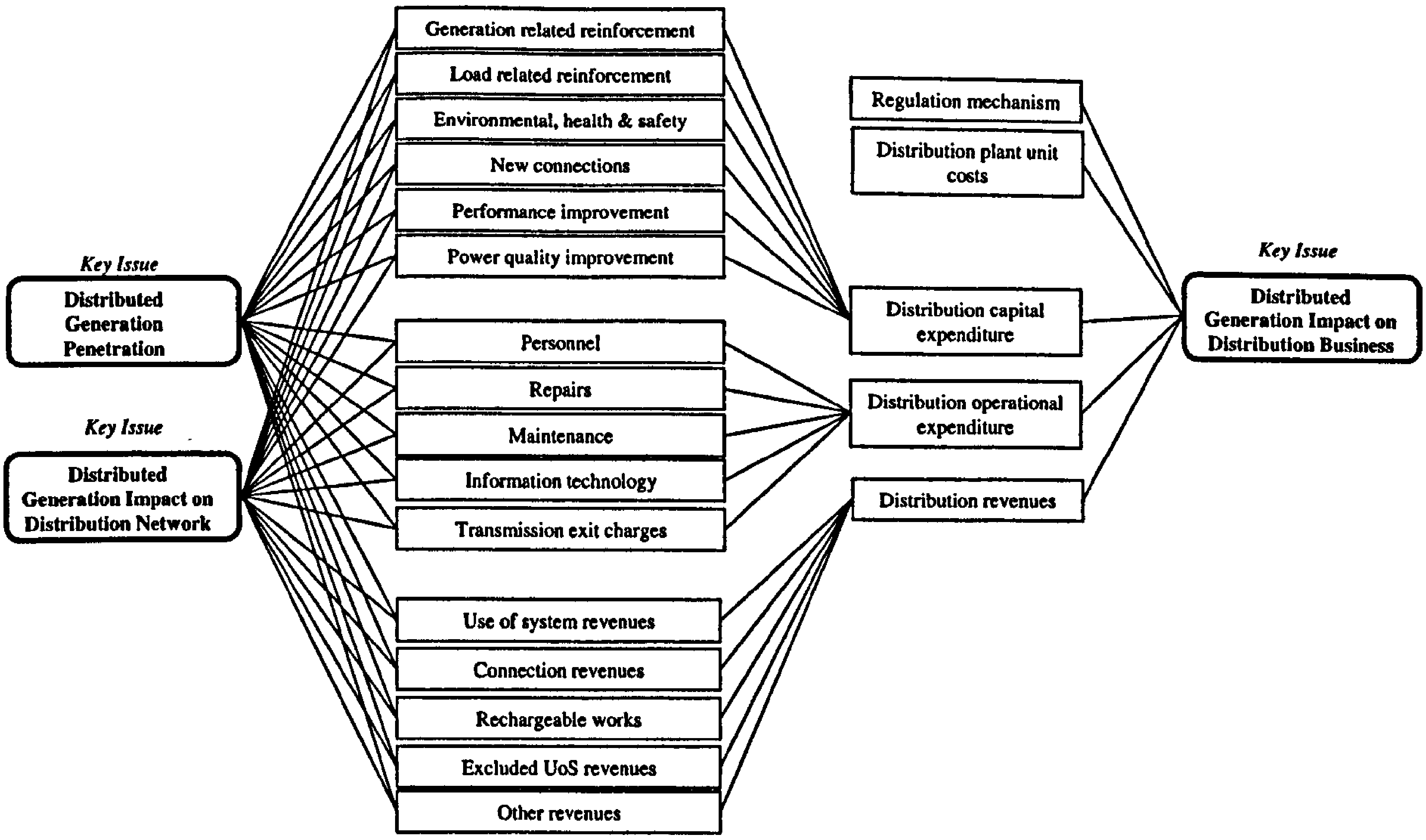


Figure 5-8: Influence diagram for distributed generation impact on distribution business.

An example of the influence of a single issue will prove the value of clearly setting out the influences on each key issue. The energy trading mechanism prescribes the access to market for distributed generation which in turn affects the revenue from energy sales. The energy trading mechanism also influences the level of risk in the revenue stream and any revenue from network services such as peaking duty (Figure 5-6). These factors affect the rate of return calculations. for a generation technology or a specific generation project thus influencing the overall level of proliferation (penetration) of distributed generation in the distribution networks.

The level of distributed generation penetration influences each of the measures of distribution network performance (Figure 5-7) whose sum can be viewed as the impact of the distributed generation on the distribution network.

This impact on the distribution network can theoretically impact on any distribution business budget item (Figure 5-8) whether capital expenditure, operational expenditure, or revenue depending on the exact nature of the effect on the distribution network and the structure of the distribution company finances.

The links shown in the influence diagrams illustrate the individual interactions between issues and parameters which must also be characterised in an implementation of the strategic analysis framework.

5.5 Distributed Generation Strategic Analysis Framework Options

One key requirement of planning techniques described in Chapter 4 (section 4.4.2) is a modular and flexible approach to analysis. The requirements and available resources for analysis in one organisation may be very different from the situation in another organisation. In respect of this, one organisation may choose to produce distributed generation scenarios in one way while another organisation chooses to conduct the same function using a different technique. These choices will be made to suit the particular situation prevailing within that organisation.

Modularity provides the benefit of building analysis blocks (as and when required) while enabling the integration of new analysis modules without substantial additional effort. A flexible planning process will perform to a reasonable standard with a range of analytical options, in each case providing information on which decisions can be based. In the following subsections, a number of analytical options are discussed to provide an overview of some of the possibilities for assessing the impact of distributed generation.

5.5.1 Energy Market Analysis

This section relates to the analysis of distributed generation from the perspective of its place in the energy market. Five techniques for assessing the economic attractiveness and, hence, penetration of different distributed generation technologies are presented:

- energy trading option
- generation technology mix optimisation
- small scale energy device penetration forecasting

- scenarios approach
- penetration rate technique

5.5.1.1 Distributed Generation as an Energy Trading 'Option'

Distributed generation provides a way for energy traders to match contracted supply and demand within a trading period. They also provide and option for the energy trader to hedge against high electricity spot prices (Ault et al, 1997). More active energy traders may also choose to use natural gas fired power generation to provide arbitrage opportunities between the wholesale gas and electricity markets.

A distributed generating unit could be dispatched by an energy trader when the prevailing electricity spot price was greater than the variable operating cost of a given generating unit.

Figure 5-9 illustrates the effect of an option to buy energy from a distributed generating unit at £20/MWh on a specific day with a given electricity spot price profile. It can be seen that the distributed generating unit would be required to operate in three distinct periods (two periods if it was economic to operate through 15:00 hours between periods when a finite benefit is gained). The saving produced by procuring power from this distributed generating unit is represented by the black shading above the £20/MWh line. The period of operation can also be calculated from the graph. The generator would operate for 21 half hour periods in this day.

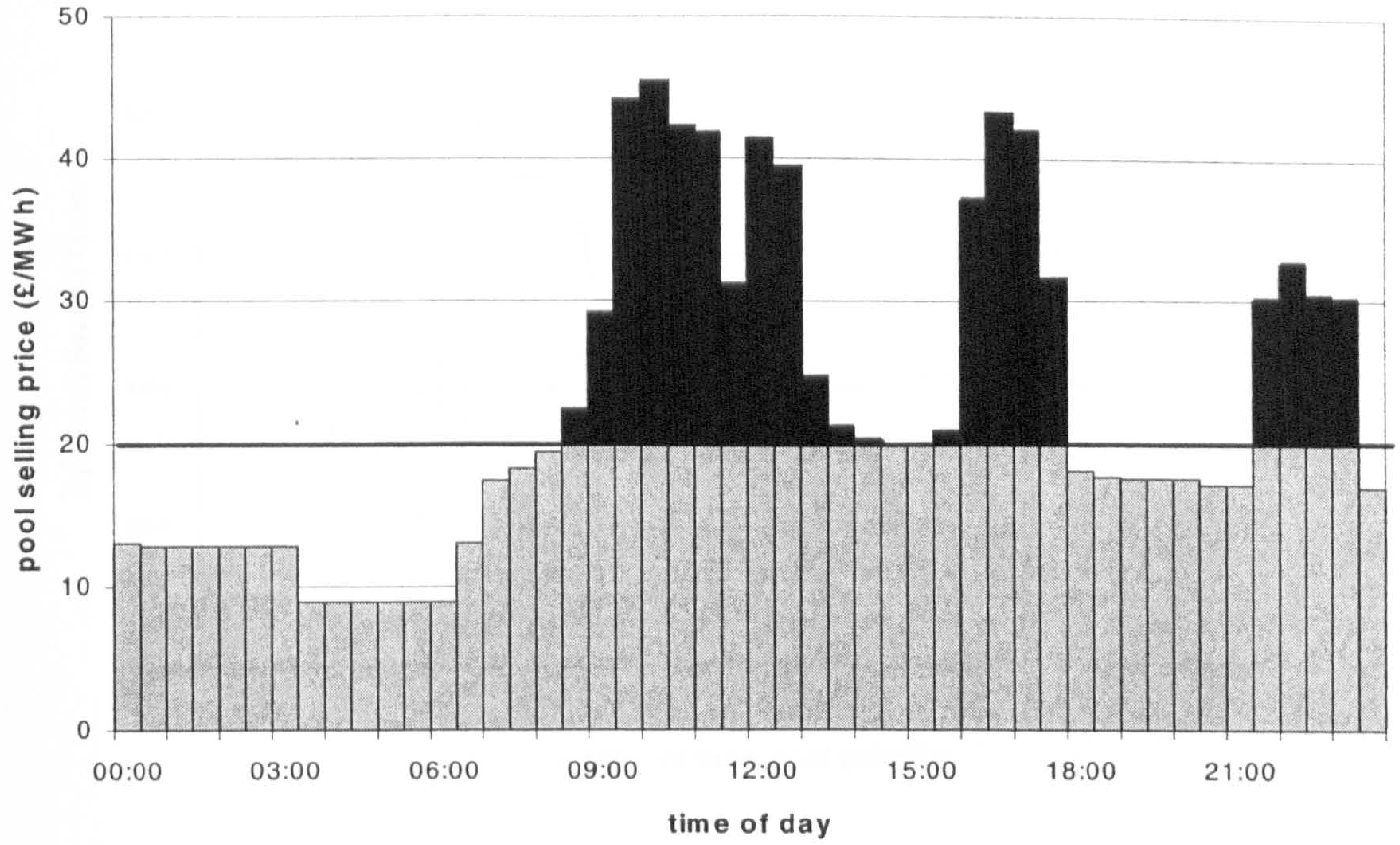


Figure 5-9: Energy trading option to buy energy at £20/MWh from a distributed generating unit

The distributed generation option utilisation level and value vary with the variable cost of the option. As the option variable cost becomes more expensive, the option utilisation factor decreases and the option value also decreases.

Figure 5-10 illustrates the variation in option utilisation factor with option variable cost over the same single day as illustrated in Figure 5-9.

The variation of option value (£/kW installed) with option variable cost over the same day is illustrated in Figure 5-11.

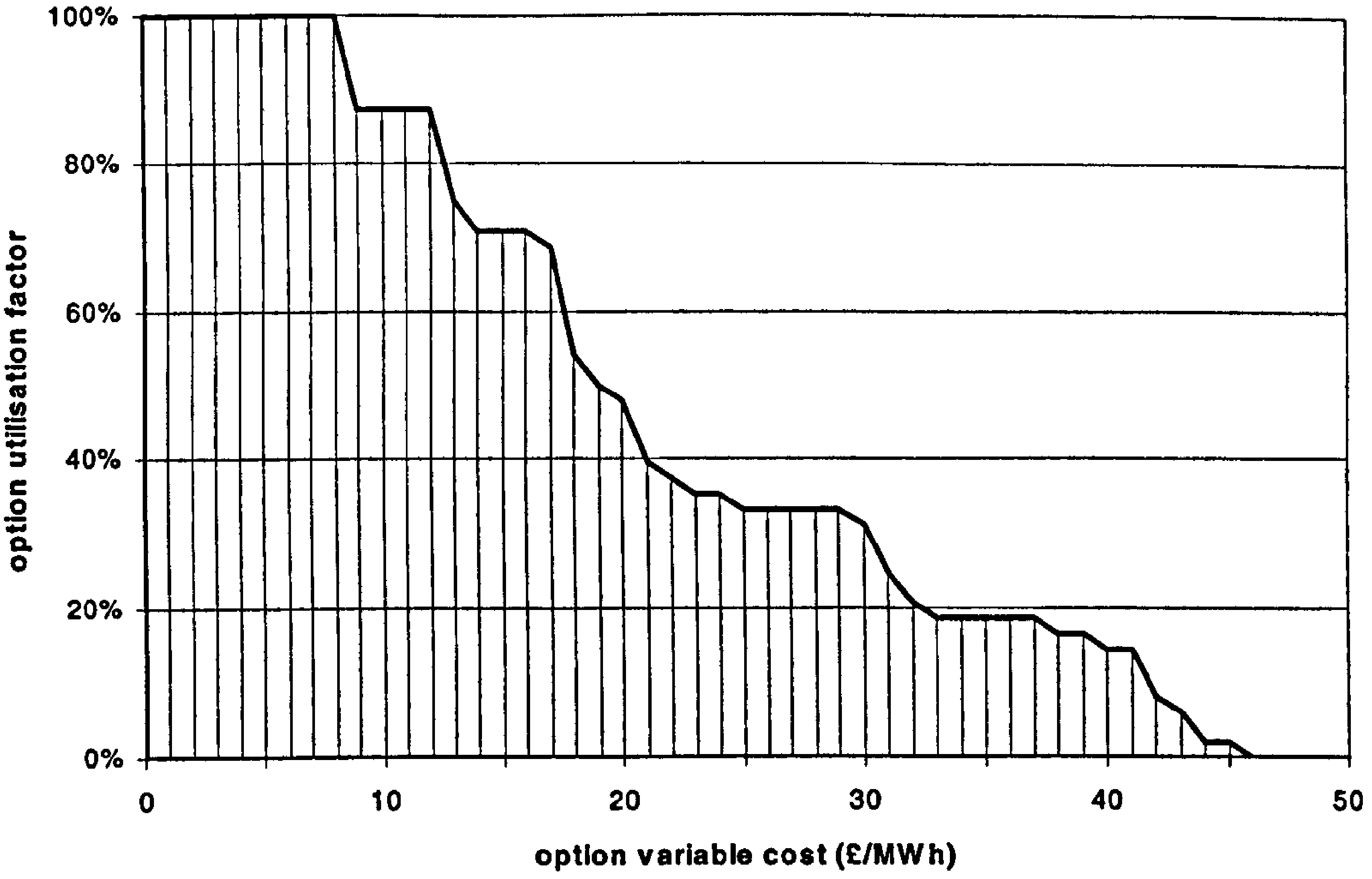


Figure 5-10: Variation of option utilisation factor with option variable cost (one day).

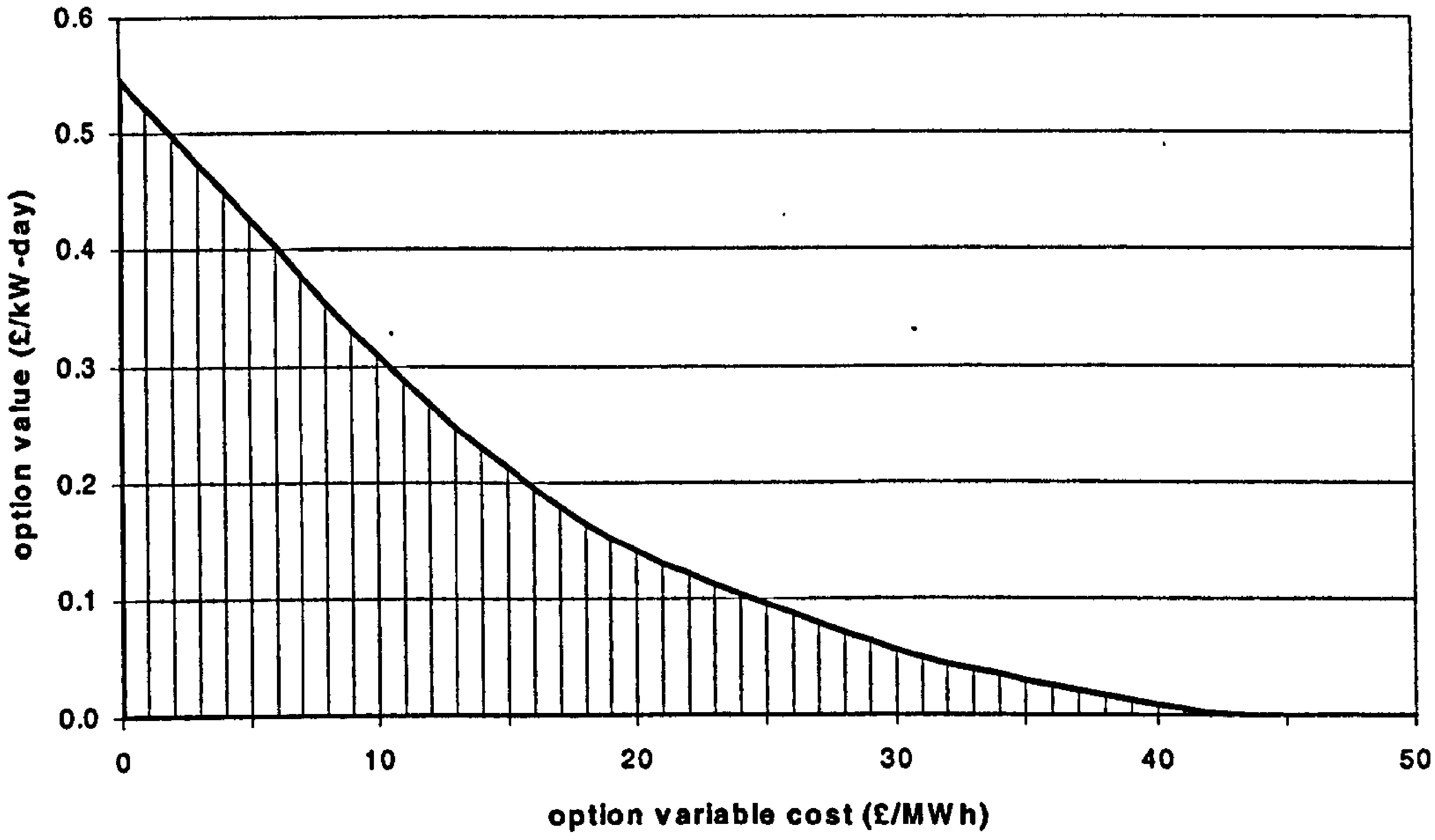


Figure 5-11: Variation of option value with option variable cost (one day).

The utilisation factor and value of a distributed generation option can be assessed over a full year. In this case, historic records of electricity spot price from the UK Electricity Pool have been used to produce the utilisation and value characteristics.

Figure 5-12 shows the variation of distributed generation option utilisation factor for one complete year (1996/97).

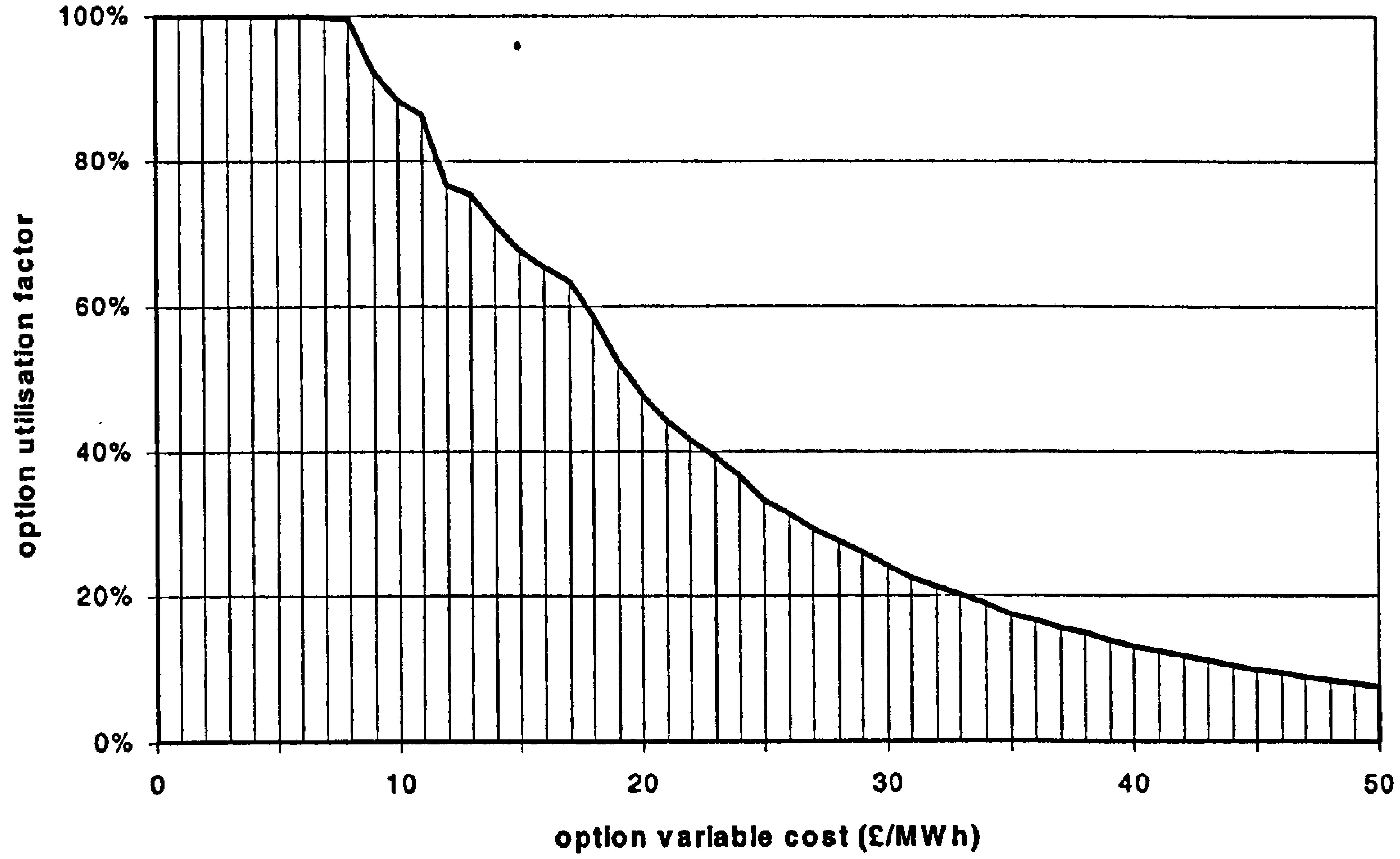


Figure 5-12: Variation of option utilisation factor with option variable cost over one year (1996/97).

Figure 5-13 illustrates the distributed generation option value (£/kW installed) for one year (1996/97). It can clearly be seen that distributed generators with low variable costs produce significant benefit in avoidance of higher spot prices on the electricity wholesale market.

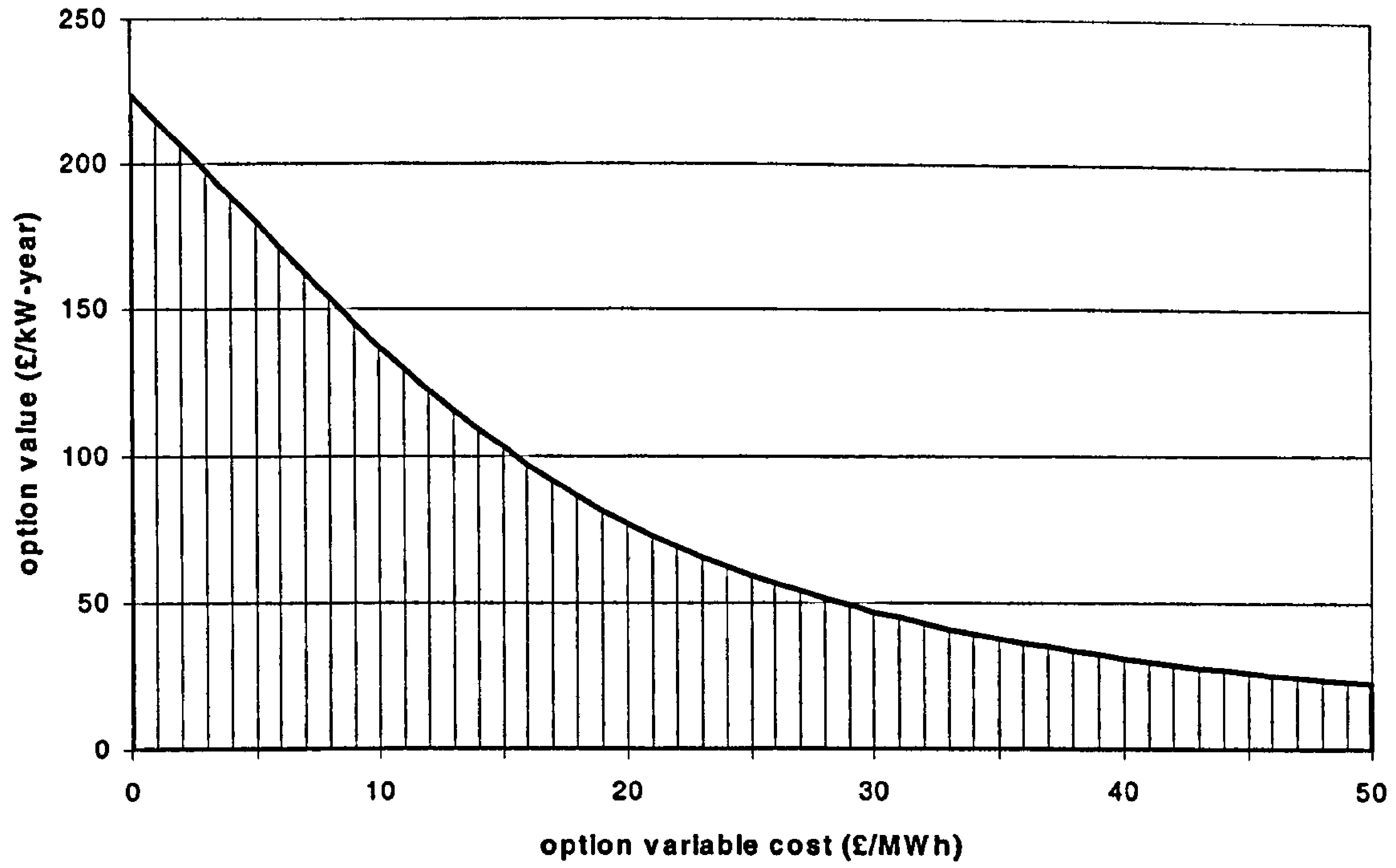


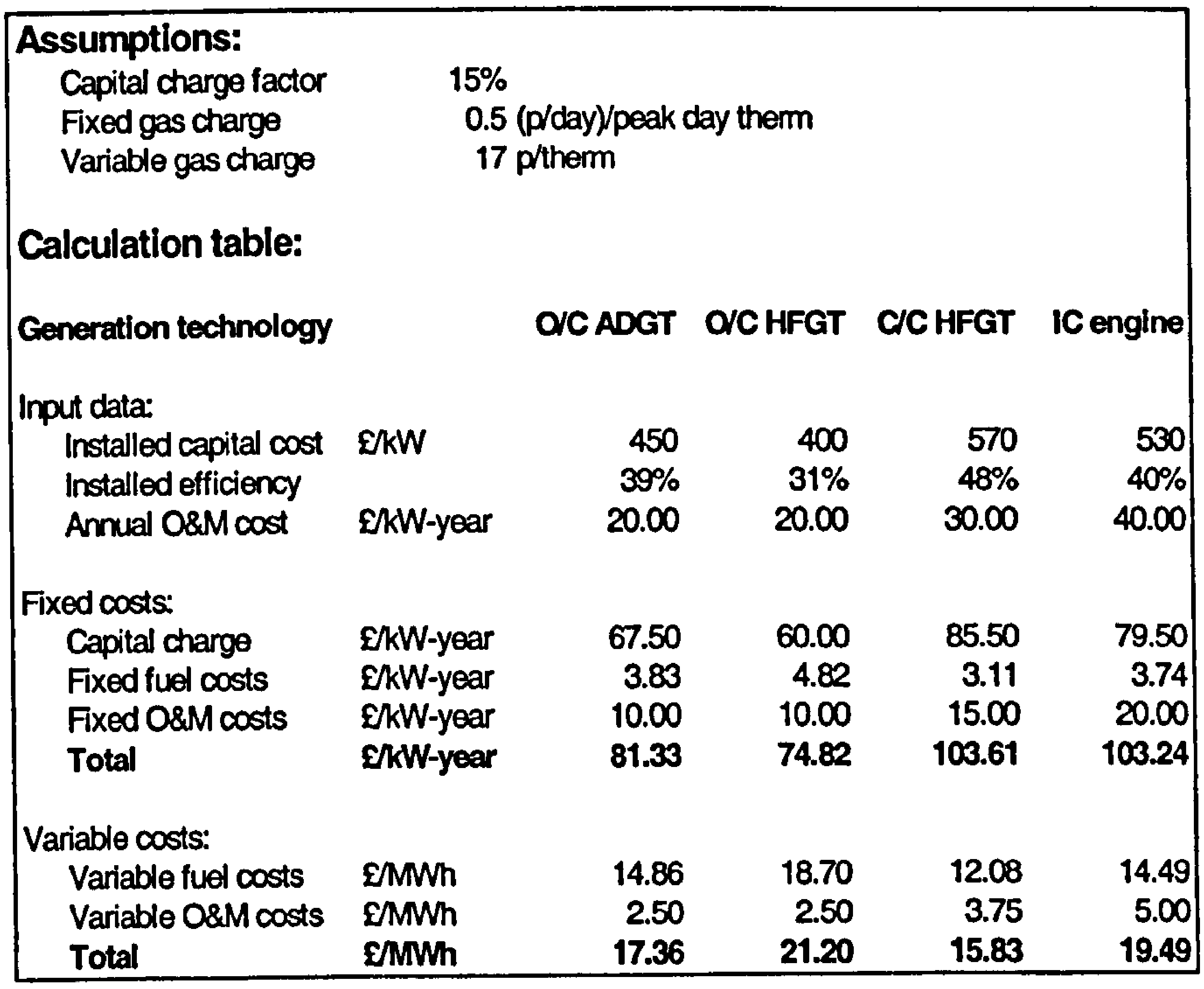
Figure 5-13: Variation of option value with option variable cost over one year (1996/97).

The option value is effectively a fixed benefit per year for owning or having an option to operate a distributed generating unit with a particular variable operating cost. If a distributed generating technology has a particular variable cost, investment in a generating unit of that technology would be profitable if the fixed cost of owning the generating unit or having the option to operate the generating unit were less than the option value of such a unit with the given variable cost as read from Figure 5-13.

If four of the more commonly found natural gas fired generating technologies are considered the relative attractiveness of each technology as a distributed generation option can be assessed. The data values for the following technologies are detailed in Table 5-1:

- Open cycle aero-derivative gas turbine (O/C ADGT)
- Open cycle heavy frame gas turbine (O/C HFGT)
- Combined cycle heavy frame gas turbine (C/C HFGT)
- Gas fired internal combustion engine (IC Engine)

A number of assumptions have been made in deriving these values including generating unit size and the split of fixed and variable operating costs (Ault et al, 1997).



Assumptions:

Capital charge factor 15%

Fixed gas charge 0.5 (p/day)/peak day therm

Variable gas charge 17 p/therm

Calculation table:

Generation technology		**O/C ADGT**	**O/C HFGT**	**C/C HFGT**	**IC engine**
Input data:					
Installed capital cost	£/kW	450	400	570	530
Installed efficiency		39%	31%	48%	40%
Annual O&M cost	£/kW-year	20.00	20.00	30.00	40.00
Fixed costs:					
Capital charge	£/kW-year	67.50	60.00	85.50	79.50
Fixed fuel costs	£/kW-year	3.83	4.82	3.11	3.74
Fixed O&M costs	£/kW-year	10.00	10.00	15.00	20.00
Total	**£/kW-year**	**81.33**	**74.82**	**103.61**	**103.24**
Variable costs:					
Variable fuel costs	£/MWh	14.86	18.70	12.08	14.49
Variable O&M costs	£/MWh	2.50	2.50	3.75	5.00
Total	**£/MWh**	**17.36**	**21.20**	**15.83**	**19.49**

Table 5-1: Generation cost data for distributed generation option evaluation.

The combination of fixed and variable cost parameters for each technology type can be assessed using the option value-option variable cost characteristic previously derived in Figure 5-13.

The results of the evaluation are illustrated in Figure 5-14.

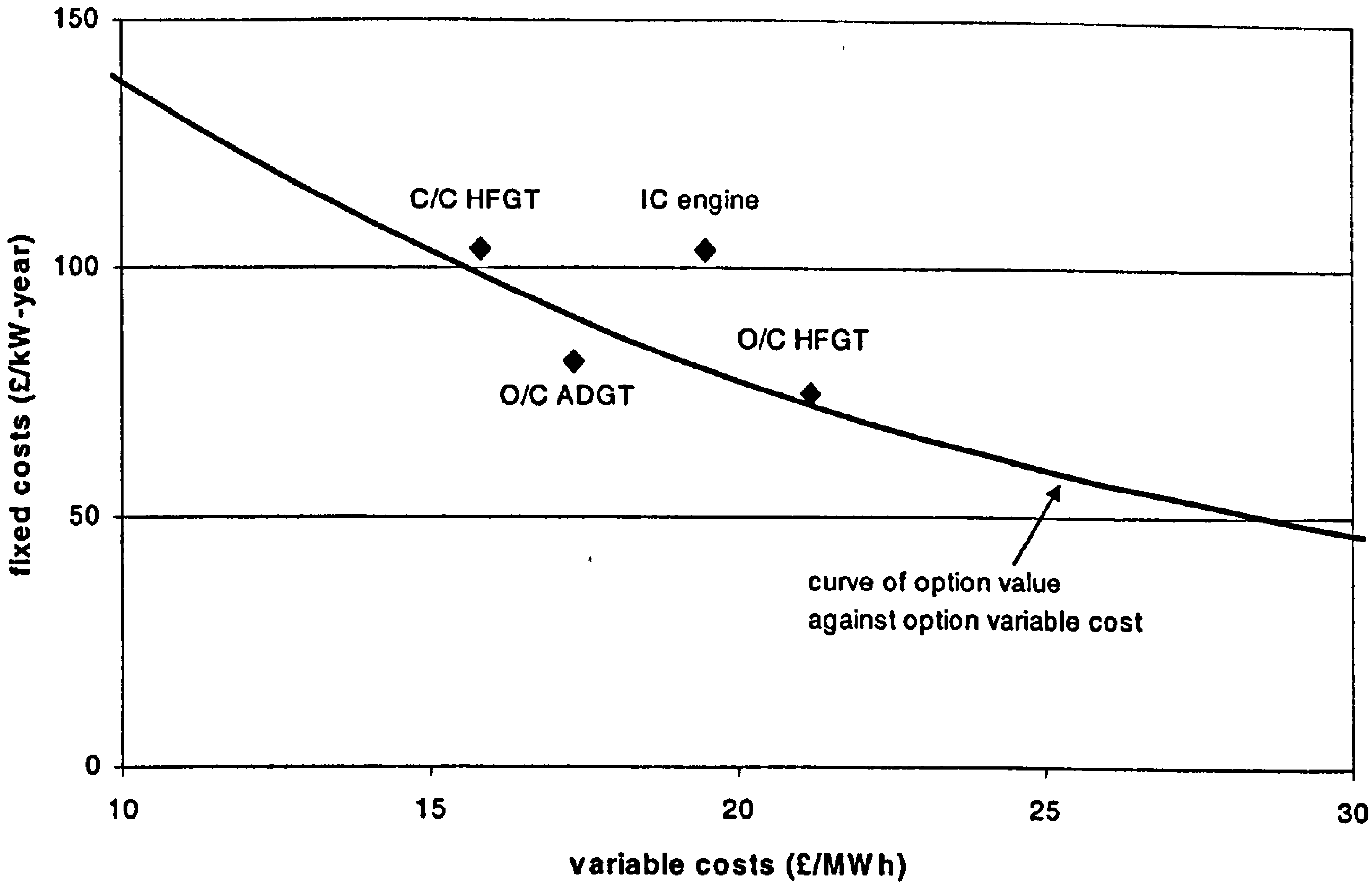


Figure 5-14: Fixed and variable cost of generation technologies relative to distributed generation option value-option variable cost characteristic.

Figure 5-14 shows that, although the combined cycle heavy frame gas turbine (C/C HFGT) has high efficiency and thus low variable costs, the high fixed capital costs make this technology relatively unattractive in this distributed generation application. The open cycle heavy frame gas turbine (O/C HFGT) has low fixed costs but the relatively high variable operating costs also make this technology unattractive in this application. The gas fired internal combustion engine (IC Engine) has high fixed and high variable costs and as such is not viable. The open cycle aero-derivative gas turbine (O/C ADGT) has neither the lowest fixed or variable costs but the combination of fixed and variable costs make it attractive as an energy purchase option for an energy trader operating in the UK Pool system.

One further issue of importance is the number of start-stop cycles to extract the benefits outlined above. For many combustion technologies, the number of start-stop cycles has a major influence on maintenance scheduling and plant or component life. These considerations could impact significantly on the economics of these technologies. In addition, the stochastic output of some distributed generation technologies would result in a different pattern of benefits from such a distributed generation option. For example, photovoltaic units would be biased to operation in daylight hours and in the summer months while wind generation output is highly variable but generally higher in the winter months. The interaction of the outputs of these and other technologies with the electricity spot price profiles is complex. In addition, the analysis presented here is based on historical electricity market price data. With the high volatility of electricity market prices (not to mention the change in trading mechanism planned for November 2000) the use of historical data may appear suspect. However, the method presented does allow a rough analysis to be made of the attractiveness of each distributed generation technology.

5.5.1.2 Optimising the Distributed Generation Technology Mix

While no individual industry player in the restructured ESI has the responsibility to 'optimise' the system, it may still be of interest to speculate on what on optimal mix of distributed generation might look like. The national government in a country with a restructured electricity industry could fashion policy to encourage investors to develop distributed generation projects to match the optimal mix.

Optimisation of generation plant mix has been conducted for large systems by Andrews (Andrews, 1990), Redmond with Huber (Huber et al, 1992) and Redmond (Redmond, 1994). Typical objectives for the problem include total system cost, reliability of the generation system, emissions and reserve capacity. In each of the examples cited, the generation mix has been optimised for a given set of uncertainties, strategies and constraints with multiple attribute tradeoff techniques used to assess the best strategies across the range of uncertainties and constraints.

The problems with using optimisation for many planning problems in the electricity industry are discussed in section 4.4.3. In addition, although it is possible to use a production simulation package such as the Electric Generation Expansion Analysis System (EGEAS) to create models of small distributed generation units, there are a number of problems with tackling the production of distributed generation scenarios in this manner.

Distributed generation technologies rarely appear in the optimal mix when compared with large scale central generation technologies. The poor showing of distributed generation can be explained by the omission of the many electricity network benefits which add a significant amount to their value. In addition, it is difficult to recreate the schemes of support for distributed generation technologies (particularly renewables and combined heat and power) within EGEAS models. This is not to say that the task of optimising the generation mix for distributed generation can not be achieved but it is simply a different problem from the creation of plausible scenarios of distributed generation to facilitate the analysis of their effect on the distribution network and business.

The EGEAS model data for an aero-derivative gas turbine including financial, environmental, availability and maintenance characteristics is shown in Appendix A and the structure of the model is described in the EGEAS user manual (Stone & Webster Management Consultants, 1991). This model was generated to assess the likelihood of the proliferation of such units in the UK electricity market and led to the conclusions described above.

5.5.1.3 Penetration Forecasting for Distributed Generation

A high volume of activity in market forecasting for energy related devices has been evident over many years. The forecasting techniques are most applicable to small devices for which a high volume market may exist. Many distributed generation technologies fall into the small scale category including photovoltaic, fuel cells, Stirling engines and some types of wind turbines.

A number of forecasting methods are available for mass produced and widely distributed energy technologies (Philipson, 1978). The applicability of the techniques is dependent on the type of technology, the perceived consumer attitude to the risks associated with fledgling technology (logistic and linear learning curves) and the marketing associated with the product launch (exponential curve).

Three general methods for forecasting small-scale energy device penetration are discussed.

- Logistic curves (S-curves)
- Exponential penetration curves
- Linear learning curves

Figure 5-15 illustrates the general shape of penetration over a period of time. The figures used are purely illustrative and not based on any particular technology or year. Annotations on the graph indicate some of the issues relating to the application of these curves.

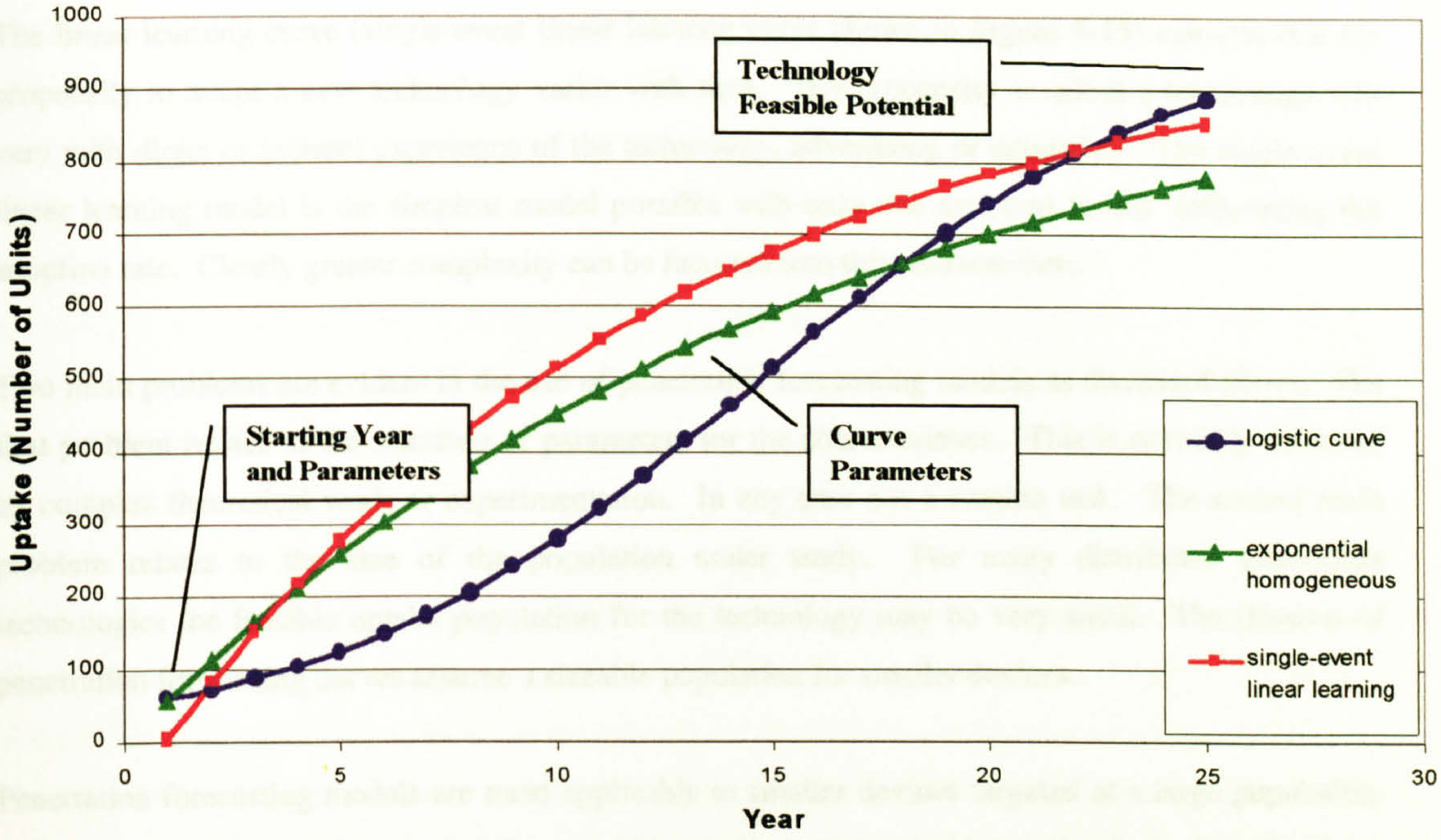


Figure 5-15: Characteristics of energy technology penetration curves.

The most basic penetration curve is the exponential curve (homogeneous exponential curve shown in Figure 5-15). The main features of the exponential curve are the factors for the propensity to adopt the new technology and the total population who could feasibly adopt the technology. Essentially, the uptake of the technology as time moves forward is proportional to the population yet to adopt the technology, thus the characteristic approaches the maximum feasible potential asymptotically. The homogenous exponential curve assumes an uniform propensity to adopt the technology. A non-homogeneous model is also possible which enables the propensity to adopt the technology to vary across the population. The exponential model is relevant in cases where adoption of the technology does not depend on observed experience of the technology and thus is characteristic of a low risk product or of a product which meets an immediate need.

The logistic curve method builds on the characteristic of the exponential model by including, in the technology adoption rate, a factor relating to the proportion of the population who have already adopted the technology. When the penetration of the new technology is low the adoption rate tends to remain low. When experience of the new technology becomes more widely known the adoption rate increases as the perceived risk of the new technology has been reduced. Finally, the adoption rate reduces later in the technology maturity cycle as the maximum feasible penetration for the technology is approached.

The linear learning curve (single-event linear learning curve shown in Figure 5-15) assumes that the propensity to adopt a new technology varies with time. The propensity to adopt a technology will vary with direct or indirect experience of the technology, advertising or education. The single event linear learning model is the simplest model possible with only one assumed 'event' influencing the adoption rate. Clearly greater complexity can be factored into this characteristic.

Two main problems are evident in the use of penetration forecasting models as discussed above. The first problem relates to the selection of parameters for the characteristics. This is normally achieved by complex theoretical work or experimentation. In any case not a routine task. The second main problem relates to the size of the population under study. For many distributed generation technologies the feasible uptake population for the technology may be very small. The theories of penetration forecasting curves assume a sizeable population for smaller devices.

Penetration forecasting models are most applicable to smaller devices targeted at a large population. In the distributed generation market they could be applied to household or 'micro' sized gas turbines, gas engines, fuel cells or combined heat and power units.

5.5.1.4 Scenarios Technique for Distributed Generation Forecasting

The use of scenarios to gauge the possible influences on a business or sector has gained great momentum in recent years. The term scenario is not new and has always been used to depict a particular set of circumstances. The use of the term 'scenario' in scenario planning can mean very different things to different people.

The 'scenario' technique as used by management scientists has come to be associated with the formation of a small set of scenarios which try to incorporate some of the flavour of all plausible future outcomes. These scenarios are painted at a 'macro' level for some years or even decades ahead.

This is very different from a more traditional 'micro' view of scenarios for say electricity demand growth. Several scenarios for load growth could be established each with a slightly different annual value which could differ by something like 0.5% in each case. The argument against this type of scenario is that it limits the level of uncertainty which is incorporated into the analysis of the future.

Scenarios have become widely used in strategic planning activities as evidenced by their adoption as one of the core techniques promoted by the Foresight programme of the Office of Science and Technology in the UK (Stout, 1999). The Foresight programme seeks to promote the use of scenarios in a wide range of industries to enable more effective planning for future business competitiveness (Foresight, 1999).

A Foresight study of the changes in attitude to the environment (Office of Science and Technology, 1999) produced scenarios for future societal and corporate values. It is interesting to note that, in three of the four scenarios depicted, distributed generation is seen to be a growth area in many world regions in the coming years.

Scenarios could be used successfully to specify different volumes and mixes of distributed generation which could subsequently be analysed for their effect on the distribution network. One further benefit of scenarios would be the clear focus on the opinions of the ultimate decision-makers who should play a key role in developing the scenarios. This focus may prevent some of the problems of acceptability of modelling techniques, tools and data which tend to arise in the simulation of complex problems.

5.5.1.5 Distributed Generation Penetration Rate Model

A two stage approach for assessing likely penetrations of distributed generation technologies has recently been used by the economics consultants OXERA (Benito, 1999). The two stages in the assessment of distributed generation technologies are:

1. calculate the internal rate of return (IRR) for the technology through time
2. estimate the number of investors in the technology through time based on the IRR.

The calculation of an internal rate of return is widely documented in the literature (Khatib, 1997). The calculation of IRR is an extension of a discounted cash flow. The discounted cash flow is calculated by applying a discount (interest) rate to all revenues and expenditures relating to a project to produce a reflection of their value in a base year. The higher, the net present value of the project at a particular discount rate, the more profitable the project, assuming the expenditure and revenues materialise as estimated. IRR is the discount (or interest) rate at which the net present value is zero or, in other words, the discount rate which equates the expenditure to revenue over the life of the project in present value terms. A full description of these concepts is provided in section 3.3.3.9.

IRR is commonly used by private enterprises to assess and compare investment options. Focusing on distributed generation, the comparison may be between locations for identical technology generation schemes. Alternatively, with a given location, different generation technologies can be compared using IRR. The higher the IRR the more attractive the project option.

OXERA produced the following bar-charts to illustrate the IRR for a number of renewable and combined heat and power distributed generation schemes operating in the UK electricity market (Ault et al, 1999). Figure 5-16 shows the IRR values for renewable technologies while Figure 5-17 shows the IRR values for combined heat and power technologies.

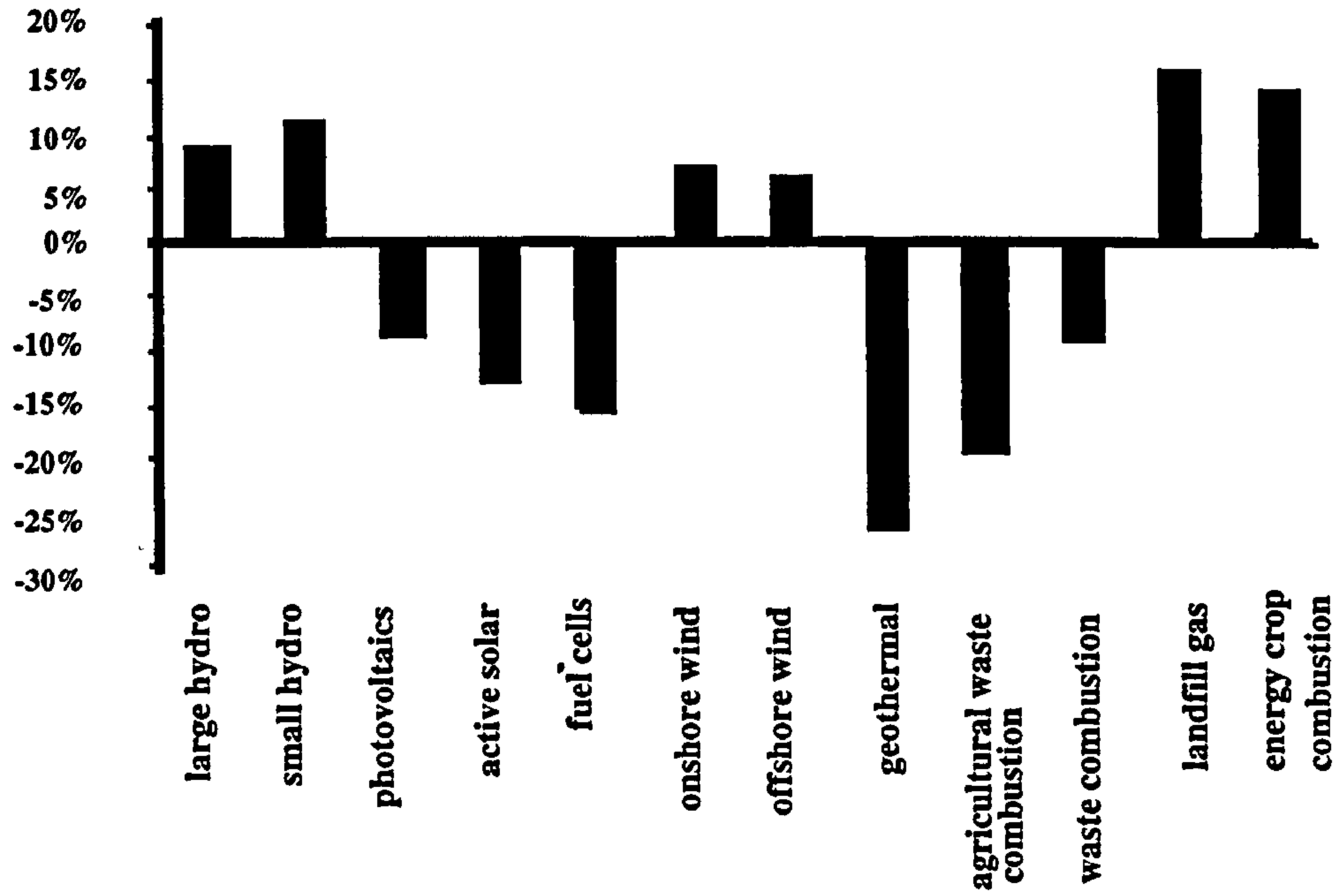


Figure 5-16: Internal Rate of Return for renewable technologies in the UK electricity market (Source: OXERA, 1999).

Figure 5-16 shows that hydro, wind, landfill gas and energy crop combustion are the most attractive generation technologies for the UK market among the renewable technologies. These technologies form the predominant majority of renewable schemes currently operating in the UK. The interest payments on the high capital cost of the other technologies forces the IRR for each into negative territory.

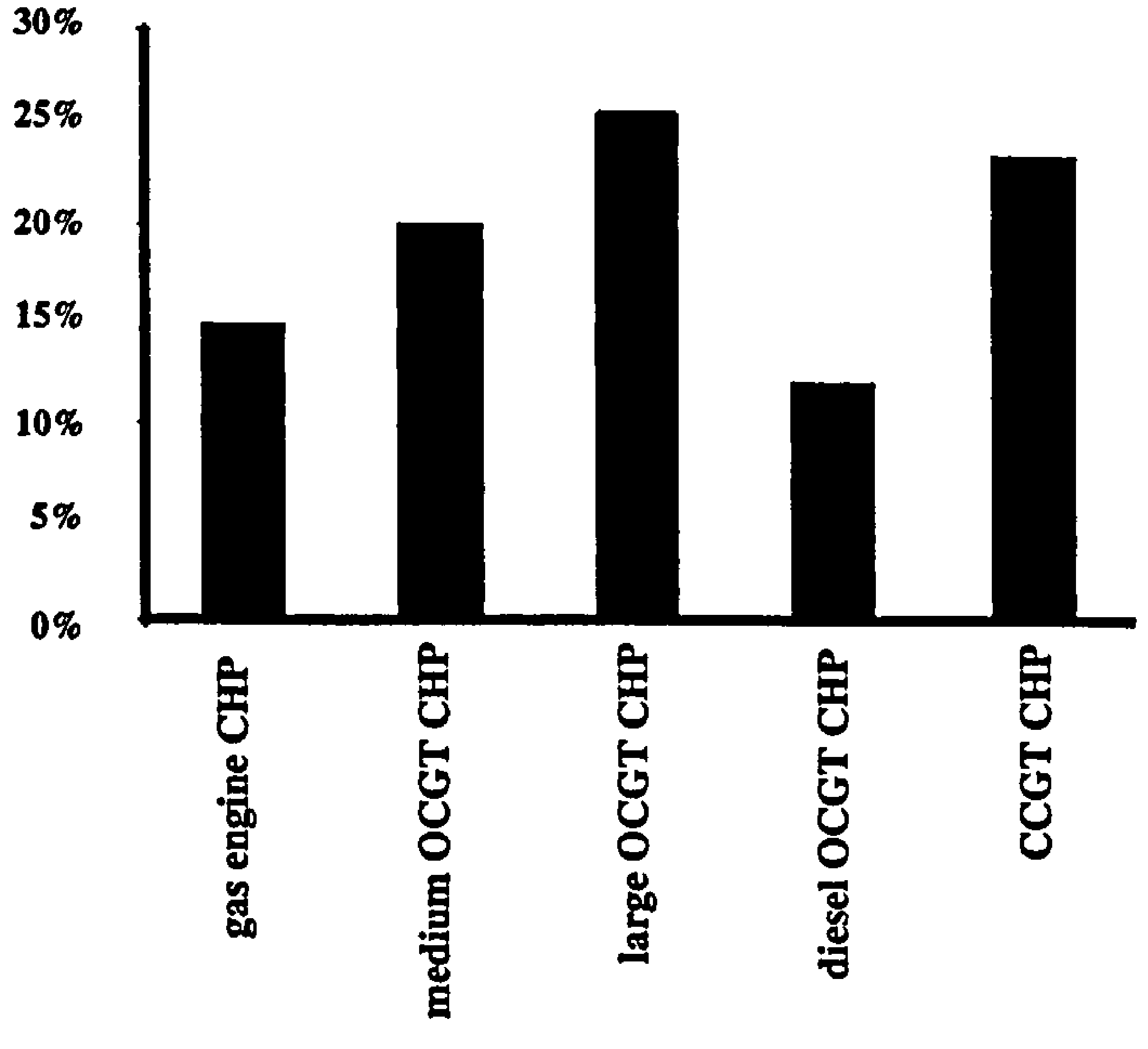


Figure 5-17: Internal Rate of Return for combined heat and power technologies in the UK electricity market (Source: OXERA, 1999).

Figure 5-17 shows the relative attractiveness of natural gas fired generation technologies in combined heat and power configurations. Gas turbine based schemes are the most attractive with high IRR values of 20% or greater. This result points to the rationale behind the 'dash for gas' in the UK electricity market which resulted in the installation of substantial capacities of natural gas turbine based generation (although mainly in larger unit sizes). The speed of the switch to natural gas fired generation in the early 1990s led to a moratorium on generation licences for gas fired generation in 1997 amidst fears of fuel dependency on natural gas.

The second part of the OXERA method for producing distributed generation scenarios is to calculate a penetration rate for each technology. The penetration rate is based on the financial incentives to invest in a generation scheme of a particular technology which relates back to the IRR value. The rate of adoption of the technology assumes a maximum technical feasible potential and a measure of the willingness of an investor to commit to a project with a given prospective IRR. Studies relating to the maximum feasible potential energy resource from new and renewable technologies have been made by the government (Department of Trade and Industry, 1999).

The willingness of an investor to invest in a generation scheme is assumed to reflect the attitude to the IRR value for the technology or scheme. If an organisation has a threshold IRR value of 15%, above which projects are viewed favourably, then an investment in a large open cycle gas turbine (OCGT) combined heat and power scheme would look attractive (Figure 5-17) while investing in onshore wind, while producing a positive return, would appear to be unattractive (Figure 5-16). This characteristic of investors to have threshold or target IRR values to trigger investments is a simplification but useful for producing generalised scenarios for distributed generation. The investment threshold characteristic used is a log-normal distribution. Figure 5-18 illustrates a log-normal penetration rate characteristic based on internal rate of return. In this case a mean internal rate of return required by investors for project feasibility is 12% with a standard deviation of 4%.

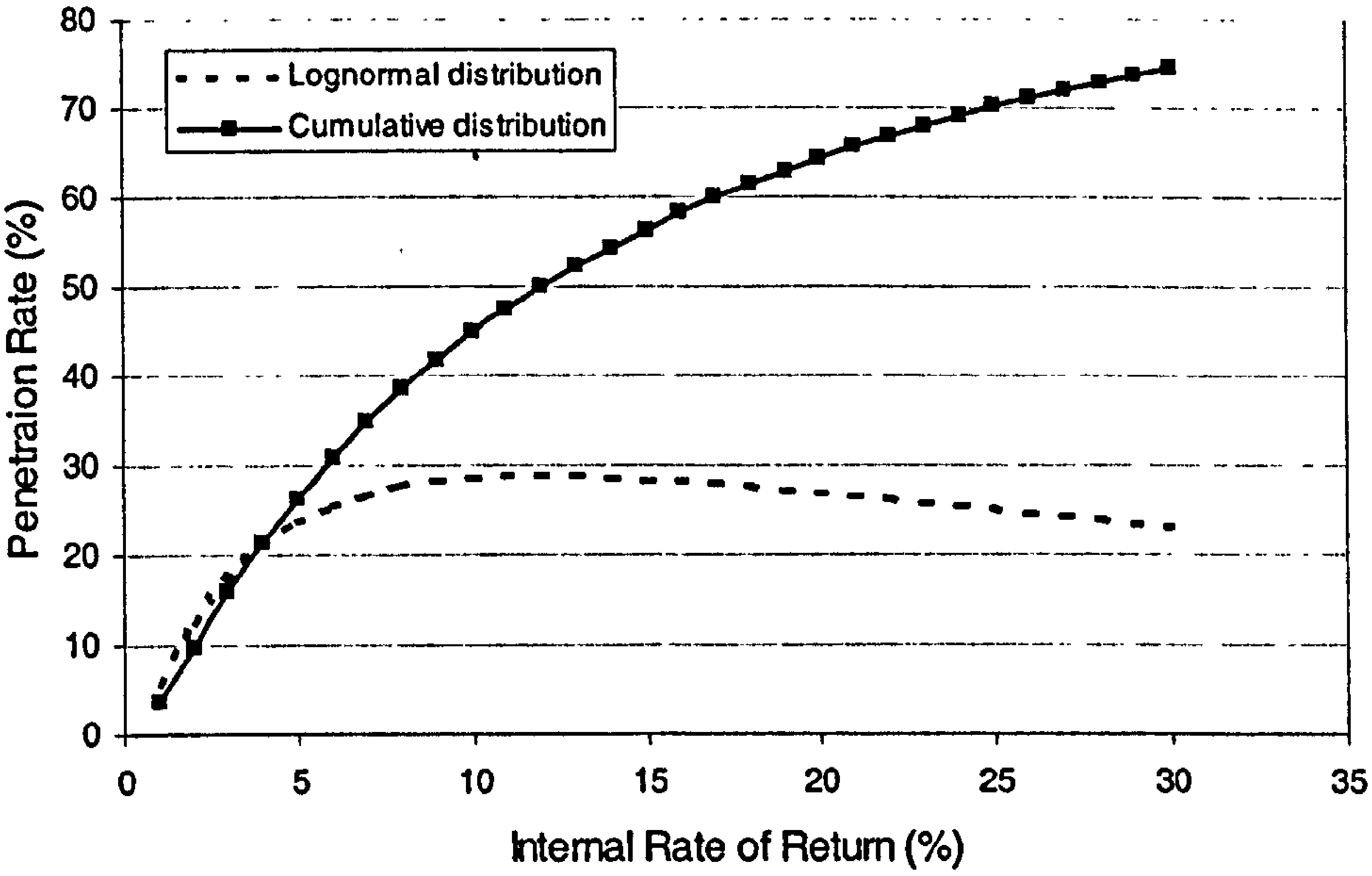


Figure 5-18: Log-normal penetration rate characteristics.

The cumulative penetration rate for the group of investors (in %) is shown by the cumulative distribution curve. For example, if a generation technology type has a prospective internal rate of return of 20% (neglecting the geographical and project specific variations) then around 65% of the possibilities for investment in this technology will be exploited. The log-normal distribution curve shows the general shape of investors attitude to internal rate of return based on the mean of 12% and standard deviation of 4%.

Problems arise in estimating the maximum technically feasible potential beyond which it is expected nobody would invest regardless of the potential returns. Problems also arise in modelling investor behaviour which is much more complex than this simple model.

5.5.2 Power System Analysis

The objective of the power system analysis module is the analysis of the physical effect of distributed generation scenarios on the power distribution network. The scope, accuracy and computation time taken for the analyses will vary with the technique(s) adopted. The sub-sections below briefly describe the various subsets of power system analysis as they might be employed to assess the impact of distributed generation on the power network.

5.5.2.1 Power Flow Analysis (a.c.)

Standard steady state power system analysis could be conducted using a readily available software package. Results would include: losses; voltages; overloads; asset utilisation; peak flows, and; peak capacity requirements. The simulations should be designed carefully to represent load growth, time of day, load and generation profiles, and different scenarios for embedded generation.

5.5.2.2 Power Flow Analysis (d.c.)

Quicker (and with more assumptions) than a.c. power flow analysis would be the use of d.c. power flow analysis. d.c. analysis is simpler to incorporate in network expansion analysis algorithms and finds many uses in optimisation procedures and pricing studies. Unfortunately some critical parameters in distribution engineering such as voltage and reactive power flow are omitted from d.c. power flow algorithms thus limiting its usefulness in some aspects of power system planning. For problems regarding capacity or pricing and where expansion algorithms are necessary, d.c. power flow could be used.

5.5.2.3 Fault Analysis

Where it is required to assess the impact of distributed generation on system fault conditions, fault analysis will become essential. Simple balanced fault analysis is simplest and quickest but in some cases a more detailed asymmetrical fault analysis will be required to assess the requirements on switchgear making and breaking duties.

5.5.2.4 Reliability Analysis

Distributed generation can contribute to overall supply reliability and security in some circumstances. It may be necessary to assess this contribution by way of probabilistic evaluation of supply security or availability. Distributed generation will have little or no effect on the reliability of the existing network plant. Probabilistic analysis using spreadsheets or a specialist system reliability software package could be used to conduct these studies.

5.5.2.5 Power Quality Analysis

In some circumstances the effect of embedded generation on power quality will be assessed. The areas of power quality affected by embedded generation will be established and specific simulation activities conducted to gauge the effect on these attributes. Conducting such simulations over a number of scenarios could be computationally intensive. The number of variables in the calculation of power quality could detach the results from the overall planning process.

5.5.2.6 Dynamic Performance Analysis

The stability of distributed generation and its impact on network stability, power quality and system security are critical issues. Stability analysis is normally reserved for much more detailed transmission expansion analysis but with growing emphasis on enhanced power quality and the maintenance of security levels, such studies may become more common with smaller scale distributed generation and distribution systems. If so, the use of dynamic simulation tools will become a necessary part of the strategic analysis framework outlined in this thesis. Detailed plant and network models are required for dynamic performance studies which generally require time and expertise to develop. Voltage stability, transient stability and small signal stability studies may be warranted under certain conditions or requirements of the planning study.

5.5.2.7 Optimal Power Flow

The effect of optimal unit location and operational characteristics of distributed generation may be investigated with an optimal power flow module within the strategic analysis framework. This type of analysis would be particularly useful for the investigation of utility options for providing incentives to distributed generators to locate and operate in a manner which is beneficial for the distribution network and distribution business.

5.5.2.8 Probabilistic Power Flow

Probabilistic load flow could become a useful technique to capture the uncertainties relating to load, generation and the distribution network. Rather than studying the effect of distributed generation over a discreet number of conditions, the full range of system conditions with the accompanying probability of their occurrence could be considered. This could provide very useful insight into the aggregate effect of distributed generation on the distribution system over time.

5.5.3 Distribution Utility Financial Analysis

5.5.3.1 Distribution utility financial analysis requirements

The distribution utility financial analysis module evaluates the financial implications of distributed generation for a distribution company. The inputs to the financial module are a set of network performance characteristics from the power system analysis module. The required output from the distribution utility financial analysis module is information on the effect of distributed generation scenarios on the distribution business.

In broad terms, three main areas of utility finance must be investigated:

1. Revenue
2. Operating expenditure
3. Capital expenditure

In addition, the longer-term effect of distributed generation on the charges that distribution companies pay for transmission exit points should be analysed. In the UK, these National Grid Company (NGC) exit charges are excluded from the distribution price control since the charges levied on the distribution companies by NGC are regulated and therefore simply passed on to customers by the distribution company (see section 3.3.7.5).

5.5.3.2 Costs and Revenues in Electricity Distribution

Electricity distribution costs can be categorised as either capital or operational costs. Capital and operational costs are treated differently within the distribution regulation mechanism.

Initially, before thinking about establishing relationships for costs and benefits associated with distributed generation, it is necessary to identify specific areas of costs under the general headings of capital and operational costs.

The primary capital expenditure budget groupings are listed in Table 5-2.

Capital Expenditure Budget Groupings
Network diversions
Generation related reinforcement
Asset replacement
Environmental, health and safety
New connections
Performance improvement
Power quality improvement
Load related network reinforcement

Table 5-2: Distribution capital expenditure budget groupings.

The primary operational expenditure budget groupings are listed in Table 5-3.

Operational Expenditure Budget Groupings
Personnel
Repairs
Maintenance
Transport
Information Technology

Table 5-3: Distribution operational expenditure budget groupings.

Trying to gauge the extent of the change in any one of these budget items due to distributed generation is potentially a difficult task. For this reason a set of equations will be established to enable the investigation of changing expenditure requirements due to distributed generation. This set of equations will enable the results from power system analysis modules to be interpreted within the distribution utility financial framework. Data from sources other than the power system analysis modules can also be entered into the financial analysis expressions to augment the investigation of the impact of distributed generation.

Distribution revenues arise from a number of sources. Table 5-4 shows the main revenue items for an UK based regional monopoly electricity distributor.

Distribution Revenues
Use of System Revenues
Connection Revenues
Rechargeable Works
Excluded Use of System Revenues
Other revenues

Table 5-4: Distribution revenue items.

5.5.3.3 Utility profit expression

A simple expression relating revenue to profit and expenditure is introduced in Equation 5-1.

$$R_t = \left(C_{Ct} + C_{Ot} + \text{Profit}_t\right)$$

Equation 5-1

Where,

R_t	is the revenue in year *t*,
C_{Ct}	is the capital investment in year *t*,
C_{Ot}	is the operational cost in year *t*,
$Profit_t$	is the utility profit in year *t*.

A new set of expressions can be derived to characterise more detail of the underlying utility cost and revenue structure. It should be noted that tax, debt and depreciation have been deliberately excluded from these expressions as they do not add anything to the analysis of distributed generation under current regulatory and legislative mechanisms.

5.5.3.4 Capital expenditure expressions

The total capital expenditure, C_{Ct}, in year t can be expressed as the summation of the individual capital cost items (Equation 5-2).

$$C_{Ct} = \sum_{i=1}^{N} \left(C_{Ct}\right)_{i}$$

Equation 5-2

For $i = 1$ to N capital cost items. If the capital expenditure items (Table 5-2) are expressed individually we can write an expression for the capital cost in year t (Equation 5-3),

$$C_{Ct} = \left(C_{C.GRRt}\right) + \left(C_{C.LRRt}\right) + \left(C_{C.EHSt}\right) + \left(C_{C.NCt}\right) + \left(C_{C.PIt}\right) + \left(C_{C.PQIt}\right) + \left(C_{C.ARt}\right)$$

Equation 5-3

Where,

$C_{C.GRRt}$	is the capital cost item relating to generation related reinforcement,
$C_{C.LRRt}$	is the capital cost item relating to load related reinforcement,
$C_{C.EHSt}$	is the capital cost item relating to environmental, health & safety,
$C_{C.NCt}$	is the capital cost item relating to new connections,
$C_{C.PIt}$	is the capital cost item relating to performance improvement,
$C_{C.PQIt}$	is the capital cost item relating to power quality improvement,
$C_{C.ARt}$	is the capital cost item relating to asset replacement.

A capital expenditure item for network diversions has not been included in the expression as it is assumed that distributed generation will have a negligible effect on network diversions.

5.5.3.5 Operational expenditure expressions

The total operational expenditure in year *t* can be expressed as the summation of the individual operational cost items:

$$C_{Ot} = \sum_{i=1}^{M} \left(C_{Ot}\right)_i$$

Equation 5-4

For $i = 1$ to M operational expenditure items. If the operational expenditure items (Table 5-3) are expressed individually, we can write the expression for the total operational cost in year *t* (Equation 5-5),

$$C_{Ot} = \left(C_{O.PERt}\right) + \left(C_{O.REPt}\right) + \left(C_{O.MNTt}\right) + \left(C_{O.ITt}\right)$$

Equation 5-5

Where,

$C_{O.PERt}$	is the operational expenditure item relating to personnel,
$C_{O.REPt}$	is the operational expenditure item relating to repairs,
$C_{O.MNTt}$	is the operational expenditure item relating to maintenance,
$C_{O.ITt}$	is the operational expenditure item relating to information technology.

An operational expenditure item for transport has not been included in this expression as it is assumed that distributed generation will have a negligible impact on transport costs.

5.5.3.6 Revenue expressions

The total revenue in year t can be expressed as follows:

$$R_t = \sum_{i=1}^{P} (R_t)_i$$

Equation 5-6

for $i = 1$ to P revenue items. Expressing the revenue items (Table 5-4) individually yields the expression for total revenue in year *t* (Equation 5-7),

$$R_t = (R_{RUSt}) + (R_{CONt}) + (R_{RWt}) + (R_{EXUSt})$$

Equation 5-7

Where,

R_{RUSt}	is the revenue item relating to regulated use of system charges,
R_{CONt}	is the revenue item relating to connection charges,
R_{RWt}	is the revenue item relating to rechargeable works,
R_{EXUSt}	is the revenue item relating to excluded use of system revenues.

Other smaller revenue items have been excluded from the expression at present.

5.5.3.7 Distributed generation influences in distribution utility financial expressions

If it is now assumed that a scenario for distributed generation will have a particular effect on revenue and expenditure, we must formulate an expression which will capture the changes directly attributable to distributed generation.

First, let us rearrange Equation 5-1:

$$\mathrm{Profit}_t = R_t - (C_{Ct} + C_{Ot})$$

Equation 5-8

If we assume (as discussed above) that each of the items in revenue and expenditure are functions of distributed generation in some way then let us differentiate Equation 5-8 with respect to distributed generation:

$$\frac{d(\mathrm{Profit}_t)}{dDG} = \frac{d}{dDG}\{R_t - (C_{Ct} + C_{Ot})\}$$

Equation 5-9

Therefore,

$$\frac{d(\mathrm{Profit}_t)}{dDG} = \frac{d(R_t)}{dDG} - \frac{d(C_{Ct})}{dDG} - \frac{d(C_{Ot})}{dDG}$$

Equation 5-10

5.5.3.8 Distribution utility financial performance impact expressions

Instead of using the word 'profit', which may become misleading, the term 'financial performance impact' will be used. The symbol F_{DG} will replace the differential term for *profit* in Equation 5-9. Therefore, Equation 5-9 becomes:

$$\mathrm{F}_{\mathrm{DGt}} = \frac{d(R_t)}{dDG} - \frac{d(C_{Ct})}{dDG} - \frac{d(C_{Ot})}{dDG}$$

Equation 5-11

Expressing Equation 5-11 in words: '*the financial performance impact of distributed generation on a distribution utility is the change in revenues due to distributed generation minus the change in capital expenditure due to distributed generation minus the change in operational expenditure due to distributed generation*'.

This expression forms the basis of for analysing the financial impact of distributed generation on a distribution utility. It should also be noted that the derivative terms are utilised to illustrate the changes on parameters resulting from distributed generation and not that R_t, C_{Ct} and C_{Ot} are known mathematical functions.

If we expand the expressions for revenue, capital expenditure and operational expenditure and use Δ to represent the differential terms, then Equation 5-11 becomes:

$$\mathrm{F}_{\mathrm{DGt}} = \begin{bmatrix} \Delta\mathrm{R}_{\mathrm{RUSt}} + \Delta R_{CONt} + \Delta R_{RWt} + \Delta R_{EXUSt} \\ -\Delta C_{C.GRRt} - \Delta C_{C.LRRt} - \Delta C_{C.EHSt} - \Delta C_{C.NCt} - \Delta C_{C.PIt} - \Delta C_{C.PQIt} - \Delta C_{C.ARt} \\ -\Delta C_{O.PERt} - \Delta C_{O.REPt} - \Delta C_{O.MNTt} - \Delta C_{O.ITt} \end{bmatrix}$$

Equation 5-12

Where the symbols represent the following parameters for year *t* (Table 5-5):

Symbol	Description
F_{DGt}	Financial performance impact of distributed generation
ΔR_{RUSt}	Change in regulated use of system revenues
ΔR_{CONt}	Change in connection charges revenues
ΔR_{RWt}	Change in rechargeable works revenues
ΔR_{EXUSt}	Change in excluded revenues
$\Delta C_{C.GRRt}$	Change in generation related reinforcement capital expenditure
$\Delta C_{C.LRRt}$	Change in load related reinforcement capital expenditure
$\Delta C_{C.EHSt}$	Change in environmental, health and safety capital expenditure
$\Delta C_{C.NCt}$	Change in new connections capital expenditure
$\Delta C_{C.PIt}$	Change in performance improvement capital expenditure
$\Delta C_{C.PQIt}$	Change in power quality improvement capital expenditure
$\Delta C_{C.ARt}$	Change in asset replacement capital expenditure
$\Delta C_{O.PERt}$	Change in personnel operational expenditure
$\Delta C_{O.REPt}$	Change in repairs operational expenditure
$\Delta C_{O.MNTt}$	Change in maintenance operational expenditure
$\Delta C_{O.ITt}$	Change in information technology operational expenditure

Table 5-5: Symbols for financial performance impact of distributed generation expression.

We can also form an expression for the value of function F_{DG} over a number of years in a planning horizon by summing the net present value of F_{DGt} (for all *t*) in the base year.

$$F_{DG.TOTAL\ 0} = \sum_{t=0}^{H} NPV.F_{DGt}$$

Equation 5-13

Where,

$F_{DG.TOTAL0}$	is the sum of net present value of the financial performance impact of distributed generation in a number of future years,
$NPV.F_{DGt}$	is the net present value of the financial performance impact in year *t*,
H	is the planning *horizon* year.

5.5.3.9 Utilising the financial performance impact expressions

Expressions have been developed to represent the revenue and expenditure budgets for a distribution utility (Equation 5-3, Equation 5-5 and Equation 5-7).

The expressions for the impact of distributed generation on the utility budgets have been developed in Equation 5-11 and Equation 5-12. Some of the items in Equation 5-12 either cancel each other out or can be neglected due to their marginal impact on the function, F_{DGt}, as a whole. For example, the parameter ΔR_{CONt} could cancel out the parameter $\Delta C_{C.NCt}$ since the revenue collected to cover distributed generation connections may be exactly equal to the capital expenditure on new connections depending on the utility connection charging policy. These terms and the values they represent, are all matters of utility strategy and therefore must remain in the expression to enable full characterisation of the impact of distributed generation and utility policy. In any case there may be a difference in the timing of the collection of connection revenues from the actual expenditure which may produce interesting conclusions relating to the connection revenue process for the distribution utility.

A means of evaluating the present value of the financial impact of distributed generation over a number of years is expressed in Equation 5-13.

The function of the change in all budget items due to distributed generation (Equation 5-12) is effectively a *linear utility function* or *value function*. The expressions in Equation 5-12 and Equation 5-13 will be shown to be worthwhile in evaluating the whole impact of distributed generation on the utility business if the change in each of the budget items can be assessed. The case studies presented in Chapter 7 quantify a small number of the budget items within the distributed generation value function. Some means must be found for assessing the impact of distributed generation on all the budget items if a comprehensive evaluation of distributed generation is desired. The case studies do not go as far as to quantify all the effects of distributed generation on distribution utility finances.

Scenarios for distributed generation and estimates of the revenue and expenditure impact of the distributed generation scenarios can be evaluated using the linear function expressed in Equation 5-12.

The overall effect of distributed generation in a number of future years can be assessed in present year values using Equation 5-13.

5.5.4 Distribution Strategy Formation and Decision Making

Given a thorough analysis of the key issues in distributed generation, distribution strategies must be developed and commitments made. Decision making in complex and multivariate environments has been discussed in section 4.4.5 relating to power system planning requirements. In the present day, with the level of uncertainty in the ESI and the multitude of possible options open to distribution utilities, it is essential that decision making techniques are used which can handle conflicting information and decision makers' preferences (Mollaghasemi and Pet-Edwards, 1997).

Neill *et al* (Neill et al, 1985) discuss the area of strategic planning for electric utilities and conclude that planning analysis is conducted solely to assist decision makers. The underlying market, network and business system along with strategic options are modelled, evaluated and interpreted to identify the best strategies, their implementation scheduling, possible fall back positions and the risks associated with each strategy.

The use of multiple criteria decision making (MCDM) methods for distribution utility decision making relating to distributed generation has been investigated (Espie et al, 1999). A case study has been developed (in this publication) to investigate the generation location preferences of a distribution utility with references to four value criteria: connection cost; electrical losses; distribution use of system revenues, and; security of supply. The ELECTRE I method is used to provide an outranking structure of preferred connection locations for distributed generation based on the four value criteria.

In a further investigation of the use of MCDM methods for distribution strategic planning (Espie et al, 2000), a set of four diverse distribution investment options are considered which provide costs and benefits across seven criteria for three different stakeholders (or customer groups). The problem includes uncertainties relating to the costs and performance of each strategic option. The use of the simple multiattribute rating technique (SMART) enables the incorporation of multiple input data types including text, rating scales and analytical results from other simulation programmes. The result of the decision making process is the ranking of investment options (according to a predefined criteria) and an indication of the risk of the investment not performing as expected due to uncertainties.

A key characteristic of the strategy formation and decision making process is the opportunity to refine strategies based on the results of analysis of the system and the strategies. Modifications are usually best made on a reduced set of strategies which show the greatest potential to perform well although it is not desirable to rule out any possible strategies too early in the strategy development process (Andrews, 1990).

The general structure of the strategic analysis framework for distributed generation (illustrated in Figure 5-5) enables strategies for distributed generation to be modelled as inputs to the relevant analytical modules. The performance of the strategies can be assessed at the analytical module outputs before refinements are made to the strategies to produce better performance. Strategies to be taken forward and developed for implementation can be selected using multiple criteria decision-making techniques outlined in this section and the referenced literature.

Section 7.9 lists and discusses some possible distribution strategies for dealing with distributed generation.

5.6 Review of Chapter 5

This chapter has established the requirements for a strategic analysis framework to assess the impact of distributed generation on distribution networks and utility businesses. A three-model general methodology has been proposed, comprising energy market, power system and utility financial models each with inputs from a small number of data blocks representing the characteristics of distribution networks, government policies, generating units, and so on (see section 5.4.1). The interaction of the issues presented in chapter 3 has been illustrated on influence diagrams to clarify the key interactions of issues and their collective influence on four key issues.

Several methods for assessing the role of distributed generation in the energy market have been discussed: energy trading option, optimisation, penetration forecasting, scenarios, and, penetration rate modelling. Several groups of power system analysis techniques of relevance to distributed generation are also outlined. Distribution utility finances are represented by a set of budget equations from which a distributed generation value function has been derived. Combinations of these methods in each of the three main analysis modules enable a flexible approach to the analysis of distributed generation to be achieved. Focus can be concentrated on the issues of most importance to the distribution strategic planner or, alternatively, on those areas of analysis where resources are available to conduct analytical activities.

5.7 Chapter 5 References

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Chapter 6

DISTRIBUTED GENERATION STRATEGIC ANALYSIS FRAMEWORK IMPLEMENTATION

6.1 Summary of Chapter 6

This chapter describes, in some detail, an implementation of the distributed generation strategic analysis framework. Each of the energy market, power system and utility financial analysis modules, along with necessary interfaces, are constructed with proprietary software packages. The incorporation of characteristics of best practice in modern power system planning, which were established in chapter 4, are referred to throughout the description of the implementation of the distributed generation strategic analysis framework.

6.2 Analysis Module Developments to Prove Strategic Analysis Framework Concept

6.2.1 Options for an Implementation of the Strategic Analysis Framework for Distributed Generation

A number of options for analysing the impact of distributed generation on distribution networks and businesses are outlined in Chapter 5. Within the three major analytical areas (energy market, power system and utility finance), a number of analysis options were described. The selection of analytical techniques and the construction of an analytical framework are the focus of this chapter.

The selection of analytical tools and techniques from the set of options can be illustrated as shown in Figure 6-1. A technique or set of techniques must be chosen to perform an energy market analysis to address the issue of how much distributed generation penetration may appear in utility distribution networks. Likewise, techniques must be selected to address the issue of quantifying the impact of the distributed generation on the distribution networks and distribution utility finances. It was noted in chapter 4 (section 4.4.3) that, often, the resources available for planning are restricted and that compromises must be made with regard to the scope of the planning activity or the depth of analysis conducted. However, the planning process must be flexible enough to cope with this and still produce robust solutions.

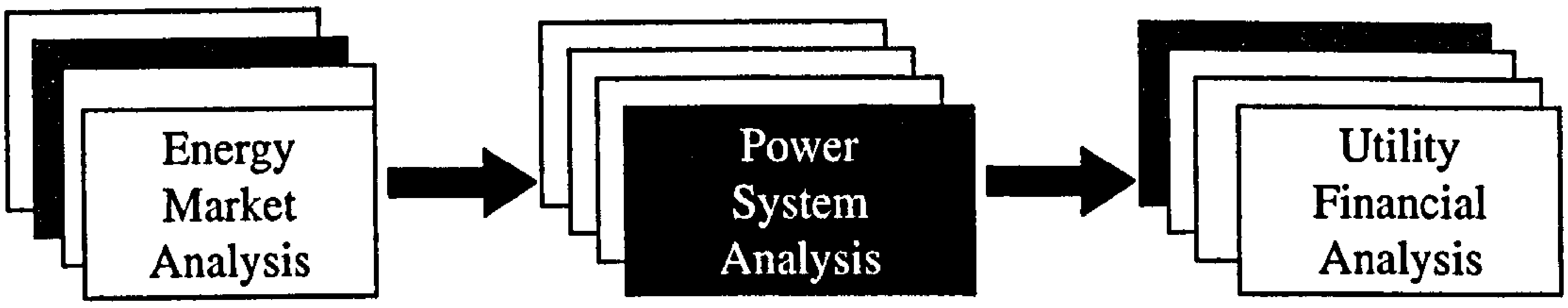

Figure 6-1: Analytical options within distributed generation strategic analysis framework.

The options for energy market analysis to produce scenarios for distributed generation penetration outlined in chapter 5 include:

- Economic models (sections 5.5.1.1and 5.5.1.5)
- Generation mix optimisation (section 5.5.1.2)
- Penetration Forecasting (section 5.5.1.3)
- Scenarios (section 5.5.1.4)

The options for power system analysis of distributed generation scenarios to quantify the impact of distributed generation on utility networks include:

- Power flow analysis (a.c.) (section 5.5.2.1)
- Power flow analysis (d.c.) (section 5.5.2.2)
- Fault analysis (section 5.5.2.3)
- Reliability analysis (section 5.5.2.4)
- Power quality analysis (section 5.5.2.5)
- Dynamic performance analysis (section 5.5.2.6)
- Optimal power flow analysis (section 5.5.2.7)
- Probabilistic power flow analysis (section 5.5.2.8)

Fewer options have been considered for distribution utility financial analysis.

The modelling options for the implementation of the distributed generation strategic analysis framework have been selected on the basis of available software tools and also with regard to preliminary studies of distributed generation. Preliminary studies of distributed generation (Ault, 1998; Edwards, 1998) and industry sentiment (Driver, 2000) point to the importance of power flow (capacity requirements, voltage and losses) and fault analysis (fault level contribution) as the important physical effects of distributed generation.

Any of the four options listed for energy market analysis can be made to produce distributed generation scenarios. Therefore, any, or all, of the energy market modelling options could be used to produce a set of plausible scenarios for analysis in the subsequent power system and utility financial analysis modules.

The power system simulations are limited to investigations of the impact of distributed generation on transformer and circuit capacity, system losses and switchgear ratings as illustrated in Figure 6-2. The results of the power system simulations are processed and analysed using a distributed generation value function to address the question of the impact of the distributed generation on the distribution business.

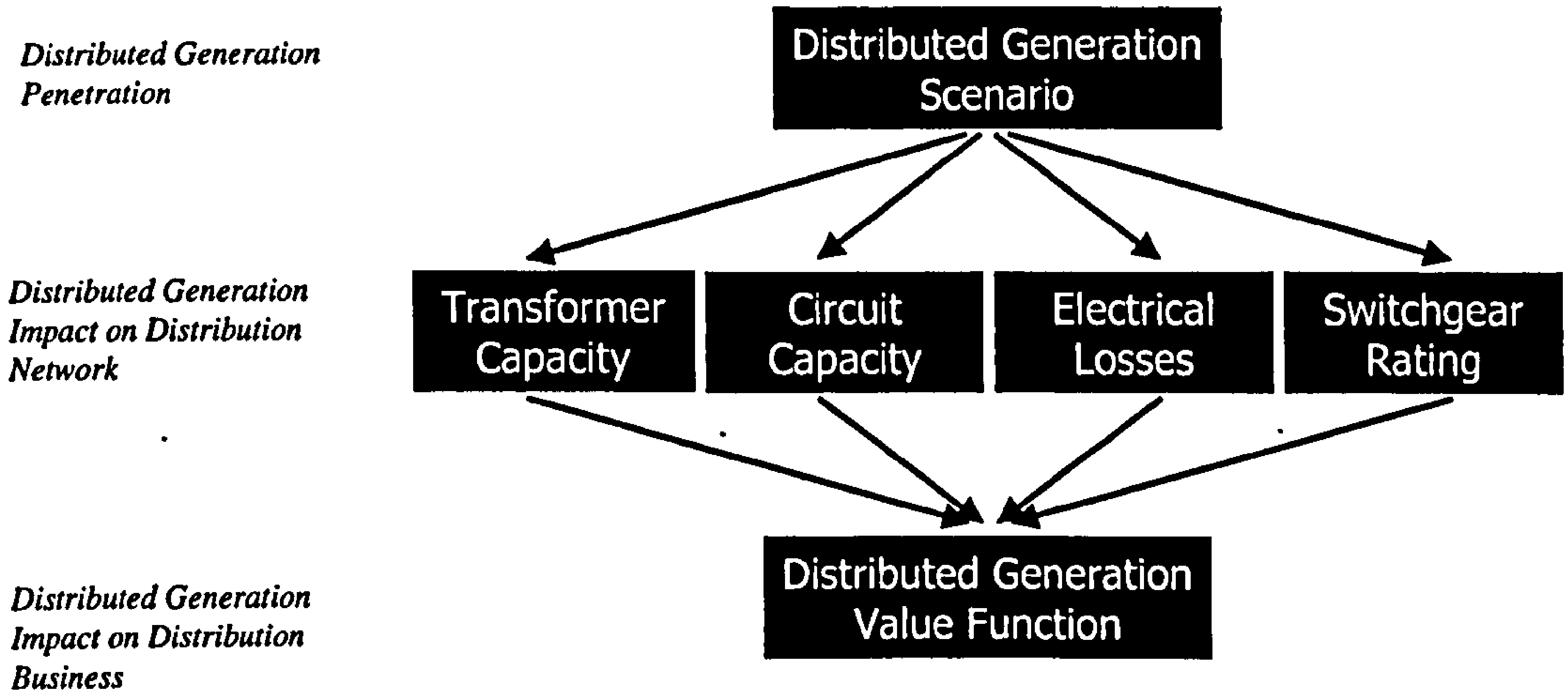

Figure 6-2: Implementation scope for distributed generation strategic analysis framework.

Each of the elements of the strategic analysis framework shown in Figure 6-5 will be described in the following sections.

6.2.2 Requirements for proving validity of Strategic Analysis Framework

In implementing the distributed generation strategic analysis framework to prove the general concept of such a framework it is important to set clear objectives which would constitute a successful proof of the concept. Reference to the list of desired characteristics for power system planning methodologies is necessary at this stage (see section 4.6). The implementation should show the incorporation of those features into the planning framework for distributed generation.

In particular, this implementation will focus on the following aspects of planning methodologies:

- deals with multiple criteria
- provides modular analytical framework
- integrates analytical modules
- provides flexibility and robustness in the planning process
- provides insight to the planning problem and solutions
- deals with uncertainties
- provides a decision focused planning framework

These are some of the less common characteristics found in modern planning techniques. Many of the characteristics omitted from the list of features to explicitly build into this distributed generation strategic analysis framework are now routinely found in planning packages. For example, the ability to reuse models, deal with large quantities of data, consider multiple and diverse solutions to problems or enhance planning productivity are now relatively common features of planning methodologies.

Two valuable features not incorporated into the strategic analysis framework are a risk focussed approach and the reuse of planning decision rationale. These characteristics could be incorporated in this implementation but have been omitted to provide a manageable scale for this proof of the general concept. Risk focus (Espie et al, 2000) and rationale (Foote et al, 2000) have been the subject of recent publications by the author of this thesis.

In addition, quantitative analysis of the impact of distributed generation on distribution networks and businesses is a desired output of the implementation.

6.3 Implementation of Analytical Modules

Two software packages have been used in this implementation of a distributed generation strategic analysis framework. Microsoft Excel has been used to implement the energy market models and distribution financial analysis model. Power Technologies' Power System Simulator for Engineers (PSS/E) has been used to implement the power system analysis models.

The macro language within Excel, Visual Basic for Applications or VBA for short (Webb, 1996), has been used extensively to provide automated processes and to enable interfaces with the power system simulation software to be established. The Interfacing Program Language or IPLAN (Glynn, 1995) which accompanies the PSS/E power system analysis software has also been used extensively, again to provide automated functionality and to enable the interface with Excel (and the other analytical modules) to be established.

6.3.1 Analysis Module Interfaces

The principal interfaces of the energy market and utility financial modules with the power system analysis software are illustrated in
Figure 6-3.

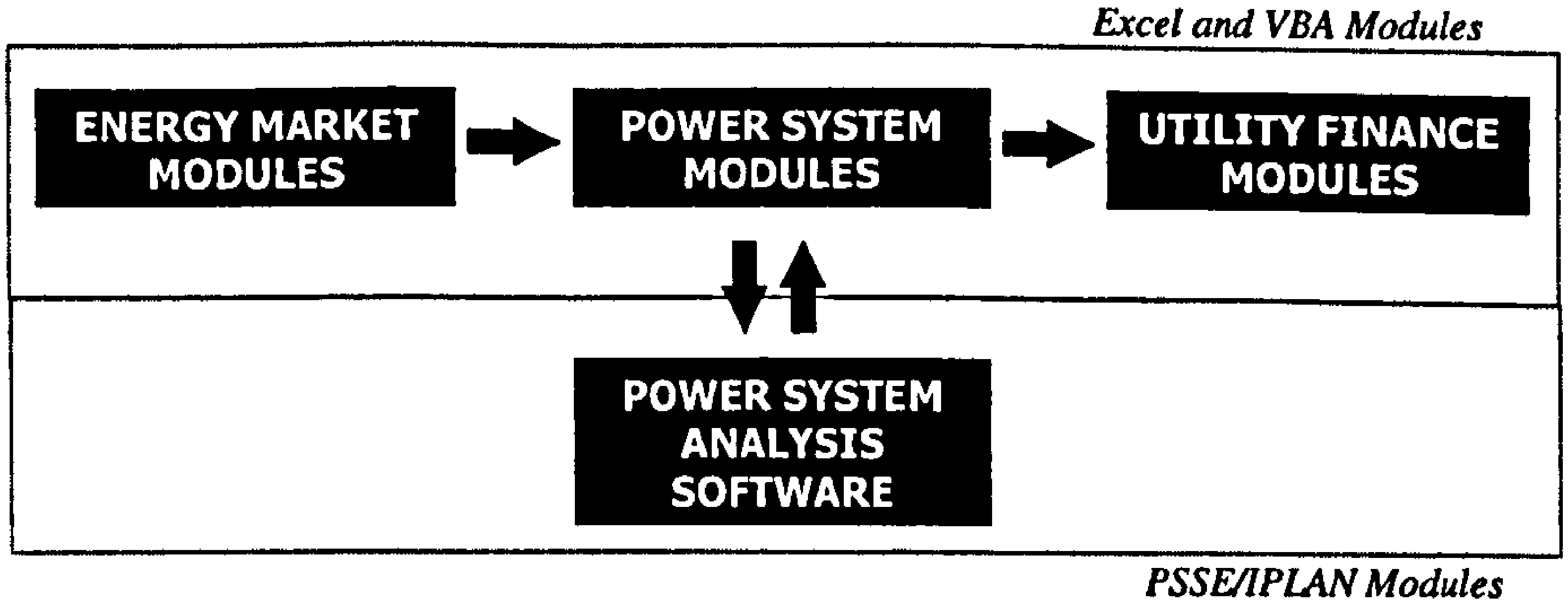

Figure 6-3: Illustration of interfaces between main analytical modules in strategic analysis framework.

Figure 6-3 illustrates the external calls from Excel/VBA to power system analysis modules with returning data and progress messages. Further external links from Excel/VBA could be made as necessary for other power system analysis types such as transients or harmonic analysis. For software applications in any of these additional areas (plus others not mentioned), the interfaces would have be established with Excel/VBA and the data interpreted in the utility financial analysis in an appropriate manner.

The Excel/VBA part of the analytical framework is illustrated in Figure 6-4. The sequences starts from the point where a generation scenario has been created using one of the energy market analysis options described in section 6.3.2 below. The 'addgenlist' procedure adds the distributed generation units within the scenario to the appropriate network model file. User interaction is normally required at this stage to select locations for the generation within the distribution network. The selection of the location for scenario generators could be automated but this step has not been made in this implementation.

Scenario data files are created in Excel spreadsheet format by the 'addgenlist' procedure. These files which contain all the necessary data for one set of power system simulations for one scenario in one year must be converted to a format which can be read automatically by the power system simulation software. The procedure 'psse_file' performs this task and generates a '*.raw' data file for this individual scenario.

The final task before running the power system simulation software is to create a control file and any auxiliary files to enable a clear power system analysis run. The 'controlfile' procedure writes the names of network '*.raw' data files, output files and auxiliary files for reading by the power system analysis IPLAN programme. Auxiliary files (load point files for losses analysis and node list files for faults analysis) are created immediately prior to running the power system analysis software.

The 'looppsse' procedure performs a predefined sequence of power system analysis runs in batch mode. For example, it may be desired to run a sequence of multiple distributed generation scenarios, with each type of power system analysis in each of the study years within the planning period. Selecting these options in an analysis control screen enables fast execution of a complete analysis sequence. The procedure 'start_psse' makes the system call to run the power system analysis software.

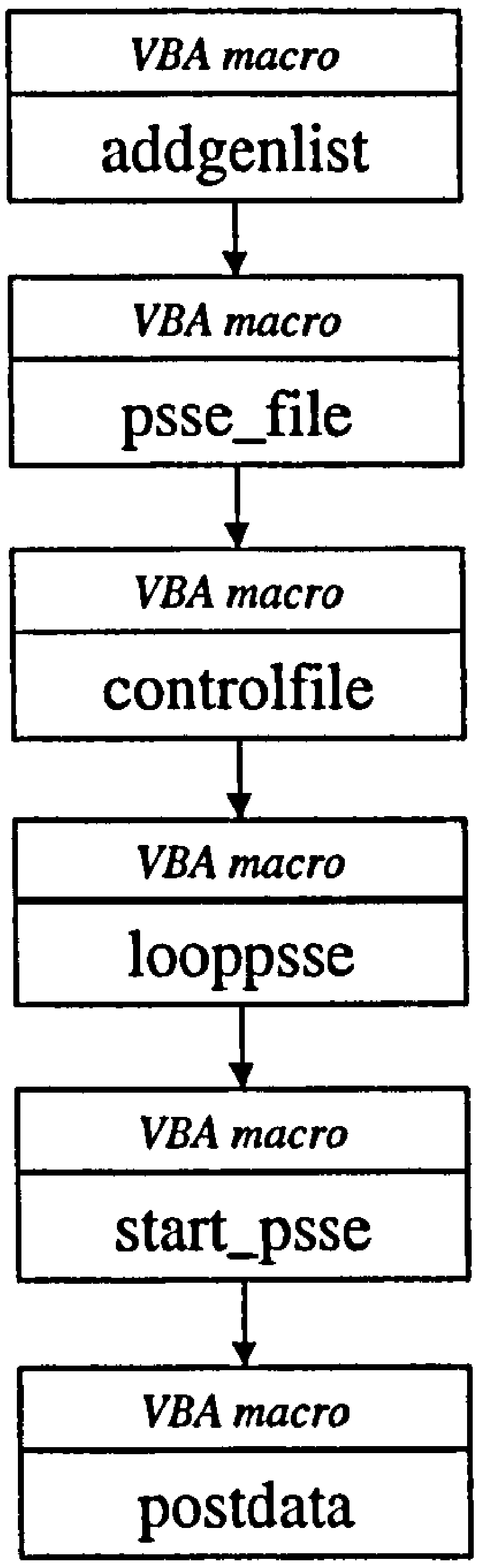

Figure 6-4: Excel/VBA sequences within strategic analysis framework.

The 'postdata' procedure retrieves the output data files from storage after a power system analysis run and creates a set of results workbooks in Excel in a user defined format. The distribution utility financial analysis functionality is performed on this data.

In addition to the programmes and procedures for each of the four power system analysis functions which are illustrated and described below (sections 6.3.3.1, 6.3.3.2, 6.3.3.3 and 6.3.3.4) there are also a number of common features of each of these modules which are essential for module interfacing.

To avoid interference or mistiming of operations between the power system analysis software and VBA a number of messages are passed by the creation of empty data files. For example, it is necessary for the IPLAN programmes to signal the end of operation and the successful creation of output data files only after which will Excel continue to process the data created.

Also, for the purposes of speeding up the simulation process, the attributes of the progress window in PSSE are changed such that the progress monitoring is redirected away from the visible window.

Diagnostics files are also produced for each power system solution so that if any thresholds on power system analysis solution tolerance levels are exceeded then a signal is provided while details of the error are stored in an appropriately named file for further investigation. This feature is of critical importance for automatic processes where grave analytical errors could be overlooked while batch operations roll on.

6.3.2 Energy Market Analysis

Energy market analysis is conducted using the penetration rate model described in section 5.5.1.5. Financial and economic analysis of a range of generation technologies has been implemented in spreadsheet format using Excel. Table 6-1 illustrates the general procedure for calculating the internal rate of return for each technology in a given base year for a specific set of assumptions regarding costs and operating parameters.

plant type	capacity (MWe)	capital cost (£/kW)	O&M fixed (£/kW)	O&M variable (£/MWh)	load factor	lifetime (years)	fuel cost (£/MWh)	pool income (£/MWh)	IRR (%)
FuelCell	0.25	1500	30	0	0.85	15	11	28.35	50%
WindOnshore	1.5	1000	15	0	0.35	20	0	42.50	23%
MunicipalWaste	25	2750	135	0	0.85	20	-26.9	28.35	19%
EnergyCrop	17.5	1150	70	0	0.85	20	26.9	28.35	-11%
GasTurbineLarge	50	350	7	1.8	0.40	25	11	40.29	43%
CHPGasEngine	1.8	540	0	5	0.90	30	11.1	27.43	71%
CHPGasTurbineSmall	6.1	674	0	3	0.90	30	8.7	27.43	43%

Table 6-1: Summary of generation plant costs and resulting internal rate of return.

The input parameters (capital costs, O&M costs, load factor, lifetime, fuel costs and electricity pool income) are varied across different scenarios which produces different results for internal rate of return (IRR). The parameters also follow predefined trajectories through the planning period within each scenario such that the relative attractiveness of the generation technology to investors changes as time progresses. For example, it is assumed in some scenarios that fuel cells achieve quite a steep decline in capital costs as a result of the technology development investments being made at present.

Each scenario is established on the basis of one set of assumptions which results in a given IRR and subsequent penetration rate for each technology. The penetration rate is used to calculate a fraction of the technically feasible potential for the technology from which a national installation capacity for each technology is calculated for each study year.

6.3.3 Power System Analysis

The following four subsections (6.3.3.1, 6.3.3.2, 6.3.3.3 and 6.3.3.4) describe the process of conducting power system studies of distributed generation scenarios within the distributed generation strategic analysis framework.

6.3.3.1 Circuit flows power system analysis module

The objective of circuit flows analysis is to gauge the capacity requirements in distribution system lines and cables throughout the planning period and assess how they are influenced by the presence of distributed generation as represented by the scenarios generated in the energy market analysis module. The circuit flows module also provides a n indication of the changes in circuit utilisation under each scenario.

Figure 6-5 illustrates the process of conducting a power flow study focussing on capacity considerations of underground cables and overhead lines. When a call is made to run a circuitflows analysis the power system analysis software is started and the 'startcircuitflows.idv' batch file is run automatically. The batch file 'startcircuitflows.idv' executes the IPLAN programme 'circuitflows.irf'.

'Circuitflows.irf' opens a data file ('circuitflowsinput.txt') which contains instructions regarding the name and location of the network model file (networkrawdatafile) which, by this time, contains one distributed generation scenario and the name and location of the output file from the programme (circuitflowsoutputfile).

The main procedures within the program are called in sequence:

1. READRAW opens and reads the network data file (networkrawdatafile) into the power system analysis program memory.
2. SOLVEIT uses the batch file 'solve.idv' to perform a predefined power flow solution.
3. GETCALCDATA reads required network solution parameters to array variables and performs required calculations and transforms.
4. WRITEOUTPUT opens the results file (circuitflowsoutputfile) and writes data required for financial analysis of the implications of the network power flows in cables and lines.

Following completion of the circuitflows program, the VBA program running in Excel is notified and control is passed back to the VBA program. The power system analysis software is shut down at this stage.

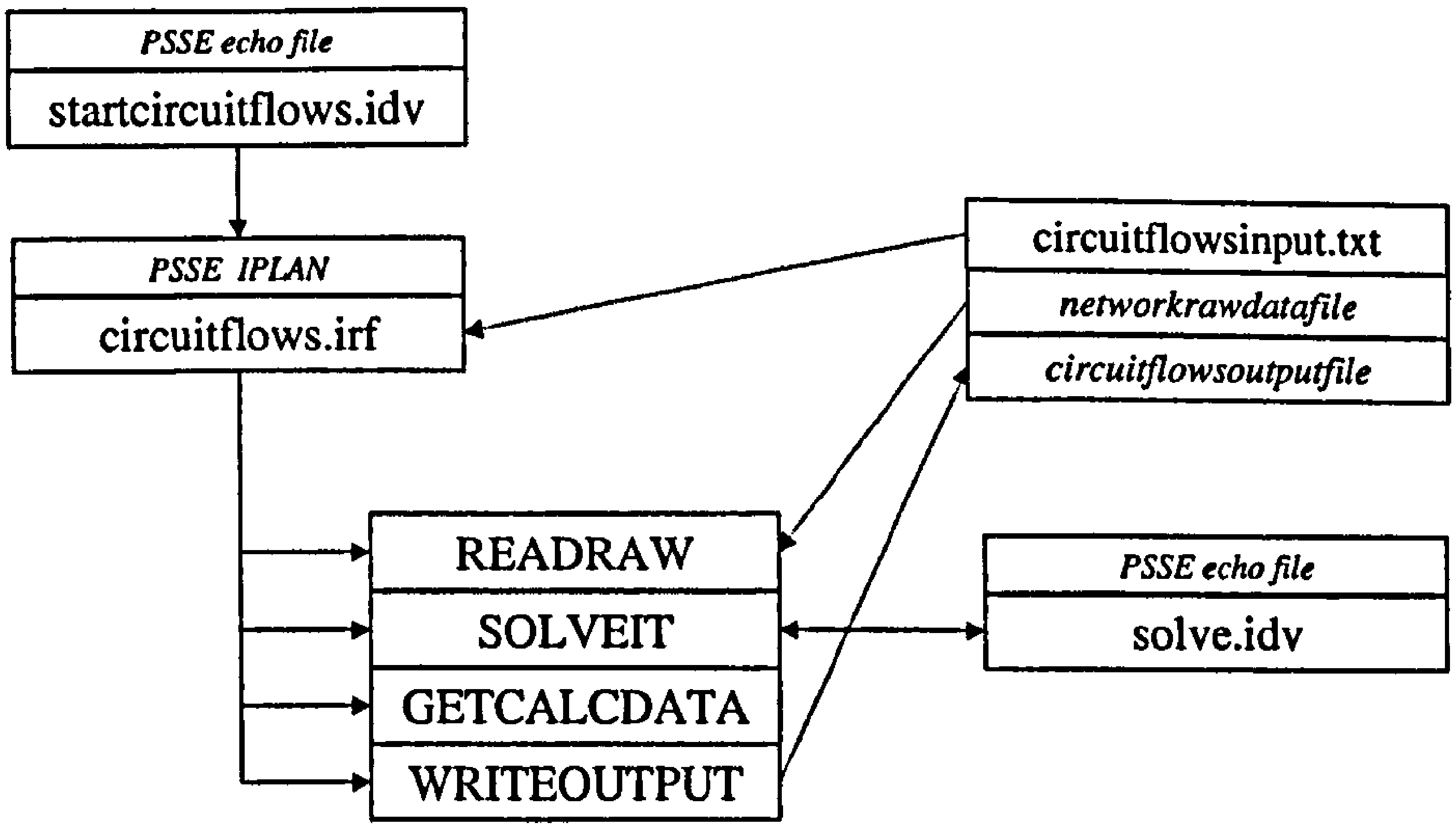

Figure 6-5: Circuit power flow analysis software module overview.

The output from this program is a list of peak power flows in each circuit element which will be assessed in the distribution financial analysis module to gauge the financial implications of the changes in peak power flows due to distributed generation.

The IPLAN programme 'circuitflows.irf' with its procedures are listed in Appendix B. The batch file contents for 'startcircuitflows.idv' and 'solve.idv' are also found in Appendix B.

6.3.3.2 Transformer flows power system analysis module

The objective of the transformer flows analysis is to gauge the capacity requirements in distribution system transformers throughout the planning period and assess how they are influenced by the presence of distributed generation as represented by the scenarios generated in the energy market analysis module.

Figure 6-6 illustrates the transformer power flow analysis process. The batch files and IPLAN programmes run in exactly the same manner as for circuit flows analysis as described in section 6.3.3.1.

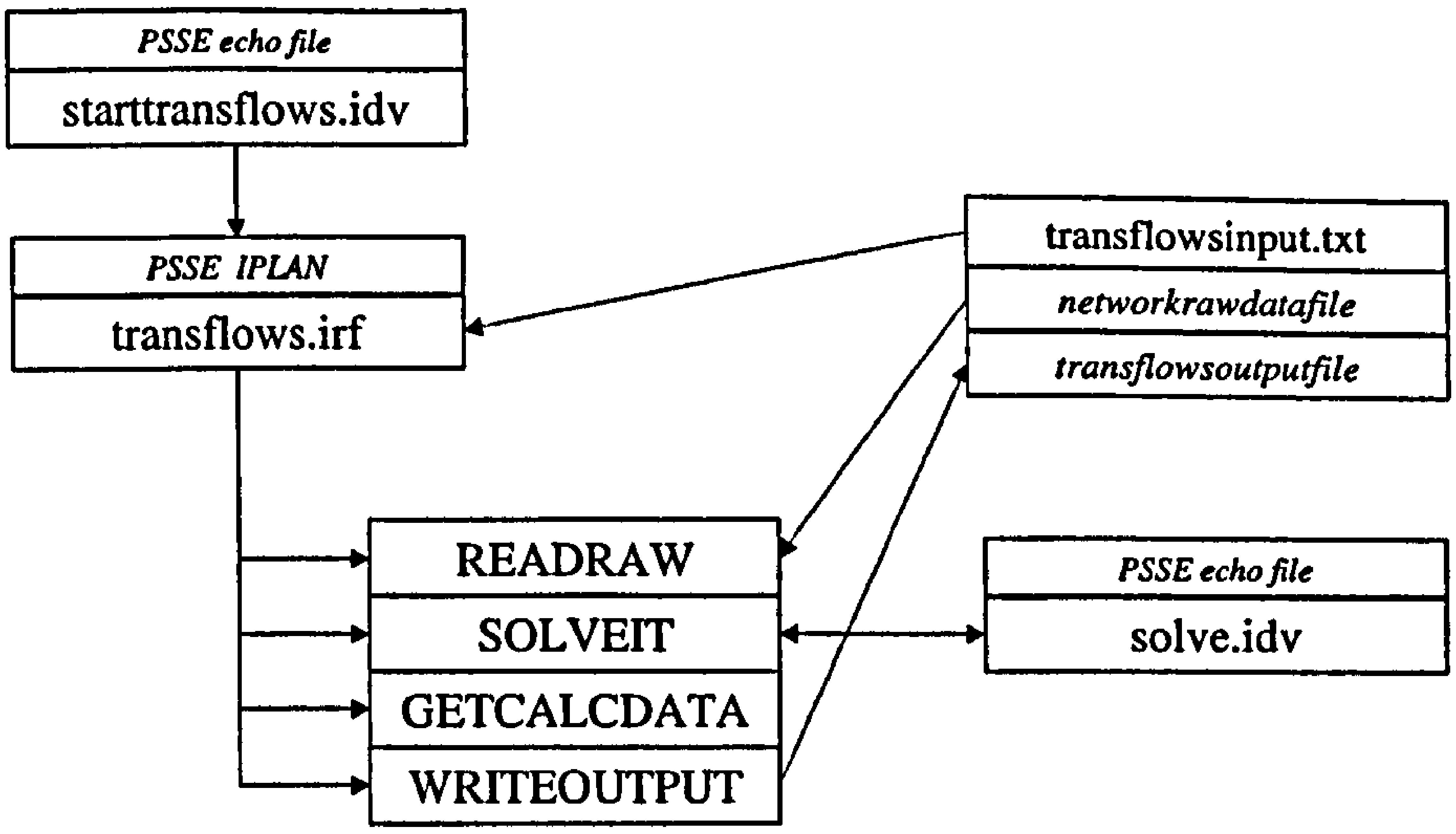

Figure 6-6: Transformers power flow analysis software module overview.

The output from this program is a list of peak power flows in each transformer which will be assessed in the distribution financial analysis module to gauge the financial implications of the changes in peak power flows due to distributed generation.

The IPLAN programme 'transflows.irf' with its procedures are listed in Appendix C. The batch file contents for 'starttransflows.idv' are also found in Appendix C.

The 'solve.idv' batch file called from the 'transflows' programme is the same file as used in the 'circuitflows' programme and can be found in Appendix B.

6.3.3.3 Fault analysis power system analysis module

The objective of the fault analysis module is to assess the effect on symmetrical fault levels in the distribution system from the presence and operation of distributed generation as represented by the scenarios generated in the energy market analysis module.

Figure 6-7 illustrates the fault analysis process. The batch files and IPLAN programme operate in a similar manner to those for the circuit and transformer programmes.

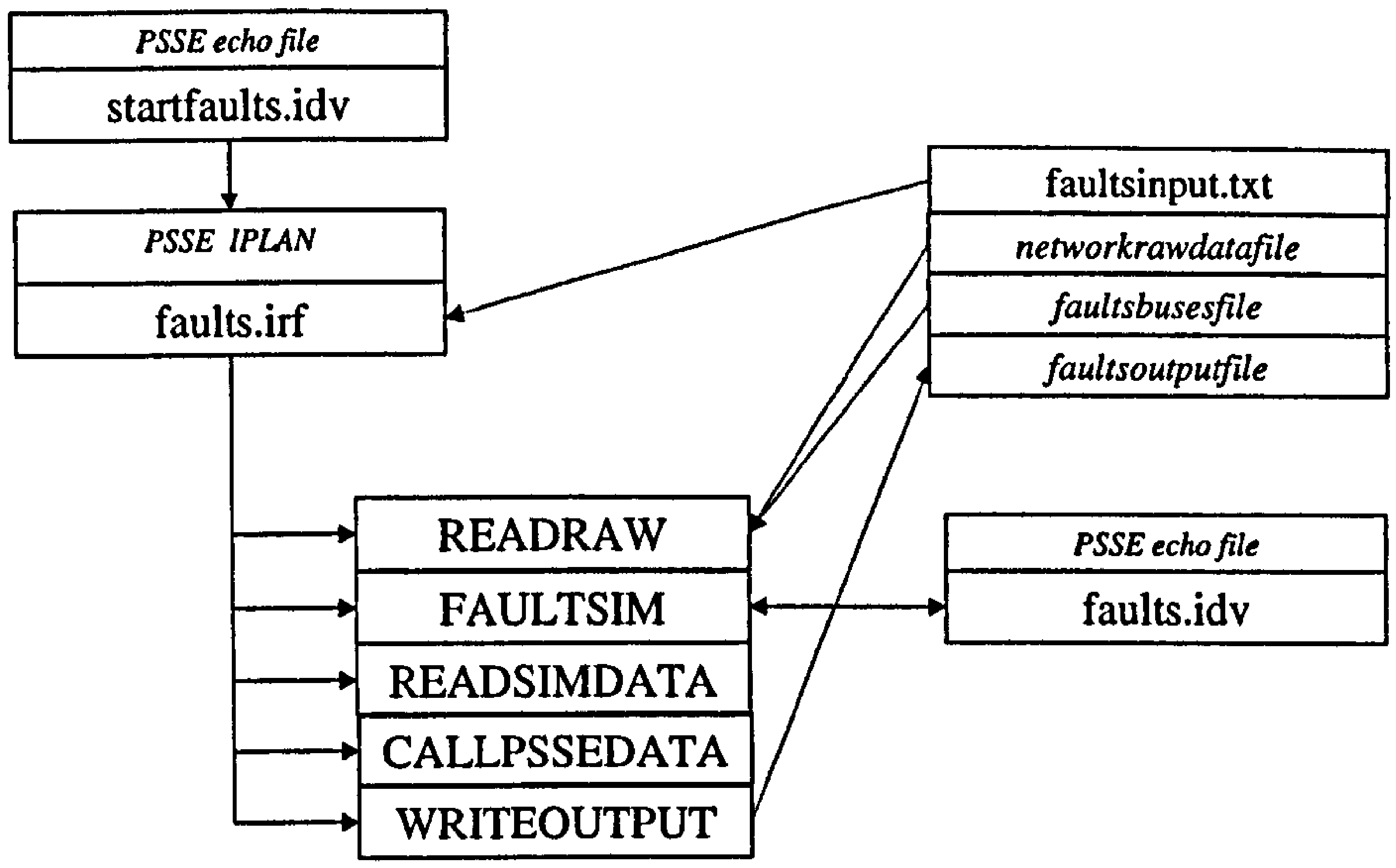

Figure 6-7: Fault analysis software module overview.

The faults programme is initiated by a call to start PSS/E and run the batch file 'startfaults.idv'. This batch file executes the 'faults.irf' programme which retrieves data relating to the name and location of the network model file (networkrawdatafile), the file containing a list of network nodes of interest for the fault analysis (faultsbusesfile) and the ultimate output file for transfer of data to the financial analysis module (faultsoutputfile). The information in these files is generated by VBA macros prior to calling for a power system simulation and contains specific information relating to the scenario and networks to be analysed.

The faults programme continues on to read the network model data from the specified file (READRAW) and conduct a balanced three phase fault analysis on the network (FAULTSIM). The FAULTSIM procedure runs a batch file ('faults.idv') which steps through the required PSS/E commands to conduct the simulation. READSIMDATA retrieves a list of network nodes of particular interest from 'faultbusesfile' and CALLPSSEDATA retrieves the appropriate data on the fault characteristics of these nodes and stores the data in an array. WRITEOUTPUT prepares a formatted output listing in 'faultsoutputfile' for subsequent access by the distribution utility financial analysis module.

The output from this module is a list of the balanced three phase MVA fault level for each pre-specified node of interest in the network.

The IPLAN programme 'faults.irf' with its procedures are listed in Appendix D. The batch file contents for 'startfaults.idv' and 'faults.idv' are also found in Appendix D.

6.3.3.4 Losses analysis power system analysis module

The objective of the losses programme is to produce an accurate assessment of the annual losses in the distribution network for each distributed generation scenario in each year of interest in the planning period.

Figure 6-8 illustrates the losses analysis process. The batch files and IPLAN programme operate in a similar manner to those for the circuit, transformer and faults programmes.

The losses programme is initiated by a system call to start PSS/E and run the batch file 'startlosses.idv' which in turn executes the 'losses.irf' IPLAN programme. The main losses program reads the names and location of relevant data input and output files from the 'lossesinput.txt' file. The 'loadpointfile' contains a list of system loading levels and the annual total number of hours the network operates at that level of load. This data is derived from load duration curves for each network model and forms the basis of the annual losses calculation. The GETDATA procedure within the losses programme retrieves the load duration data.

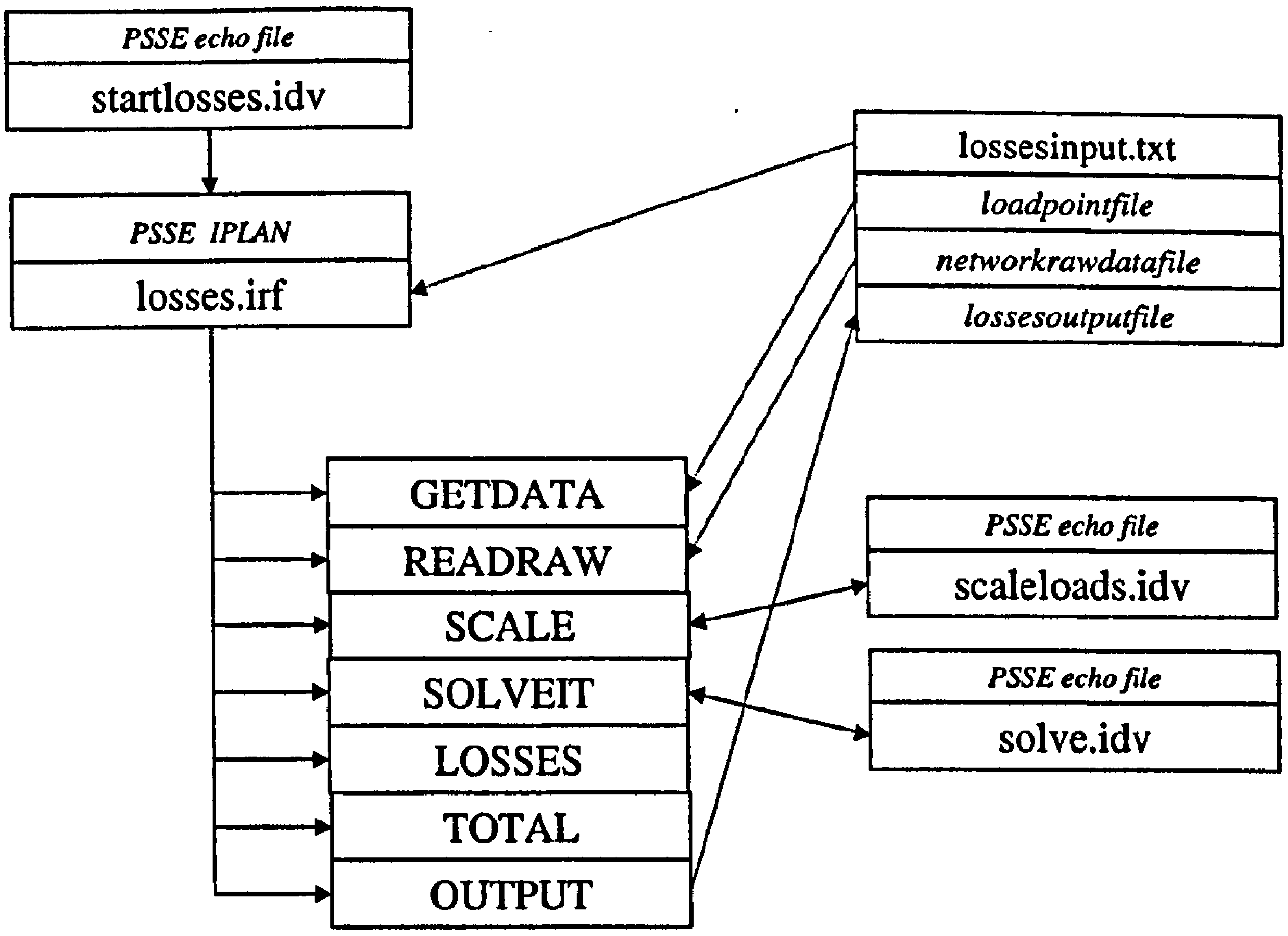

Figure 6-8: Annual losses analysis software module overview.

The next four procedures within the losses programme (READRAW, SCALE, SOLVEIT and LOSSES) are repeated for each load level through the load duration curve.

1. READRAW reads the network model into the PSS/E memory.
2. SCALE scales the system loads to the next level in the load duration curve.
3. SOLVEIT makes a load flow solution for the given load level.
4. LOSSES call for PSS/E data and performs calculations relating to lost energy in the system.

The SCALE procedure works sequentially through each loading level provided in the load point file. If a short simulation time is required then a lower number of load levels can be simulated. If much greater accuracy is required then a large number of load levels can be used and individual load levels can be applied at individual load points within the system rather than a common scaling factor across the whole system. The SCALE procedure calls the batch file 'scaleloads.idv' to perform the scaling operation.

The SOLVEIT procedure calls the common solution batch file 'solve.idv' to perform a sequence of steps to provide a high accuracy load flow solution.

The LOSSES procedure calls internal PSS/E system data on power losses for the given load level. The annual lost energy value is calculated by multiplication of the lost power at the given load level by the number of hours in the year that the system is at the given load level. Calculations are performed for active and reactive power since distributed generation has an effect on both.

The TOTAL procedure makes a summation for the annual lost energy value from all the energy loss levels at each system load level. Thus an annual value for active and reactive energy losses is produced for each distributed generation scenario. The OUTPUT procedure writes formatted simulation data to an output file for analysis by the distribution utility financial analysis module.

The output from this module is a list of the power loss levels for each system load level and an annual total lost active and reactive energy.

The IPLAN programme 'losses.irf' with its procedures are listed in Appendix E. The batch file contents for 'startlosses.idv' and 'scaleloads.idv' are also found in Appendix E.

The 'solve.idv' batch file called for the 'losses' programme is the same file as used in the 'circuitflows' programme and can be also be found in Appendix B.

6.3.4 Distribution Utility Financial Analysis

A method of analysing the impact of distributed generation on distribution utility budgets was outlined in Chapter 5 (section 5.5.3). The distributed generation value function is based on the assumption that any characteristic identified in energy market analysis or power system analysis can be represented by some monetary value through financial analysis. For example, a change in the annual losses can be represented by the value of those losses to the distribution utility under the efficiency incentives embedded within the regulatory price control formula.

6.3.4.1 Illustrated use of Distributed Generation Value Function

The use of the Distributed Generation Value Function can be illustrated through a hypothetical case for the growth of distributed generation and a utility strategy for distributed generation.

Let us assume that distributed generation capacity and output grows substantially over a ten-year period from 1998. Some impacts of this growth are outside the control of the distribution company, such as the total annual distributed units which are a function of the actions of all consumers and generators connected to the network. Under the control of the distribution company are strategies regarding location specific incentives to generators aimed at harnessing the value of distributed generation to reduce reinforcement costs and losses. In addition to location incentives, the distribution company decides to install new control equipment later in the ten-year period to deal with the additional complexity in system management.

The specific details of these strategies with reference to revenue and expenditure are provided in Table 6-2.

Item	Value Function Item	Detail
Loss of revenue from reduced distributed units	ΔR_{RUSt}	Reduces by additional £0.2 million per annum.
Gained revenue from reduced system losses	ΔR_{RUSt}	Increases by £0.4 million per annum
Deferred capital expenditure on reinforcement	$\Delta C_{C.LRRt}$	Reduced by £1million per annum
Cost of new control system	$\Delta C_{O.mt}$	£2 million each year in years 6 to 8.
Cost of additional staff time on planning and administration	$\Delta C_{O.PERt}$	Increased by £0.5 million per year

Table 6-2: Details of hypothetical budget impact of distributed generation and utility strategy.

The annual financial outcome of the hypothetical distributed generation scenario and a hypothetical distribution utility strategy for distributed generation is illustrated in Table 6-3.

	Item	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
ΔRRUSt	Reduced Distributed Units	-	(200)	(400)	(600)	(800)	(1,000)	(1,200)	(1,400)	(1,600)	(1,800)
ΔRRUSt	Reduced Losses	-	400	800	1,200	1,600	2,000	2,400	2,800	3,200	3,600
ΔRCONt	-	-	-	-	-	-	-	-	-	-	-
ΔRRWt	-	-	-	-	-	-	-	-	-	-	-
ΔREXUSt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.GRRt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.LRRt	Deferred reinforcement	-	(1,000)	(1,000)	(1,000)	(1,000)	(1,000)	(1,000)	(1,000)	(1,000)	(1,000)
ΔCC.EHSt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.NCt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.PIt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.PQIt	-	-	-	-	-	-	-	-	-	-	-
ΔCC.ARt	-	-	-	-	-	-	-	-	-	-	-
ΔCO.PERt	Planning and administration	-	500	500	500	500	500	500	500	500	500
ΔCO.REPt	-	-	-	-	-	-	-	-	-	-	-
ΔCO.MNTt	-	-	-	-	-	-	-	-	-	-	-
ΔCO.ITt	Control System	-	-	-	-	-	-	2,000	2,000	2,000	-
FDGt		-	700	900	1,100	1,300	1,500	(300)	(100)	100	2,300

Table 6-3: Financial outcome (in £ '000s) of hypothetical distributed generation impact and utility strategy.

It can be seen that the impact of distributed generation is favourable for the years 1999 through to 2003. The costs of the new control system produce negative value in years 2004 and 2005. The increasing benefits from reduced electrical losses force a positive value in years 2006 and 2007. It should be noted that distributed generation value (F_{DGt}) is derived by subtracting the ΔC items from the ΔR items.

The present value of the financial implications set out in the hypothetical case can now be calculated in accordance with Equation 5-13. Using a discount rate of 10%, the value of distributed generation for the ten year period under study, in the base year, is £4,827,000.

In this hypothetical case, a large positive value results from distributed generation. It should be noted that the regulatory and pricing structures currently in place in the UK may make it difficult for distribution companies to extract this positive value arising from distributed generation. Any distribution utility strategy for distributed generation would necessarily start with discussions on the issue with the electricity regulator to reach consensus on what action by the distribution company was deemed appropriate.

6.3.4.2 Unit costs for Distributed Generation Value Function

To facilitate financial analysis of the distribution system issues selected in section 6.2.1, a set of unit costs are required which translate physical effects into financial terms. The unit costs used in the case study are detailed in Table 6-4. Unit cost and benefit values are based on several industry sources including:

- a distribution utility connection charging statement (Scottish Power plc, 1997) for capital equipment costs
- an electricity distribution licence (Office of Electricity Regulation, 1999) for MWh energy loss value
- an industrial report on electricity trading arrangements (Knight, 1999).

Item	Unit	Unit Cost or Benefit
132kV OH	£/km	150,000
132kV UG	£/km	1,000,000
33kV OH	£/km	50,000
33kV UG	£/km	150,000
132kV transformer	£	1,000,000
33kV transformer	£	400,000
MWh loss	£/MWh	30.656
MVArh loss	£/MVArh	0.25
132kV substation	£	10,000
33kV substation	£	10,000
11kV substation	£	10,000
132kV switchgear	£	500,000
33kV switchgear	£	100,000
11kV switchgear	£	25,000

Table 6-4: Unit values for distributed generation costs and benefits.

The unit costs of capital expenditure on circuits, transformers and switchgear have also been based on the unit costs used by the UK distribution companies in their submissions to regulator for the purposes of the distribution price control review.

These unit costs are used to assess the value of any change in system performance identified in the scenario analyses. For example, if a particular distributed generation scenario results in additional capital expenditure in the distribution network for a transformer upgrade then the appropriate unit cost will be multiplied by an annual cost of capital factor to yield the annual cost resulting from the generation scenario. Equation 6-1 illustrates the general formulation for assessing the annual cost or benefit to the capital expenditure budget.

$$\text{Annual Cost or Benefit} = (\text{Unit Cost or Benefit}) \times (\text{Cost of Capital})$$

Equation 6-1

A 10% cost of capital has been assumed in the results presented in this thesis.

6.3.4.3 Distribution Utility Financial Analysis Process

The distribution financial analysis process is a relatively simple implementation of the distribution utility value function as discussed above. The results from the power system analysis modules are imported into Excel and converted to spreadsheet form. The results are processed to yield figures for each term of the distributed generation value function. The processing of results varies between result type.

The power flow in each circuit and transformer at system peak demand is compared with the secure capacity for each component to determine the need for reinforcement. In the 'circuitflows' and 'transflows' modules the peak load flow is compared to the security constrained rating of the components. For example, in a primary substation (33/11kV) with twin identical feeds and transformers and minimal transfer capacity, as defined in the security of supply standard P2/5 (The Electricity Council System Design and Development Committee, 1978), the secure capacity of each transformer and circuit will be approximately 50% of the thermal rating to ensure that the group demand can be met following an outage of one transformer or circuit.

Switchgear ratings in the case study network are compared with the fault level at each node of interest in the 'faults' module. Where the fault level rating of any switchgear has been exceeded, the cost of required switchgear is added into the appropriate column of the distributed generation value function for that scenario.

The output from the 'losses' module for each scenario and year is compared with the system annual losses in the base year (1998) which acts as a proxy to the regulatory allowed losses in the distribution price control formula (section 2.2.1).

Each of the comparisons of an outcome for a particular scenario and year with a base level for the parameter can be summarised in a matrix (similar to Table 6-3) to which the unit costs are applied to provide corresponding entries to the distributed generation value function. The distributed generation value function entries are summed to produce a value for distributed generation under the given scenario in that year. If distribution policy options are being assessed, then the policies or strategies that yield the greatest value are those which warrant further analysis and refinement and ultimately a plan for implementation.

6.4 Review of Chapter 6

The implementation of the distributed generation strategic analysis framework has been described in this chapter. This implementation is based on a subset of the analytical options outlined in chapter 5. The implementation of the distributed generation strategic analysis framework has incorporated many of the desired characteristics for modern planning methodologies as developed in chapter 4. The integration of analytical modules has been highlighted throughout the description to illustrate how the general methodology for assessing the impact of distributed generation across many issues can be realised. An integrated modular analytical approach is appropriate for distributed generation, as argued in earlier chapters, and has been realised in a limited way in the implementation described in this chapter.

6.5 Chapter 6 References

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CHAPTER 7

ANALYSIS OF DISTRIBUTED GENERATION IMPACT ON DISTRIBUTION SYSTEMS

7.1 Summary of Chapter 7

This chapter introduces the case studies used for the dual purpose of testing the distributed generation (DG) strategic analysis framework and also providing quantitative information relating to the impact of distributed generation on distribution networks and distribution businesses in the UK.

Several distributed generation scenarios are proposed, based on two of the scenario production techniques discussed in chapter 5 (section 5.5.1). The modelling and simulation methods applied to the scenarios are discussed. The results from each stage of the power system simulation and financial analysis process are presented and discussed at length. The significance of all results are discussed with respect to a reference distribution utility onto which the results are projected.

In summary, the analyses of the distributed generation scenarios in two case study networks have shown that there is great potential for benefit to the distribution utility. It is acknowledged that the issues analysed are only a subset of the full quota of distributed generation costs and benefits. However, the analysis of distributed generation in this manner shows great promise for more extensive analyses using the DG strategic analysis framework.

Comments on the use of the analytical methodology proposed in this thesis are provided. The framework incorporates (or provides the flexibility to incorporate) the best features of modern power system planning techniques. The general analysis methodology provides the framework to deal with the great uncertainties that distribution companies face in relation to distributed generation through a scenario based approach. The modular nature of the analytical framework provides the scope to extend the framework to incorporate further issues or make more cursory evaluations in an environment of limited planning resources such as skilled personnel time, analytical tools or data. Each of these limitations has been faced in the implementation of the strategic analysis framework described in the preceding chapter. However, useful indications of the effect of distributed generation have been produced in a short period of time and with a reasonable amount of effort given the input data deficiencies.

7.2 Distributed Generation Scenarios

This section outlines the scenario construction process for the case studies and describes five scenarios which have been analysed using the scenario based strategic analysis framework described in the preceding chapters.

The range of generation technologies included in the scenario construction process has been deliberately restricted for these case studies since the primary objective of the case study simulations is to demonstrate the strategic analysis framework. However, the information relating to distributed generation effects on distribution networks and businesses will be highly valuable. Details of the selected generation technologies are provided in Table 7-1.

Generator Type	Capacity (MW)
Fuel Cell	0.25
Wind (Onshore)	1.5
Municipal Waste	25
Energy Crop	17.5
Gas Turbine (Large)	50
CHP Gas Engine	1.8
CHP Gas Turbine	6.1

Table 7-1: Generation technologies and ratings considered in case studies.

Five scenarios are considered:

- ndgu – no distributed generation units
- dtl1 – DTI linear interpolation
- prm1 – penetration rate model one
- prm2 – penetration rate model two
- prm3 – penetration rate model three

Five years intervals between study years have been used. This results in 4 study years selected from a fifteen year planning period. The study years are 1998, 2003, 2008 and 2013.

7.2.1 Distributed generation scenario 'ndgu'

The *ndgu* scenario is the base scenario and makes an assumption of no distributed generation growth in future years. Load growth of 1.2% per annum is factored into this scenario and all other scenarios. This scenario acts as a base case against which the other scenarios for distributed generation can be compared.

7.2.2 Distributed generation scenario 'dtll'

The *dtll* scenario is based on a linear interpolation and extrapolation of UK Department of Trade and Industry (DTI) forecasts for distributed generation. The set of generator types considered for analysis in the case studies relating to this project is shorter than the full list assessed in the DTI forecast. The total capacity per technology in the national scenario used in these case studies contains the same capacity as for all similar technologies in the DTI forecasts. For example, the technically feasible capacity for municipal waste in this scenario construction process also includes the DTI projection for landfill gas which shares many of the same characteristics as municipal waste. In this way, the effect of all additional capacity under the DTI forecasts is reflected in the case study scenarios although the generating technology list is not as extensive. To cite another example, in Table 7-3 the 2010 forecast figure for 'Energy Crops' is 300MW. In the construction of the 'prm' scenarios, a value of 600MW has been used to represent the additional capacity from the 'similar' technology type of Biomass which also has a forecast capacity of 300MW in 2010 (Table 7-3). These assumptions have been made to allow the scenario *dtll* to reflect the actual capacities of distributed generation expected regardless of the reduced technology list utilised.

The methods and assumptions used in the construction of the *dtll* scenario are in contrast to the methods and assumptions used in 'prm' scenarios (sections 7.2.3, 7.2.4 and 7.2.5). This illustrates the diversity of the techniques available derive scenarios for future distributed generation levels.

Table 7-2 summarises the high level DTI forecast to the year 2010 (Baker, 1999). These forecasts represent a three- to four-fold increase over current installed capacity of distributed generation.

Technology Grouping	Forecast Capacity by 2010 (MW)
Combined Heat and Power	8000
Renewables	7000 – 8000
Open Cycle Gas Turbines/Diesels/Others	3000 – 4000

Table 7-2: High level DTI forecasts for distributed generation in the UK in 2010.

In addition, Table 7-3 shows the DTI forecasts specifically for renewable technologies. These projections assume no planning constraints although the issue of local planning authority hostility to some generation types seems to be one of the largest inhibitors of renewable generation growth.

Generation Technology	Forecast Capacity by 2010 (MW)
Onshore Wind	3100
Offshore Wind	1730
Hydro	230
Landfill Gas	1010
Waste Combustion	560
Biomass	300
Energy Crops	300
Other Technologies	150
Existing Capacity	600

Table 7-3: DTI forecast for renewables in the UK in 2010.

Using the base data from Table 7-3 and estimates of existing capacity in each technology type, a linear function is drawn from the current situation (actually 1999) to the DTI forecast year (2010). The new technology in each of the study years 2003, 2008 and 2013 is derived from this curve between and beyond the current capacity of distributed generation and the DTI forecasts.

7.2.3 Distributed generation scenario 'prml'

The *prml* scenario is derived from a direct economic modelling methodology which assesses the profitability of each generation technology considered. The model simulates generation developers' investment decision-making relating to the attractiveness of technology profitability and the national feasible capacity which reflects the opportunity to invest in a scheme of that technology.

The base economic data for each generation technology and the assumptions of technically feasible resource exploitation potential are derived from the UK Department of Trade and Industry (Energy Technology Support Unit - ETSU) research into new and renewable technologies (Department of Trade and Industry, 1999).

The Internal Rate of Return (IRR) is calculated for each technology in each study year taking account of movements in capital costs and underlying market prices for fuel. The electricity market revenues and operations costs are assumed to stay constant in each study year. A nominal income from transmission and distribution costs savings is built into the profitability of each generator to reflect current levels of remuneration to distributed generators from transmission and distribution companies.

The national penetration level is calculated in each study year by comparing the IRR for the technology with the IRR required by investors. The required IRR for investors is assumed to have a log-normal distribution around a mean of 20% with a standard deviation of 2%. This technique has been described in section 5.5.1.5. This calculation results in a proportion of schemes which will proceed on an economic and investment decision basis. The target value of 20% for IRR is based on personal knowledge of investment return targets for industrial enterprises. The target for IRR does not take account of any special reasons for investing in new generation technologies such as a desire to be an 'early-adopter' or to gain from fiscal or other subsidies in place for investing in clean energy technologies.

Finally, the capacity of distributed generation installed in each of the study years is calculated from the proportion of investors willing to develop a distributed generation scheme and the feasible installation capacity. The science in this method becomes less secure in this step since the technically feasible capacity for each technology is a tremendously difficult parameter to estimate. The feasible capacity depends on a number of factors including the mission of the generator, the local planning regime for each area of the country, the technology type and the local resources required to support the generation scheme. As noted, the technically feasible capacity has been based on DTI data with some further assumptions (Department of Trade and Industry, 1999).

Translating the national penetration capacities into actual generating units within the case study networks is undertaken using the scaling factors outlined in section 7.2.6.

7.2.4 Distributed generation scenario 'prm2'

The *prm2* scenario is based on the same penetration rate modelling methodology and parameters as *prm1* (section 7.2.3). Clean technologies receive a subsidy of 3£/MWh per unit generated which is in line with current thinking regarding the magnitude of the Climate Change Levy (CCL) in the UK. The natural gas fired generation receives an equivalent penalty of 3 £/MWh. This assumes that the full tax revenue raised from the Climate Change Levy is redistributed into subsidies for clean technology investments on a one for one basis as is common for new tax regimes. In addition to the subsidy for clean technologies, the capital cost trajectories for fuel cells and onshore wind are made more favourable for those technologies (-15% and -5% per annum respectively). These values of capital costs reductions are not based on any external source but reflect the possibility that developments in new generation technologies will be made on a faster track than assumed in the *prm1* scenario.

Large municipal waste schemes and large GT schemes are excluded from the scenario since they are subject to planning permission and gas moratorium barriers. In addition, it is wise to remove these technologies from some scenarios since the capacity of these generating units are much larger than the other technologies modelled and could potentially skew the subsequent analysis.

7.2.5 Distributed generation Scenario 'prm3'

The prm3 scenario is also based on the penetration rate modelling methodology and parameter values of the *prm1* scenario (section 7.2.3). The clean technologies subsidy is simulated and the capital cost reduction of fuel cells is accelerated as per scenario *prm2*. The capital cost reduction of wind is not as steep as in scenario *prm2*.

The feasible capacity of fuel cells, wind and municipal waste are increased to simulate the effect of more favourable planning consent and technology awareness conditions which are favourable to new and renewable technologies. These assumptions reflect the type of changes in sentiment in local planning authorities and the public at large which are likely to occur as a result of government backed promotional campaigns relating to public use of energy resources aimed at bolstering the countries efforts at achieving control over climate changing activities.

7.2.6 Scaling distributed generation scenarios to case study network level

Two stages are required to scale a national scenario for each generation technology to a local area level which will enable modelling and simulation of the scenario with particular emphasis on a section of utility network – represented by the two case study networks in these studies.

Firstly, the national scenario must be scaled to the reference distribution utility level. This is achieved by comparing the relative size of the reference distribution utility to the sum of all the utilities (i.e. the national picture). The factor 0.069 has been used to represent the average of the adjusted customer number metric (0.06667) and the ratio of regulated units delivered by the average distribution utility to the sum total (0.0714). See Table 7-17.

Secondly, the reference distribution utility level generation scenario must be scaled to a local area scenario to reflect the size of the case study network. This is achieved by dividing the annual energy demand in the case study network (1464 GWh for Network 1 and 608 GWh for Network 2) by the annual energy demand by the average distribution utility in 1998 (18,910 GWh). The resulting ratio is 0.077 for Network 1 and 0.032 for network 2.

The combined ratio for national to case study Network 1 scaling is:

0.069 x 0.077 = **<u>0.00528</u>**

The combined ratio for national to case study Network 2 scaling is:

0.069 x 0.032 = **<u>0.00221</u>**

These factors are used to multiply the national level scenarios for distributed generation and provide a local level estimate of the capacity installed in each study year for each case study network. The number of generating units is calculated by dividing the capacity for each generation technology defined for the scenario in the local area by the rated capacity of the appropriate generation technology. An integer value of installed generation is derived by rounding up the product of the total generation capacity and the rated capacity for that generation technology.

It is acknowledged that such a uniform spread of generation across the country and also the rounding-up of generation unit numbers will introduce some error. It must be remembered that the purpose of the scenario development exercise is to provide an indication of the likely levels of distributed generation in a representative section of utility distribution network rather than provide a wholly consistent set of forecasting models. At nearly every stage of the numerical derivation of distributed generation scenarios, the data could be challenged in some way. The aim of the scenario development exercise is the production of a set of plausible scenarios with a degree of numerical justification.

7.2.7 Locating the scenario generating units in the case study networks.

The construction of plausible distributed generation scenarios must also take account of the location of the generation within the network. Generator placement must be as realistic as possible to establish a good estimate of the effect of the impact of distributed generation on the distribution network. The problem of producing realistic locations for generation within the network reflects a major underlying problem faced by the distribution companies with respect to distributed generation. The generation is independent and the distribution company is limited to influencing but not controlling the siting decisions.

Work carried out under the author's supervision investigated the use of scoring methods to assess the likelihood of particular generator types being installed at particular points in the network (Hossack, 1999). The method investigated in this work found that the placement (and investment) in distributed generation was quite sensitive to the input data and weightings utilised. The input data for the connection points are load characteristics (magnitude and composition), costs and revenues for generation at that point and operating mode of the generation. Each of these factors was given a weighting to establish the likelihood of location of each generator type at each connection point in the network.

To avoid the 'opaqueness' and other difficulties of a scoring method, a simpler method will be used in these case studies. For each of a set of designated connection points, percentage weightings of rural to urban will be set by reference to maps and load data. This will be used to assess the most likely location in the network for various types of generation. For example, it is likely that wind turbines will be located in predominantly rural areas while municipal waste burning schemes will be located close to urban population centres while not being located within the urban area (in this case a split of urban and rural will guide the generation location). The designated connection points are limited to existing substations in these case studies and only these connection points will be assessed.

The urban and rural load split for each designated connection point in case study Network 1 is shown in Table G-1 (Appendix G).

This method of selecting the likely locations of generators in the scenarios is more intuitive (particularly for a power system planner with knowledge of the area) and more transparent than a highly sensitive weighting based method. Once again, it is acknowledged that there are gross simplifications in this method but, again, the focus is on the production of plausible scenarios in order to assess the general effects of distributed generation to aid distribution utility strategy development and decision making.

7.2.8 National distributed generation scenarios

The general processes of scenario construction has been described in the preceding sections (7.2.1 to 7.2.7). The distributed generation scenarios produced using these methods are outlined below. The scenarios are described in terms of capacity of distributed generation within the case study networks in each study year through the planning period.

The preceding tables have outlined the capacities for generation under each scenario. Once the financial and economic models of the generation have been established it becomes a matter of routine to generate new scenarios with modified assumptions. For example, the *prm* scenarios have been generated assuming a particular level of energy sales revenue based on the existing UK Electricity Pool system. When the Electricity Pool is replaced by the new NETA trading system in November 2000 then the future revenues from distributed generation may be able to be forecast more reliably in which case the new data could be added to the model and all the scenarios revised promptly. In essence, the production of scenarios based on different sets of assumptions can be achieved with only a little further effort.

7.2.9 Summary of Distributed Generation Scenarios

The capacity of distributed generation in each of the case study networks for all the scenarios are illustrated in Figure 7-1 (for Network 1) and Figure 7-2 (for Network 2). The peak load in each year is also shown to provide perspective on the relative capacity of distributed generation within the networks under each scenario.

The national distributed generation scenarios detailed in Appendix F are scaled to case study network level in two steps as described in section 7.2.6. The local case study network scenarios for distributed generation are summarised in the following tables and graphs.

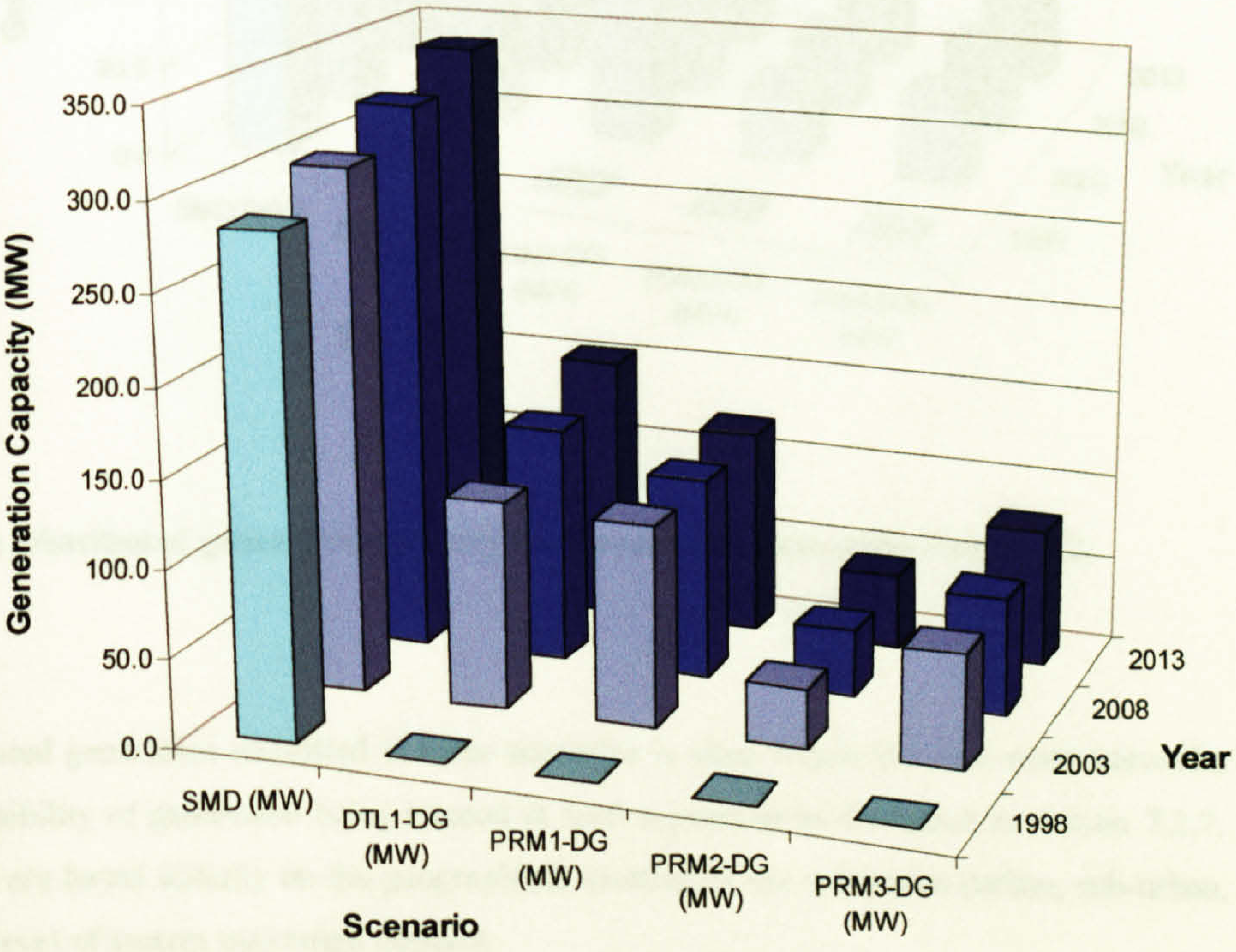

Figure 7-1: Distributed generation capacity for scenarios in case study Network 1.

It can be seen from Figure 7-1 that the government forecasts for distributed generation in the UK (scenario *dtl1*) foresees the greatest capacity of distributed generation in the horizon year 2013. The penetration rate models (*prm*) yield capacities of distributed generation in accordance with the underlying financial and economic parameters assumed for each generation technology. The least favourable economics for distributed generation are modelled in scenario *prm2* which can be seen to yield a modest capacity of generation in comparison to the other scenarios and the total distribution system load.

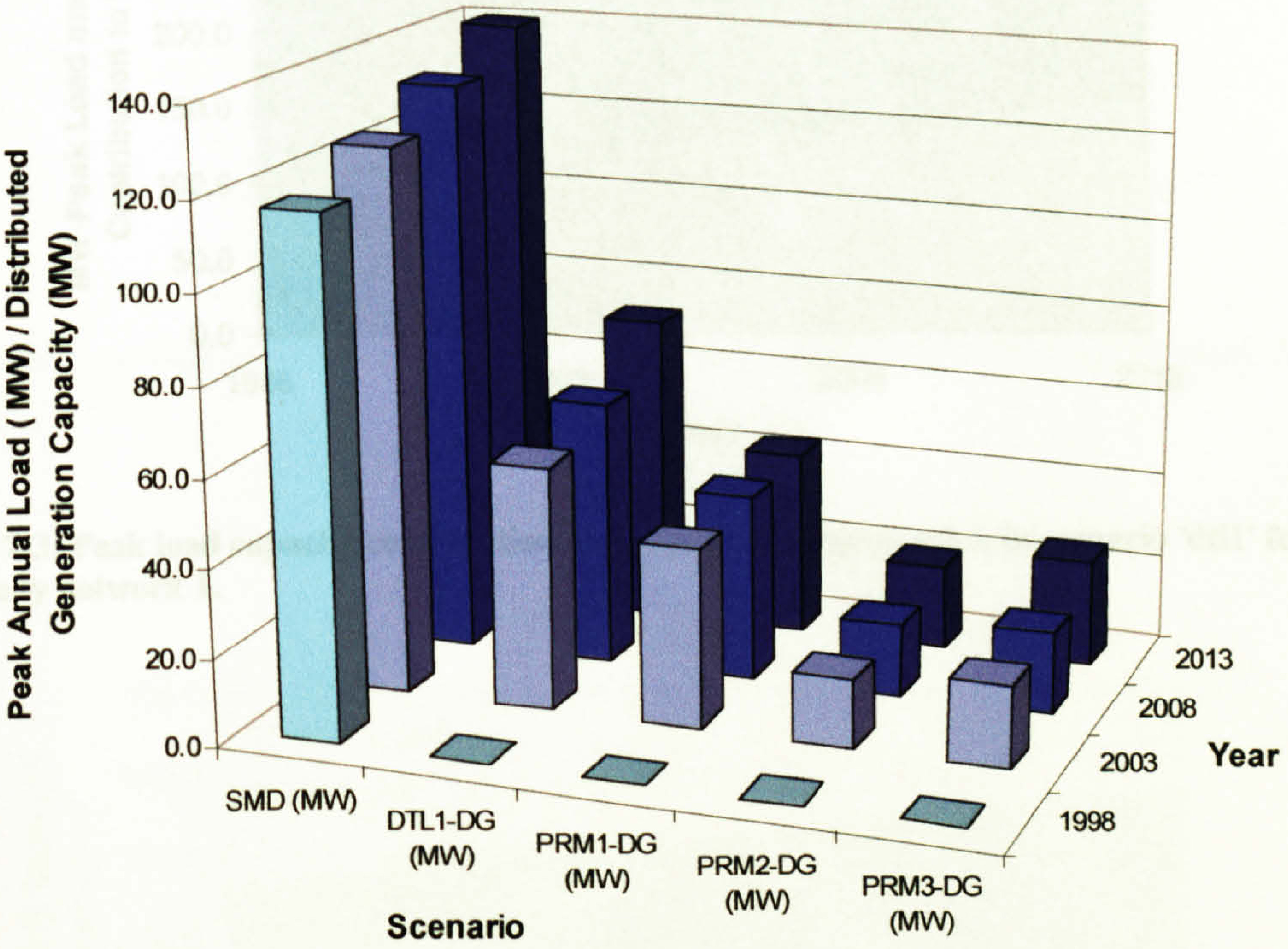

Figure 7-2: Distributed generation capacity for scenarios in case study Network 2.

The distributed generation identified in these scenarios is sited within the case study networks based on the plausibility of generation being located in such a position as discussed in section 7.2.7. Such judgements are based initially on the geographical location of the substation (urban, sub-urban, rural) and on the level of system maximum demand.

The distributed generation contribution to peak load is illustrated more clearly in Figure 7-3 to Figure 7-6 for the four distributed generation scenarios in case study network 1 while Figure 7-7 to Figure 7-10 illustrate the same characteristics for the four distributed generation scenarios in case study network 2.

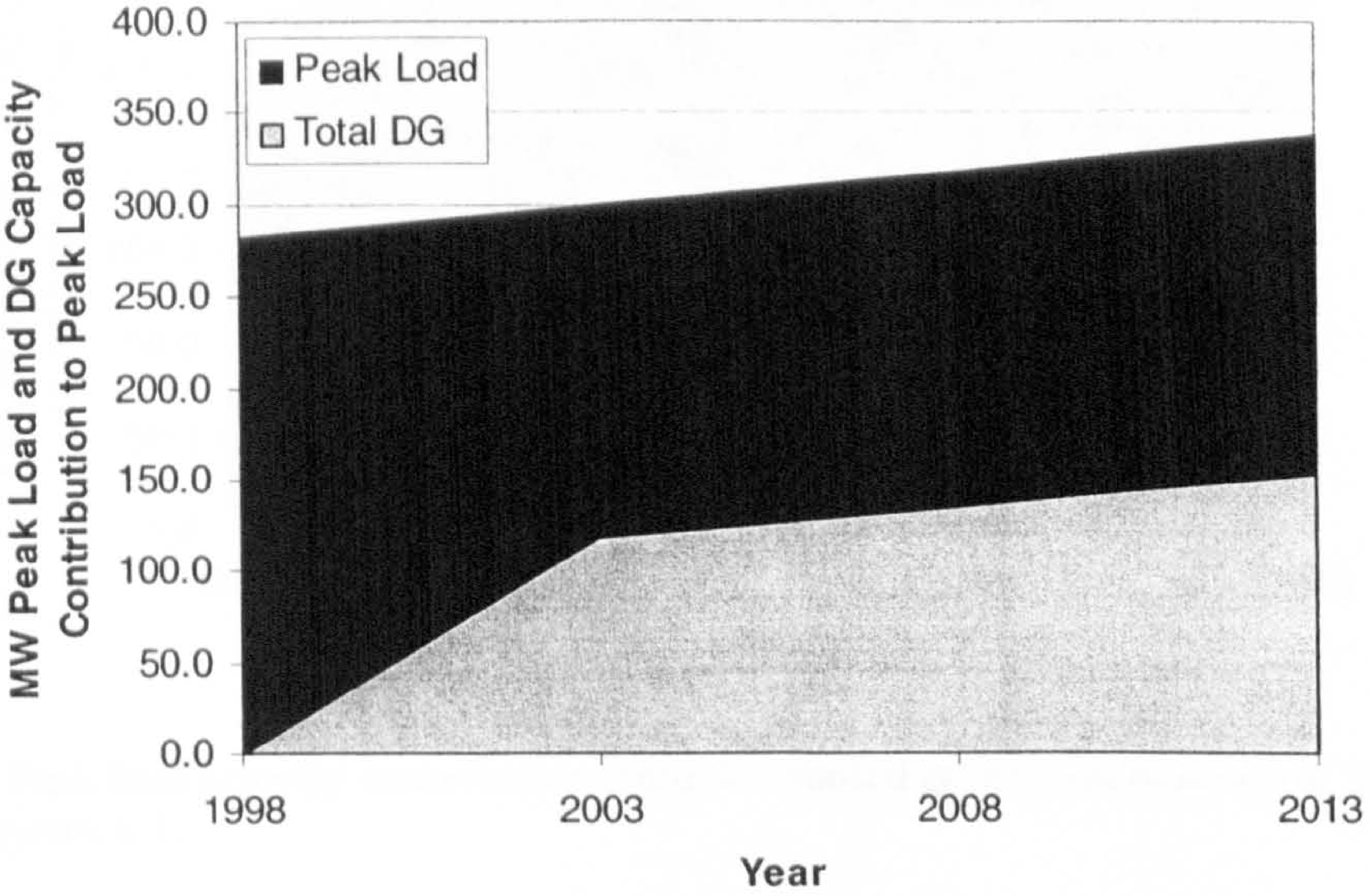

Figure 7-3: Peak load capacity contribution from distributed generation in scenario 'dtl1' for case study network 1.

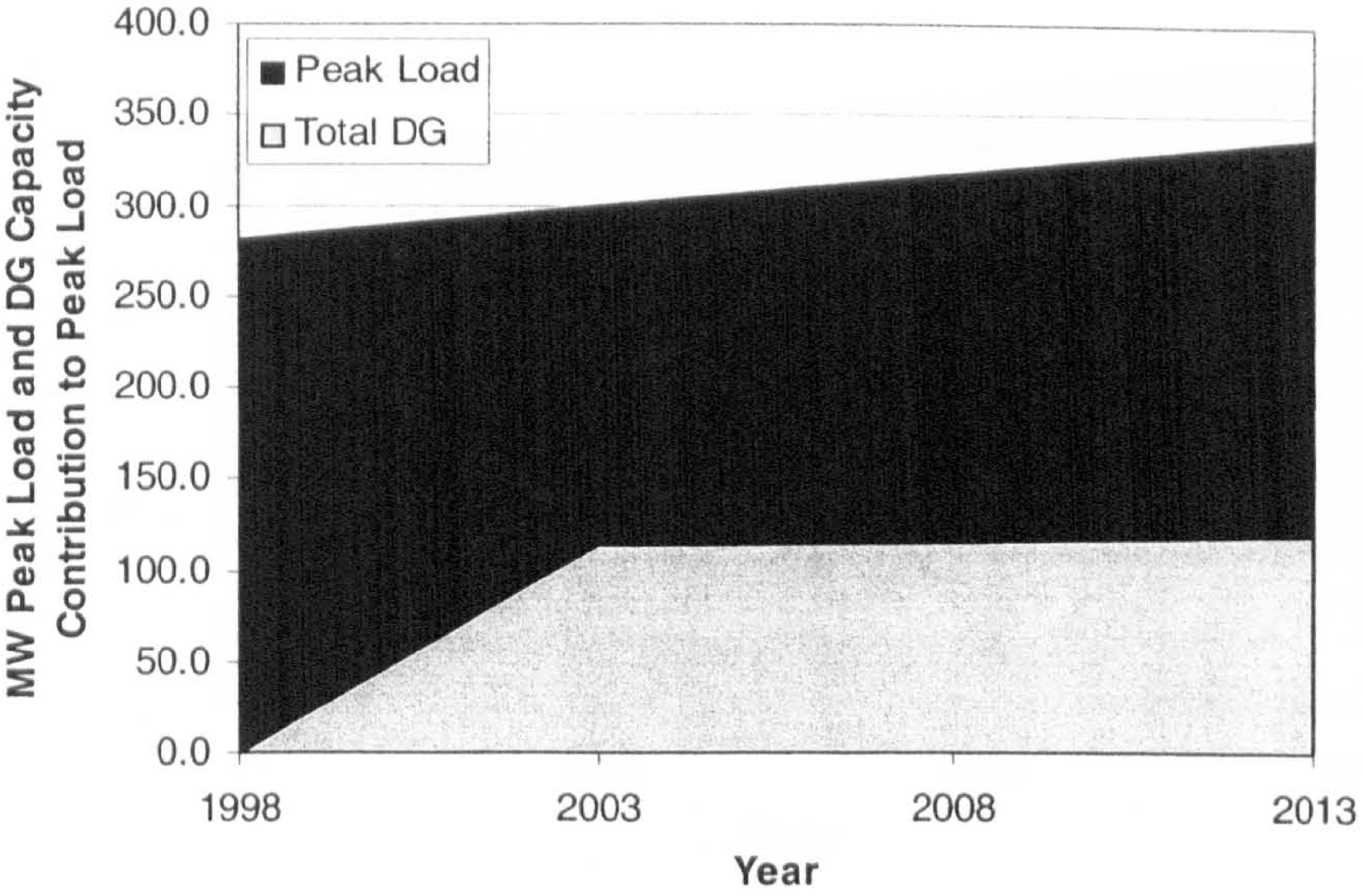

Figure 7-4: Peak load capacity contribution from distributed generation in scenario 'prm1' for case study network 1.

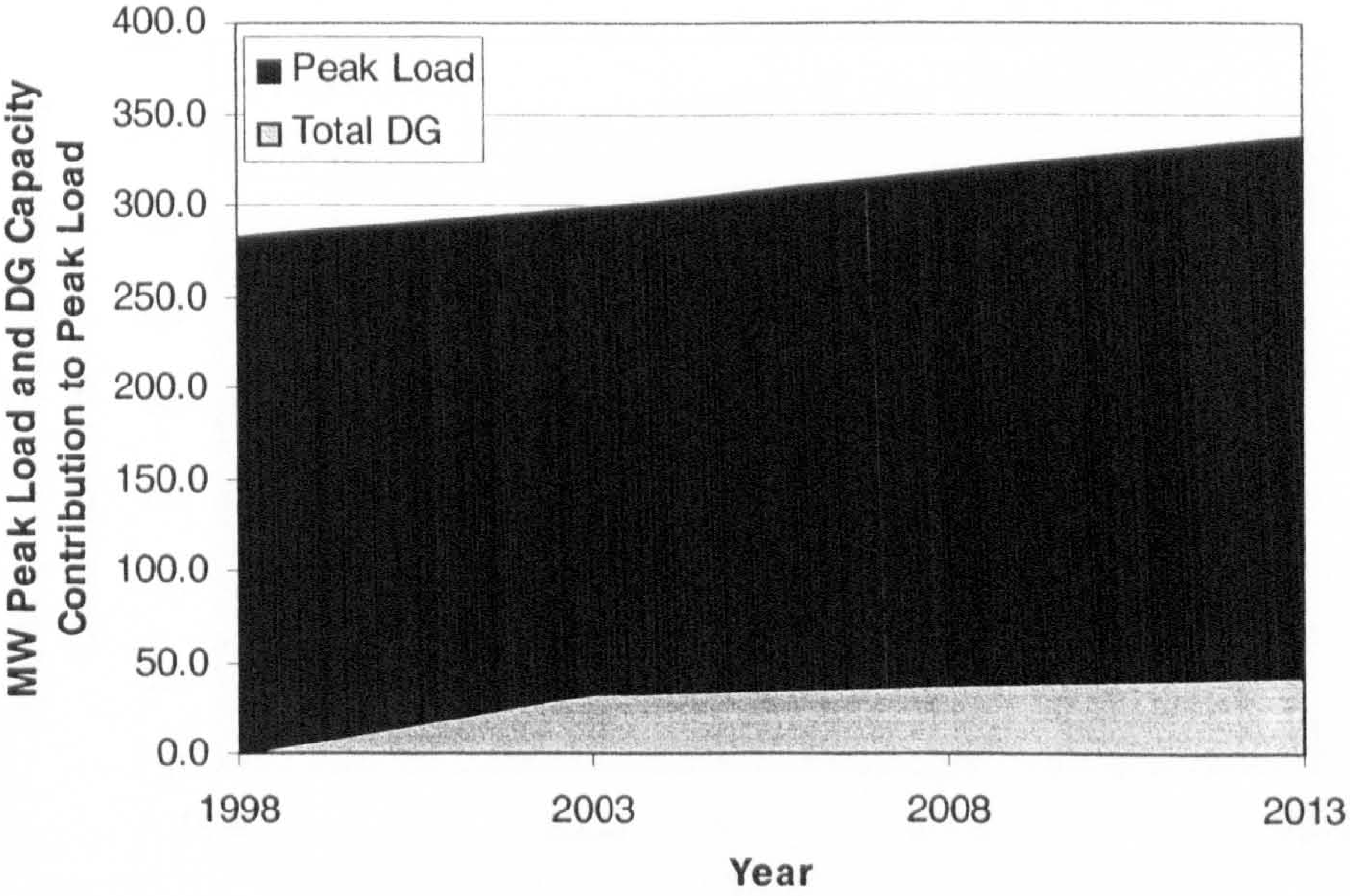

Figure 7-5: Peak load capacity contribution from distributed generation in scenario 'prm2' for case study network 1.

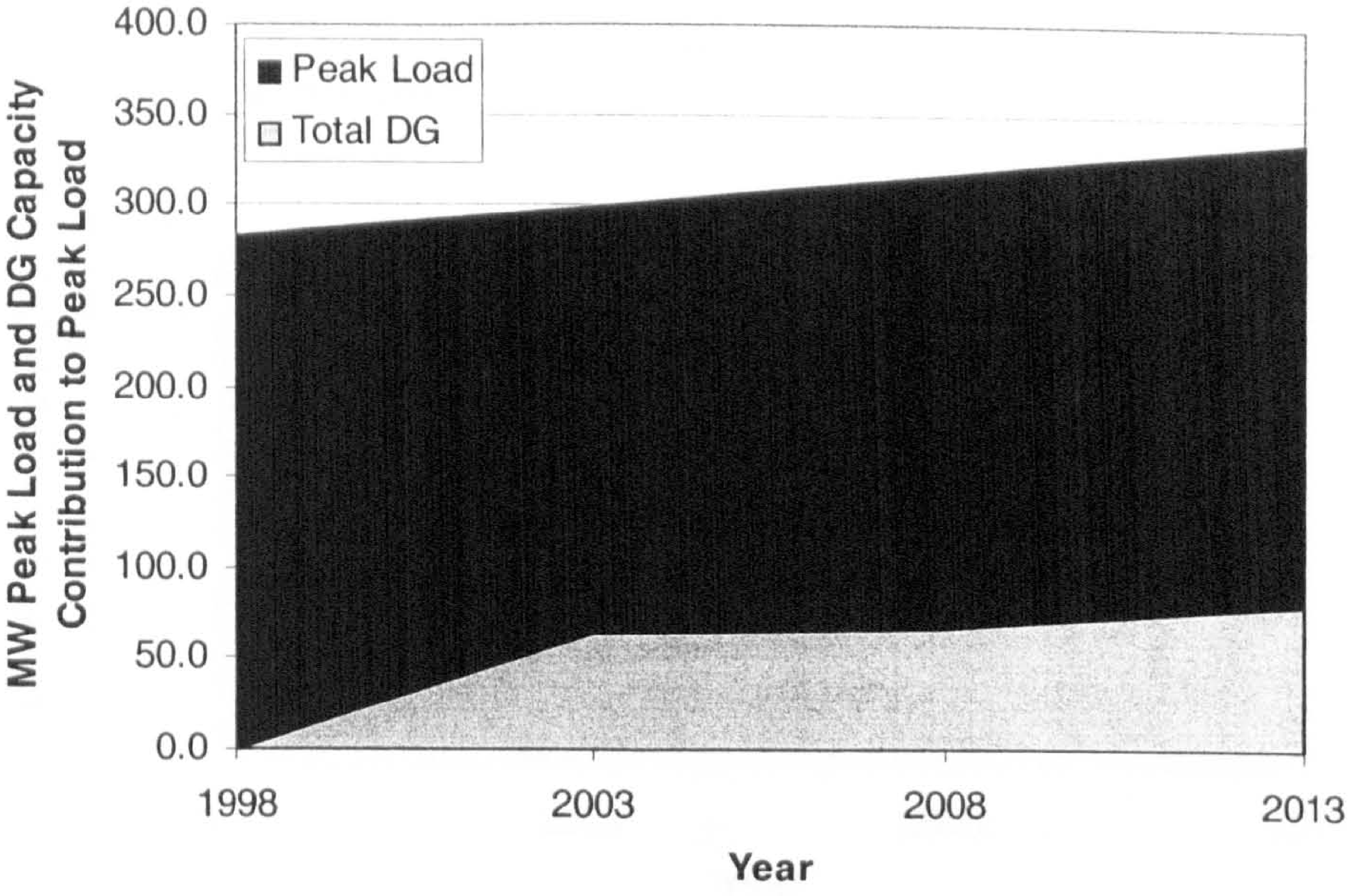

Figure 7-6: Peak load capacity contribution from distributed generation in scenario 'prm3' for case study network 1.

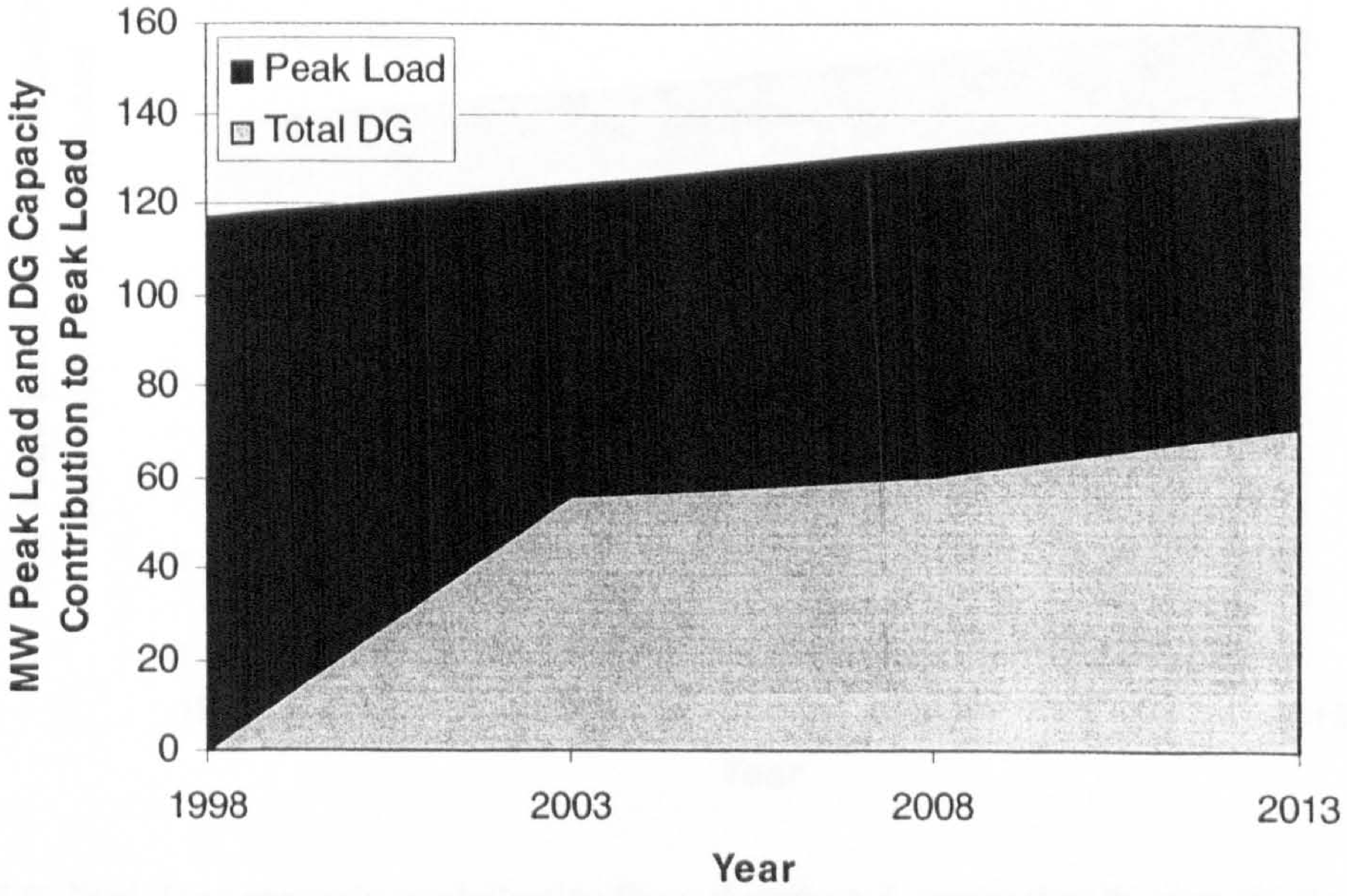

Figure 7-7: Peak load capacity contribution from distributed generation in scenario 'dtl1' for case study network 2.

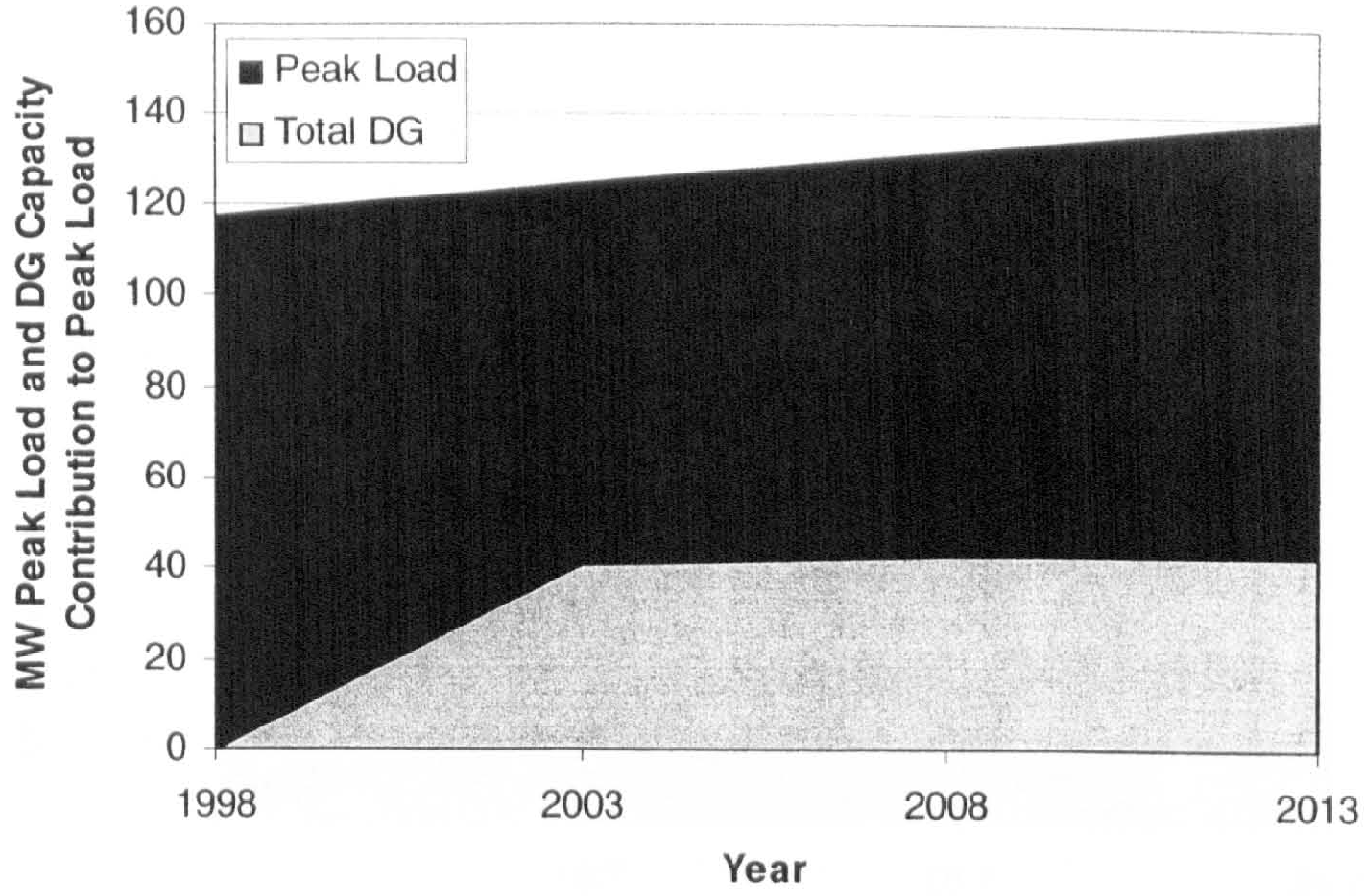

Figure 7-8: Peak load capacity contribution from distributed generation in scenario 'prm1' for case study network 2.

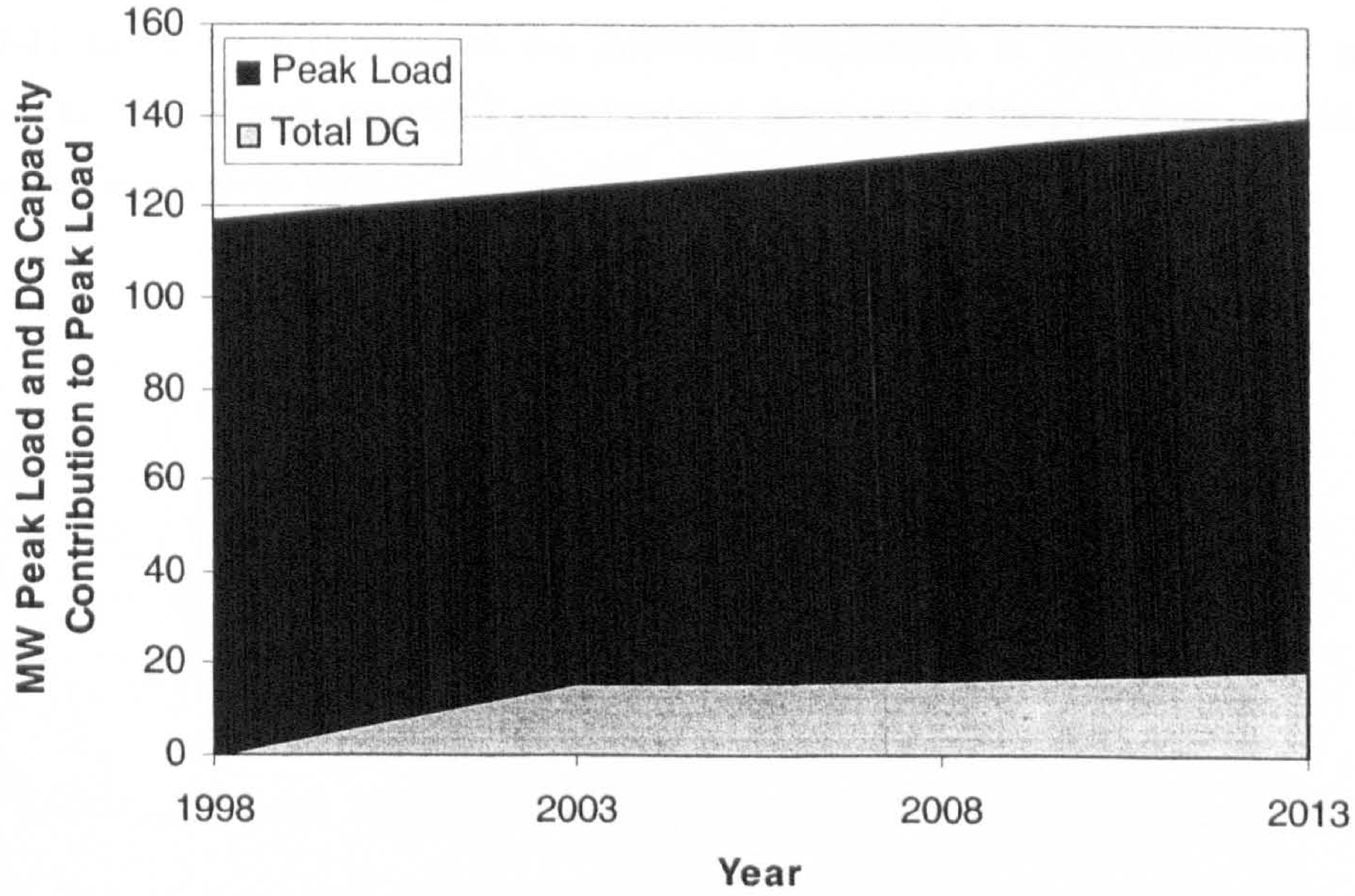

Figure 7-9: Peak load capacity contribution from distributed generation in scenario 'prm2' for case study network 2.

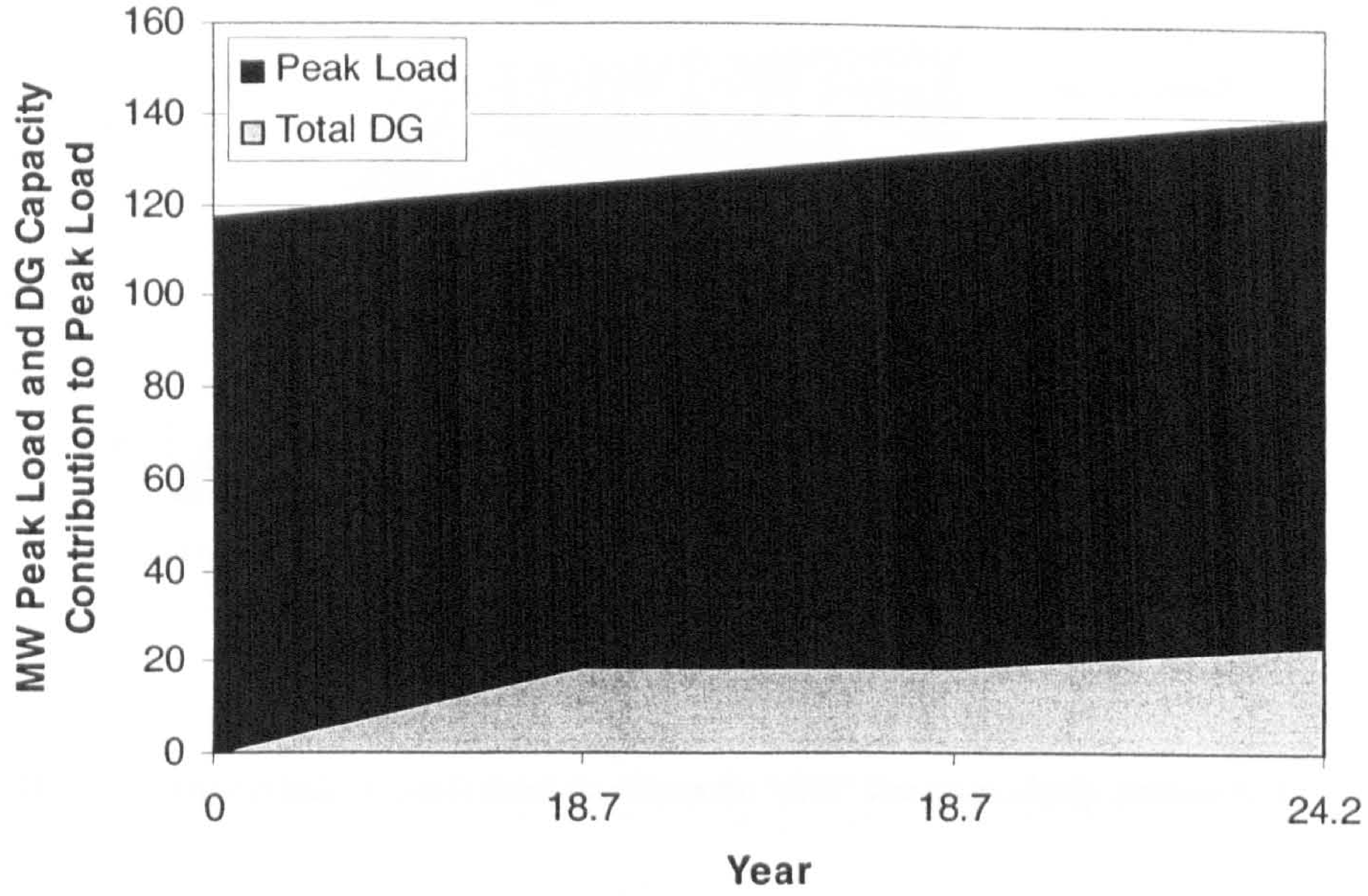

Figure 7-10: Peak load capacity contribution from distributed generation in scenario 'prm3' for case study network 2.

Figure 7-11 to Figure 7-14 illustrate the individual contribution of each distributed generation technology to the case study network 1 peak load as a percentage of the peak load value for the case study network in the given year.

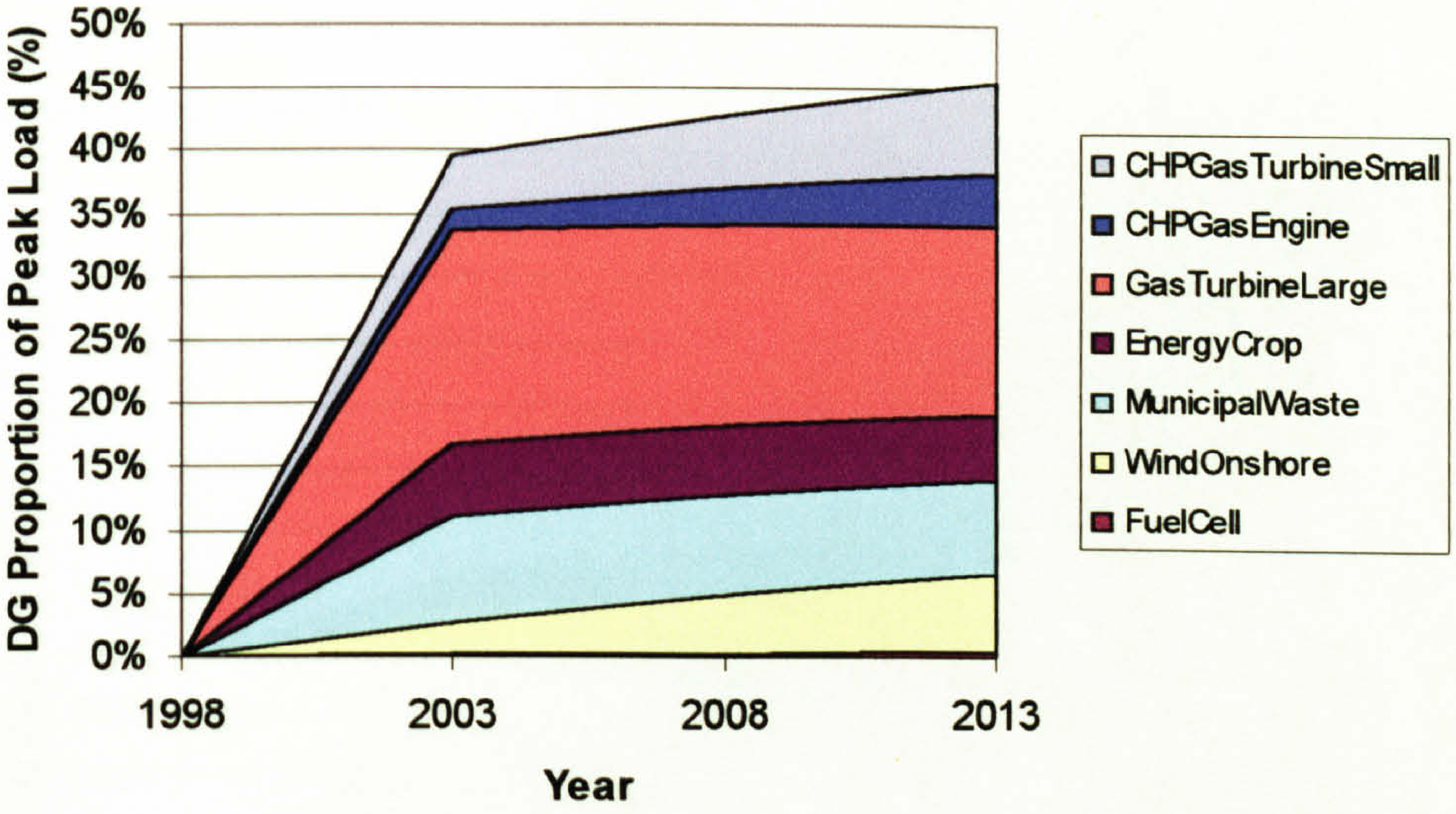

Figure 7-11: DG proportion of peak load in scenario 'dtl1' for case study network 1.

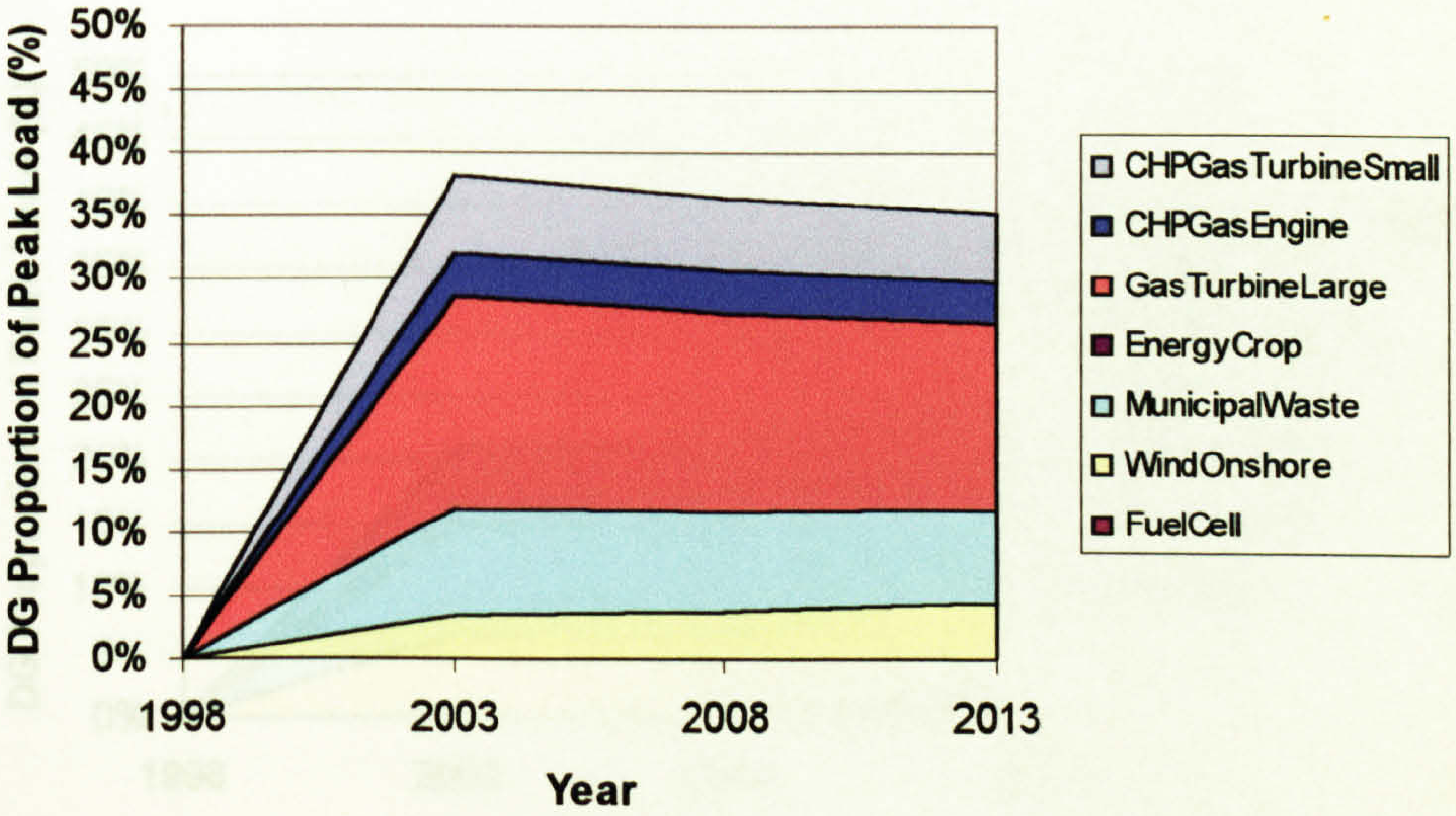

Figure 7-12: DG proportion of peak load in scenario 'prm1' for case study network 1.

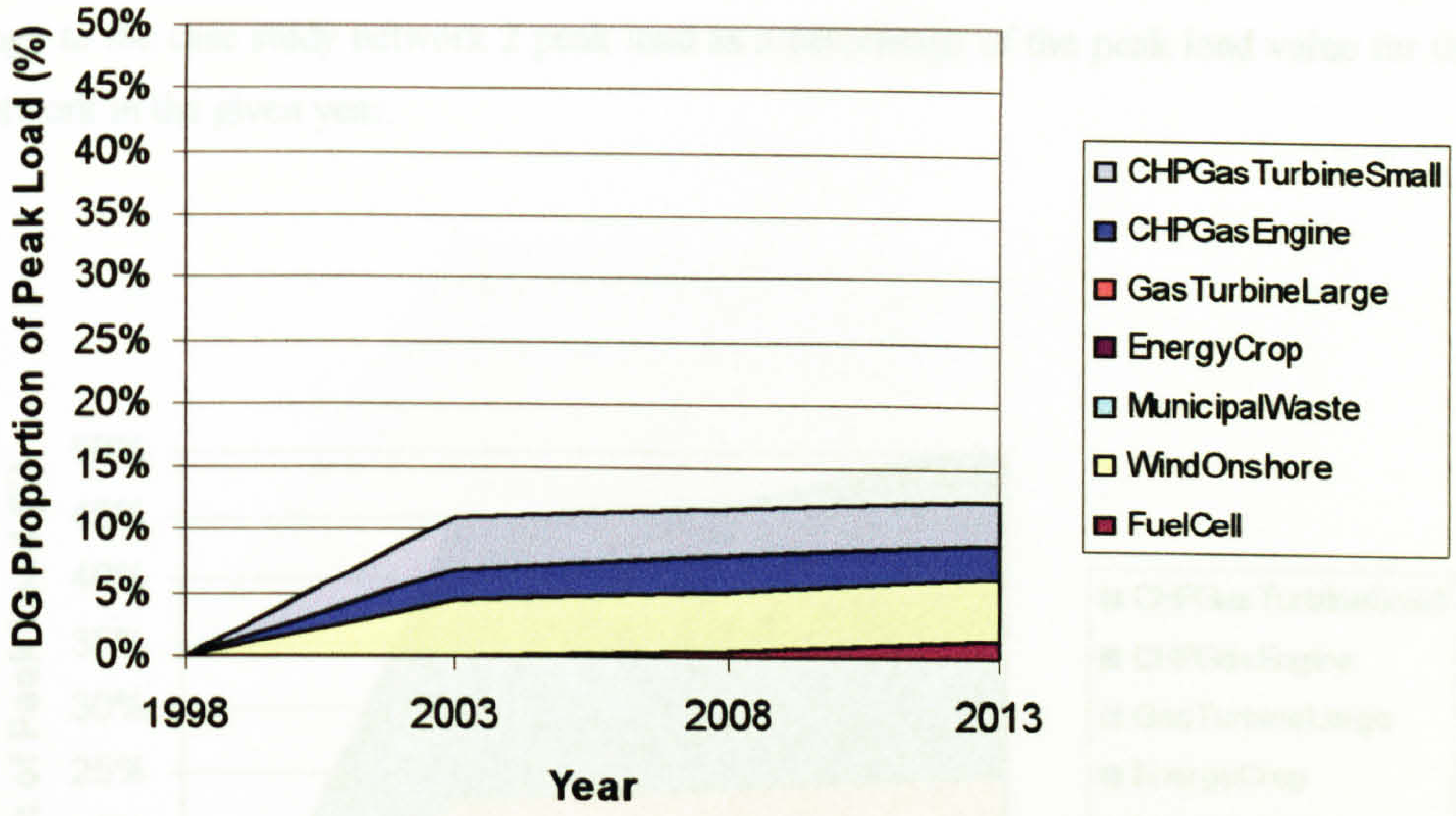

Figure 7-13: DG proportion of peak load in scenario 'prm2' for case study network 1.

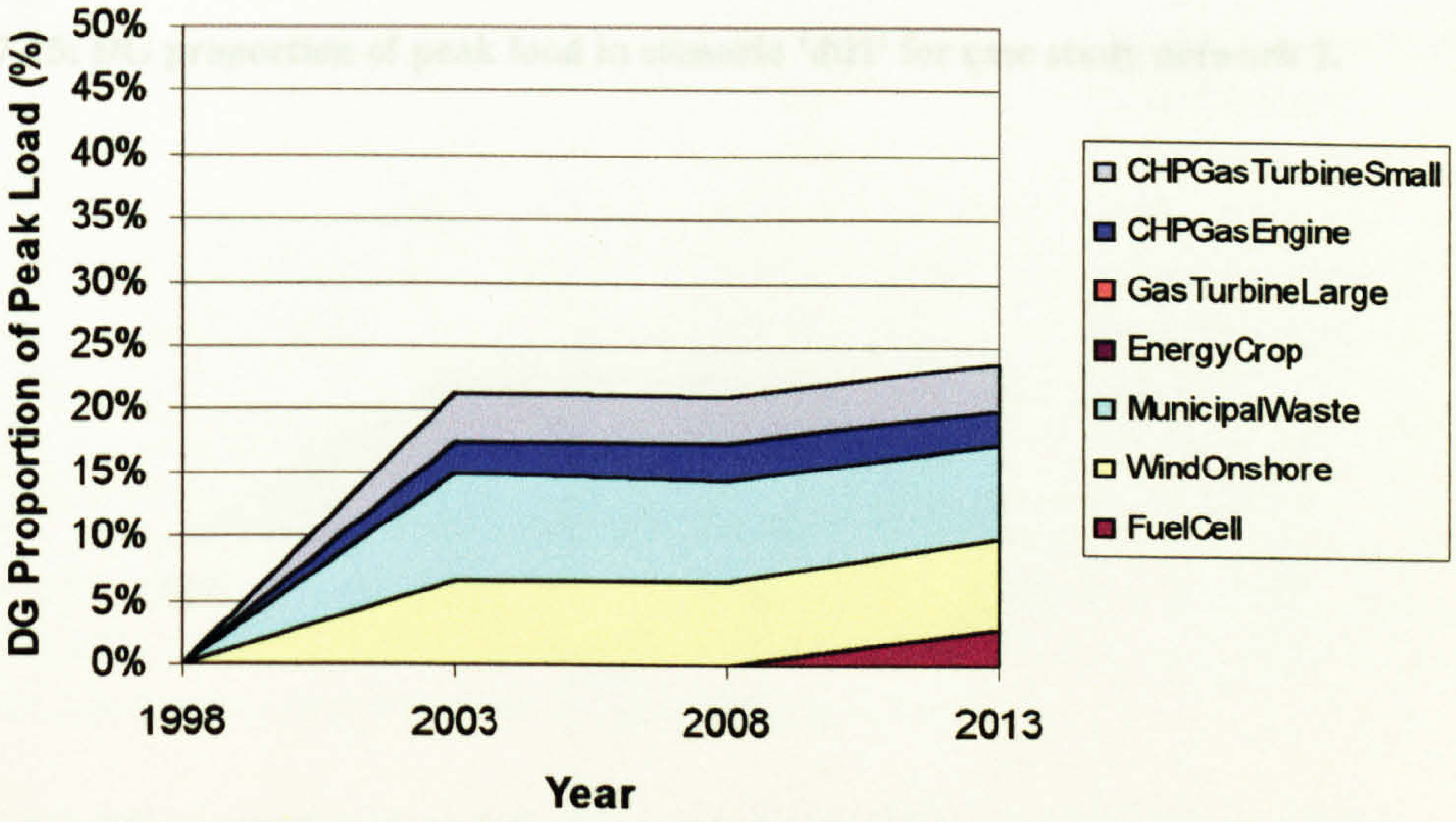

Figure 7-14: DG proportion of peak load in scenario 'prm3' for case study network 1.

Figure 7-15 to Figure 7-18 illustrate the individual contribution of each distributed generation technology to the case study network 2 peak load as a percentage of the peak load value for the case study network in the given year.

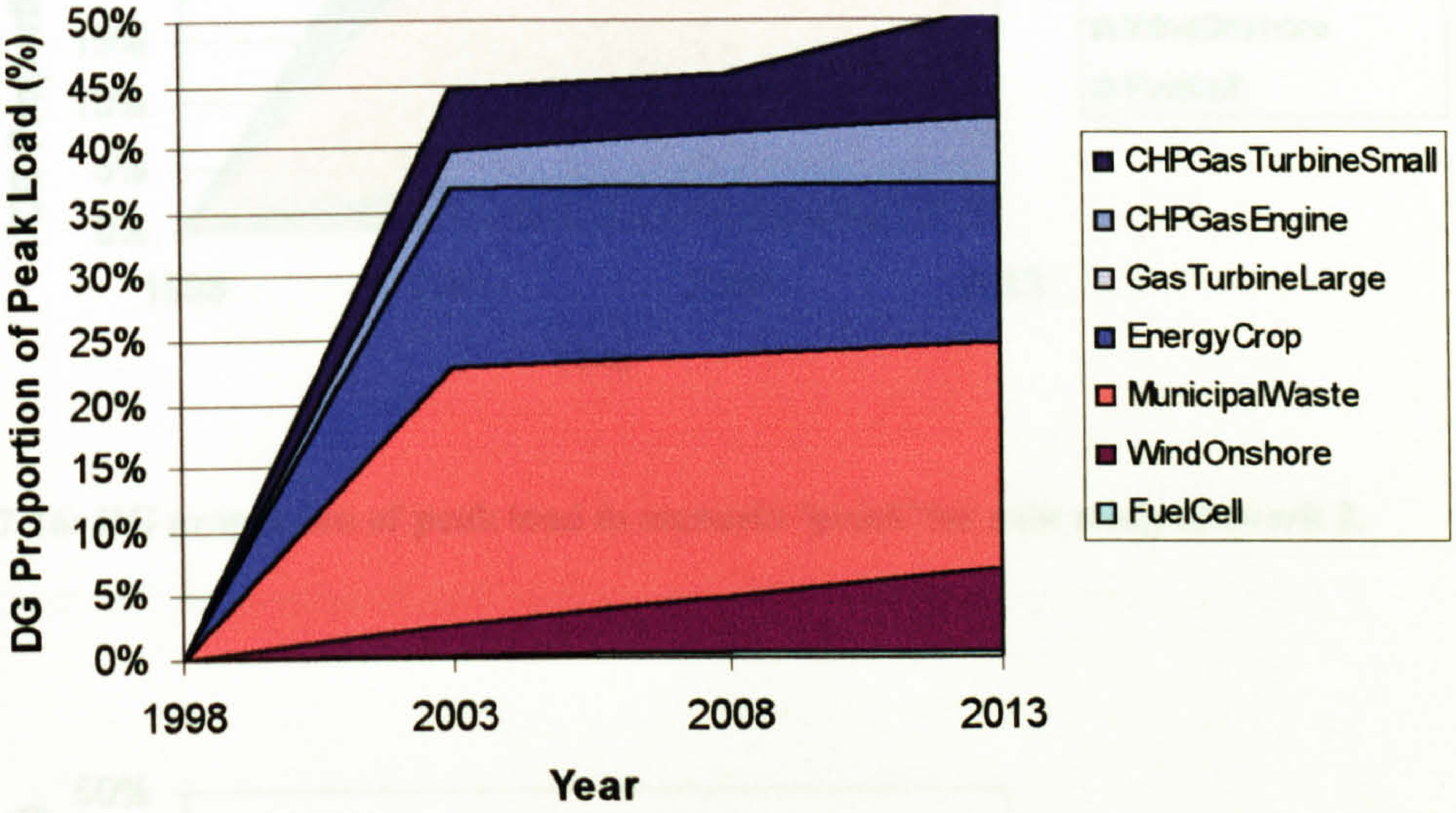

Figure 7-15: DG proportion of peak load in scenario 'dtl1' for case study network 2.

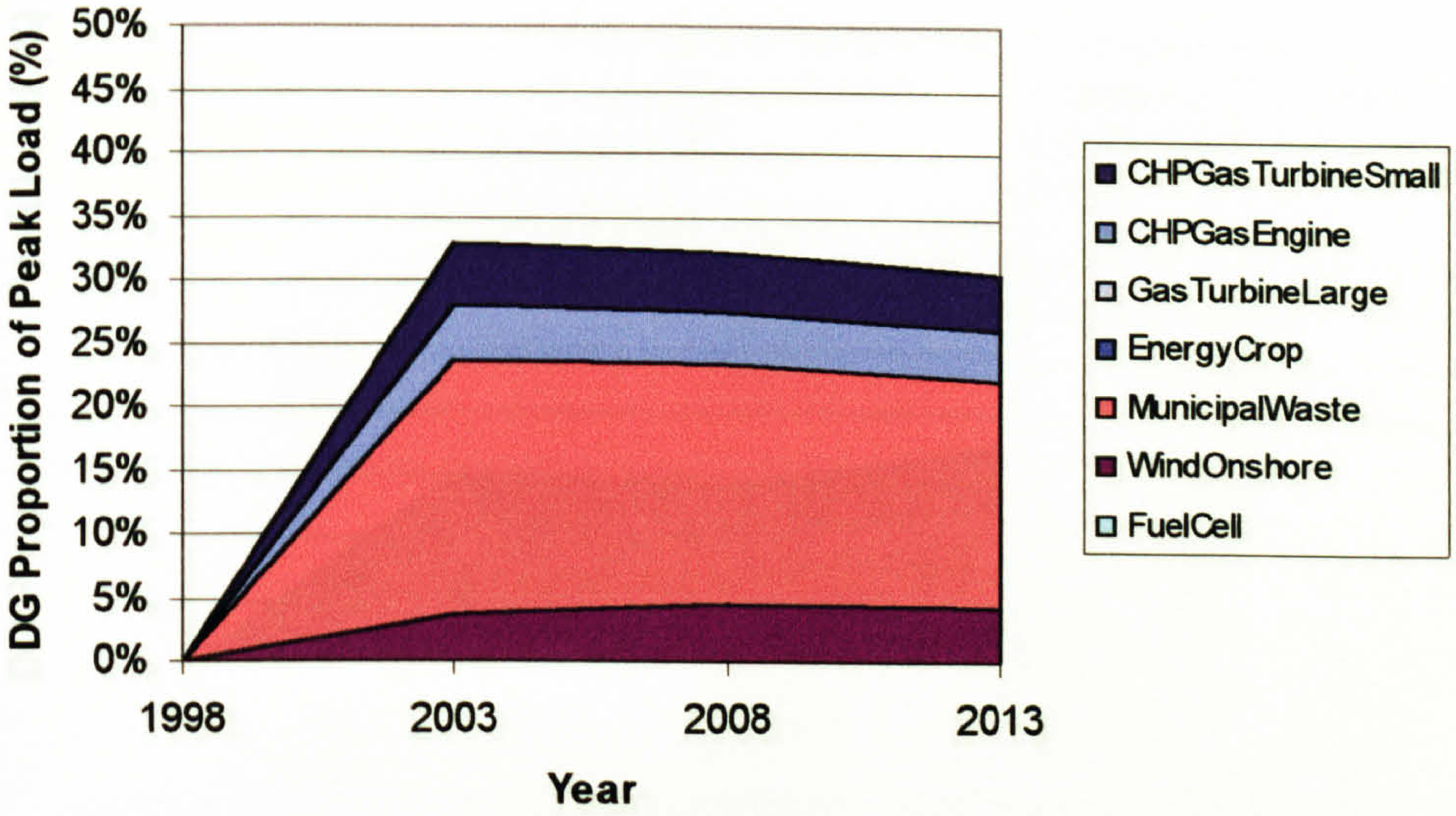

Figure 7-16: DG proportion of peak load in scenario 'prm1' for case study network 2.

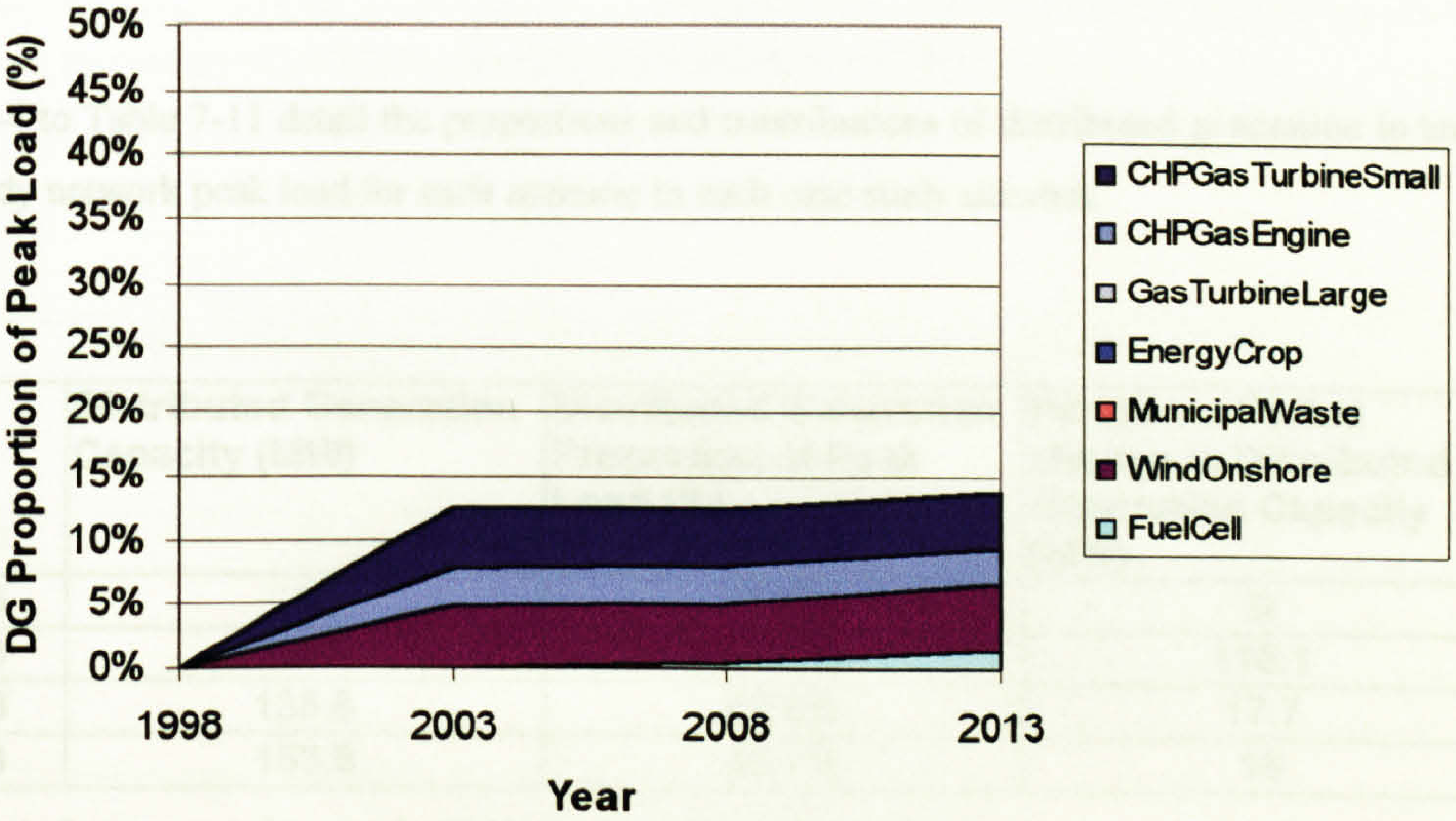

Figure 7-17: DG proportion of peak load in scenario 'prm2' for case study network 2.

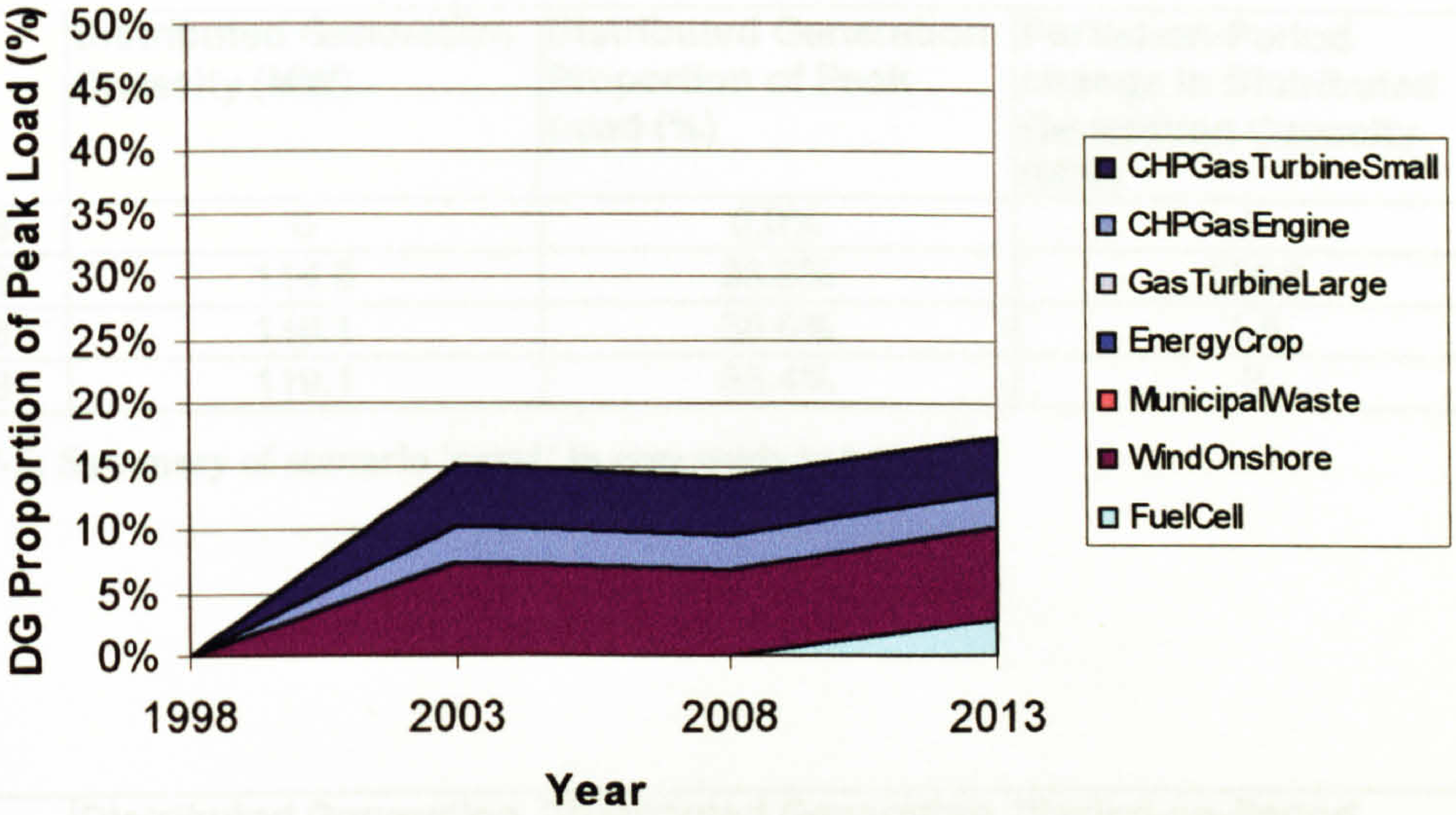

Figure 7-18: DG proportion of peak load in scenario 'prm3' for case study network 2.

Table 7-4 to Table 7-11 detail the proportions and contributions of distributed generation in terms of case study network peak load for each scenario in each case study network.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	118.1	39.5%	118.1
2008	135.8	42.8%	17.7
2013	153.8	45.7%	18

Table 7-4: Summary of scenario 'dtl1' in case study network 1.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	114.6	38.3%	114.6
2008	116.1	36.6%	1.5
2013	119.1	35.4%	3

Table 7-5: Summary of scenario 'prm1' in case study network 1.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	32.9	11.0%	32.9
2008	37.7	11.9%	4.8
2013	42.7	12.7%	5

Table 7-6: Summary of scenario 'prm2' in case study network 1.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	63.9	21.4%	63.9
2008	67.2	21.2%	3.3
2013	79.7	23.7%	12.5

Table 7-7: Summary of scenario 'prm3' in case study network 1.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	55.5	44.6%	55.5
2008	60.5	45.9%	5.1
2013	71.7	51.2%	11.2

Table 7-8: Summary of scenario 'dtl1' in case study network 2.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	41	33.0%	41
2008	42.5	32.2%	1.5
2013	42.5	30.4%	0

Table 7-9: Summary of scenario 'prm1' in case study network 2.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	15.7	12.6%	15.7
2008	16.45	12.5%	0.75
2013	19.2	13.7%	2.75

Table 7-10: Summary of scenario 'prm2' in case study network 2.

Year	Distributed Generation Capacity (MW)	Distributed Generation Proportion of Peak Load (%)	Period-on-Period change in Distributed Generation Capacity (MW)
1998	0	0.0%	0
2003	18.7	15.1%	18.7
2008	18.7	14.2%	0
2013	24.2	17.3%	5.5

Table 7-11: Summary of scenario 'prm3' in case study network 2.

7.3 Case Study Background

Two case study networks will be utilised to demonstrate the use of the DG strategic analysis framework to provide information for distribution utility strategy formation with regard to distributed generation.

The case studies have been created from distribution utility and public domain data which has mainly been sourced from government and regulatory reports. There have been some limitations regarding the data available for the construction of the case studies presented. It is believed that data unavailability has not materially altered the results since power network modelling data was available and much of the remainder of the economic and financial data relating to generation is subject to alteration across the set of scenarios.

7.3.1 Case Study Network Models

The first case study network will be referred to as 'Network 1' throughout the subsequent chapters of this thesis.

Table 7-12 details the quantities of each of a number of different network asset types within case study Network 1.

Asset	Quantity
Primary substations	18
400-132kV transformers	2
132-33kV transformers	7
33-11kV transformers	35
132kV OH circuit (km)	47.7
132kV UG circuit (km)	1.1
33kV OH circuit (km)	59.9
33kV UG circuit (km)	161.1

Table 7-12: Network asset details for case study network 1.

Network 1 is located in a mixed urban-rural area with some high density population centres spread over a predominantly agricultural area. The composition of the higher voltage circuitry backs this up with all but a very small length (1.1km) of the 132kV circuits being overhead lines while quite a high proportion of the overall 33kV circuit length being underground cables.

Table 7-13 details the load characteristics for case study Network 1. The annual energy consumed at load points is based on the peak maximum power demand shown in the table along with a load factor of 0.593. The load factor is derived from load metering data for the network.

Load Feature	1998	2003	2008	2013
Maximum Demand Power (MW)	281.7	299.1	317.4	336.9
Maximum Demand Reactive Power (MVAr)	57.3	60.8	64.5	68.5
Annual Energy Demand (MWh)	1,464,438	1,554,438	1,649,787	1,751,144

Table 7-13: Annual load details for case study network 1.

The annual load growth factor between years is 1.2% per annum which is the national average load growth expected by the National Grid Company for some years to come (National Grid Company plc, 1997). Some areas within Network 1 may experience much higher load growth due to a higher level of economic activity related to research and technology developments in this area but the case study is focused on the general effects of distributed generation and therefore will not progress into investigating these factors.

The second case study network will be referred to as 'Network 2' throughout the subsequent chapters of this thesis.

Table 7-14 provides details of the distribution assets within case study Network 2.

Asset	Quantity
Primary substations	15
132-33kV transformers	4
33-11kV transformers	20
132kV OH circuit (km)	134
132kV UG circuit (km)	0
33kV OH circuit (km)	222.5
33kV UG circuit (km)	9

Table 7-14: Network asset details for case study network 2.

In contrast to case study Network 1, case study Network 2 is based on a rural and more sparsely populated area. It should be noted that a very high proportion of the 33kV and all of the 132kV circuits are overhead constructed. The number of primary substation in Network 2 (15) is almost the same as the number of primary substations in Network 1 (18) but the maximum demand power in Network 2 (117 MW in 1998) is much less than half the maximum demand power for Network 1 in the same year (281.7 MW in 1998) demonstrating the characteristic low power density of a rural and sparsely populated area.

The annual energy demand is also based on the maximum demand power and a load factor of 0.593. The same load shape data has been used for Network 2 as for Network 1 since it was not possible to obtain a similar level of detail from the distribution company in whose territory Network 2 lies. The load characteristics for case study network 2 are shown in Table 7-15.

Load Feature	**1998**	**2003**	**2008**	**2013**
Maximum Demand Power (MW)	117.0	124.2	131.8	139.9
Maximum Demand Reactive Power (MVAr)	23.8	25.2	26.8	28.4
Annual Energy Demand (MWh)	608,145	645,569	685,072	727,175

Table 7-15: Annual load details for case study network2.

The annual load growth for Network 2 is identical to the national average load growth described for Network 1 (i.e. 1.2% growth per annum).

The single line diagrams for the case study network 1 and case study network 2 are illustrated in Figure 7-19 and Figure 7-20 respectively. Node numbers are shown alongside the main network nodes and the colour scheme highlights the different voltage levels in the case study networks. The 132kV networks are shown in blue, the 33kV networks are shown in green and the 11kV networks are shown in red. It can be seen that the case studies span from the grids supply points (GSPs) into the 132kV networks and down through the 33kV networks to the 11kV load points at 33/11kV primary substations.

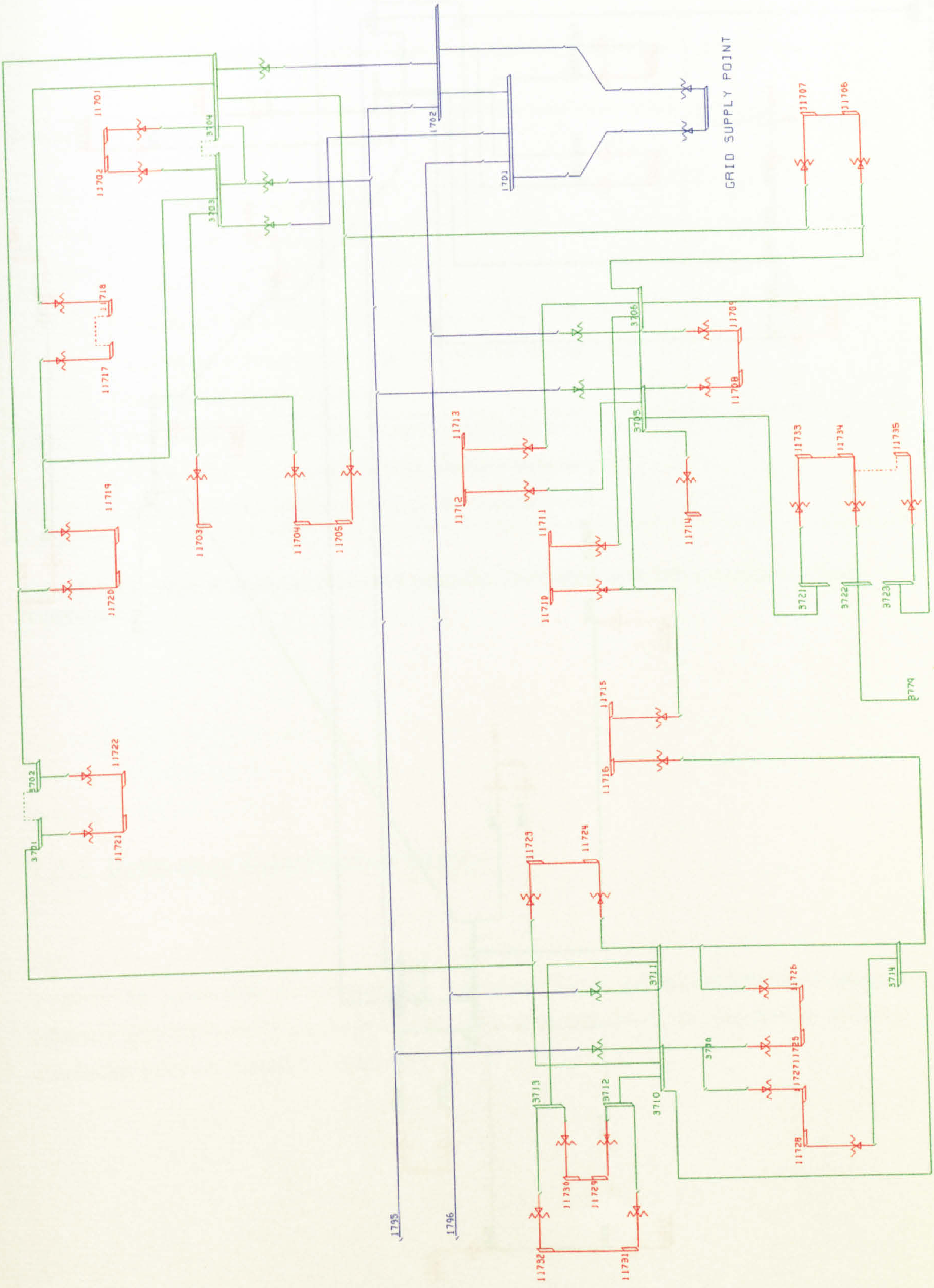

Figure 7-19: Single line diagram for case study Network 1.

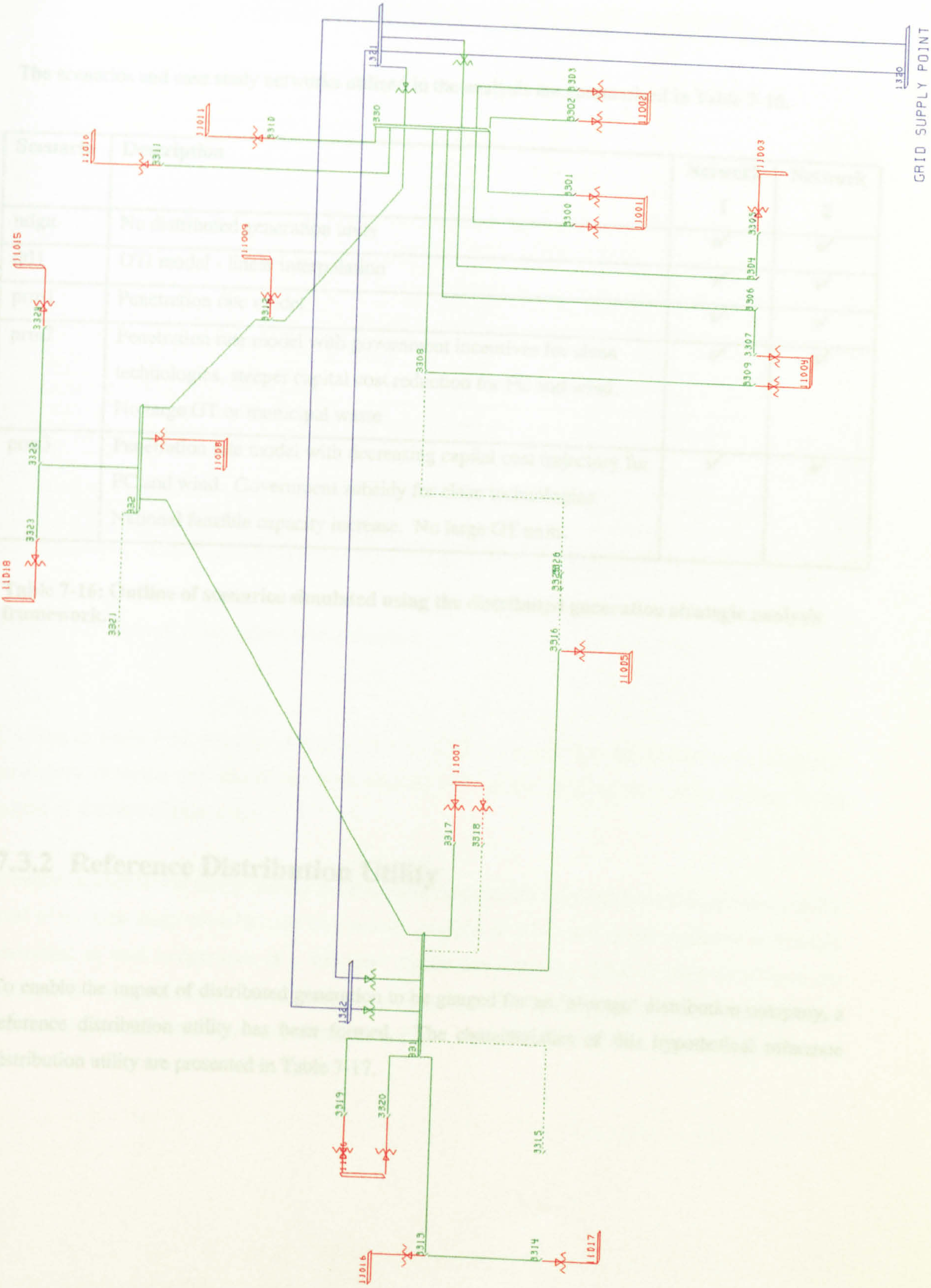

Figure 7-20: Single line diagram for case study Network 2.

The scenarios and case study networks utilised in the analysis are summarised in Table 7-16.

Scenario	Description	Network 1	Network 2
ndgu	No distributed generation units	✓	✓
dtl1	DTI model - linear interpolation	✓	✓
prm1	Penetration rate model	✓	✓
prm2	Penetration rate model with government incentives for clean technologies, steeper capital cost reduction for FC and wind. No large GT or municipal waste	✓	✓
prm3	Penetration rate model with decreasing capital cost trajectory for FC and wind. Government subsidy for clean technologies. National feasible capacity increase. No large GT units.	✓	✓

Table 7-16: Outline of scenarios simulated using the distributed generation strategic analysis framework.

7.3.2 Reference Distribution Utility

To enable the impact of distributed generation to be gauged for an 'average' distribution company, a reference distribution utility has been formed. The characteristics of this hypothetical reference distribution utility are presented in Table 7-17.

Characteristic	Value
Area (sq km.)	16,336
Customers	1,887,714
Adjusted Customer Numbers (for comparisons between companies)	1,862,571
O/H circuit (km)	21,532
U/G circuit (km)	32,672
Transformers	39,010
Transformer (aggregate MVA)	23,306
Supply Interruptions	96
Minutes Lost per Connected Customer	99
Quantity Distributed LV (GWh)	13,224
Quantity Distributed HV (GWh)	5,686
Total Regulated Units Delivered (GWh)	18,910
Units per customer (MWh)	10
Total Distribution Operating Costs (£m 1997/98 prices)	162
Distribution non-operational CAPEX (£m 1997/98 prices)	29
Distribution Load related CAPEX (£m 1997/98 prices)	42
Distribution Non-Load related CAPEX (£m 1997/98 prices)	56
Distribution Total CAPEX (£m 1997/98 prices)	98
Connection Charge Receipts (£m 1997/98 prices)	19
Base Annual Operating Costs (£m 1997/98 prices)	70
Annual Average Capital Expenditure (£m 1997/98 prices)	83
Domestic DUoS Standing Charge (£ /year) - 1998	25
Domestic DUoS Unit Rate (p/kWh) - 1998	1.7
Domestic Average DUoS Charge for 3,300 kWh (p/kWh) - 1998	2.4
Domestic Total DUoS Charge for 3,300 kWh (p/kWh) - 1998	80
Distribution Operating Profits (1996/97) 1996/97 prices (£m)	125
Distribution Losses (LV and HV) 1997/98 (% of Units Distributed)	7.1

Table 7-17: Average distribution utility data set.

The data in Table 7-17 will appear in a number of the steps involved in the formation of distributed generation scenarios and also in the final analysis and interpretation of the results relating to the impact of distributed generation.

A reference distribution utility enables the scaling of national and regional generation scenarios to the level of the case study networks and also enables analysis of the extent of the impact of distributed generation on each budget item of a 'life-size' distribution company. Both of these benefits of the reference distribution utility will enable greater awareness of the significance of the results from the distributed generation strategic analysis framework.

7.4 Power System Analysis of Distributed Generation Scenarios

The results presented in this section detail the physical impact of each scenario of distributed generation on the performance of the network. The comparative effect of scenarios with distributed generation to the 'no distributed generation units (*ndgu*)' scenario is also detailed. Finally the results of the power system simulations are translated as distributed generation value by means of unit costs for plant and services.

It is emphasised that only a selection of results are illustrated in the following subsections to show the general effect of distributed generation on the distribution networks under study. These results illustrate, relatively clearly, the general trends discovered in the complete set of results obtained from the simulation of each scenario in each case study network in each year.

The computer time taken to conduct simulations of scenarios is very short and with a fully automated process, as proscribed in the specification of the strategic analysis framework, there is really no limit to the number of scenarios simulated and analysed. With an extended set of scenarios and analytical modules it would be even more important to streamline the production of charts, graphics and tables detailing the results and providing the information needed by decision makers.

7.4.1 Results of Power System Simulations

7.4.1.1 Utilisation of network capacity ('circuitflows' analysis module)

Selected results from analysis conducted according to the process described in section 6.3.3.1 are presented in this section.

Figure 7-21 and Figure 7-22 give an overall view of the system peak period reduction in utilisation in the 132kV and 33kV circuits in Network 1 for the years 2003 and 2013 respectively.

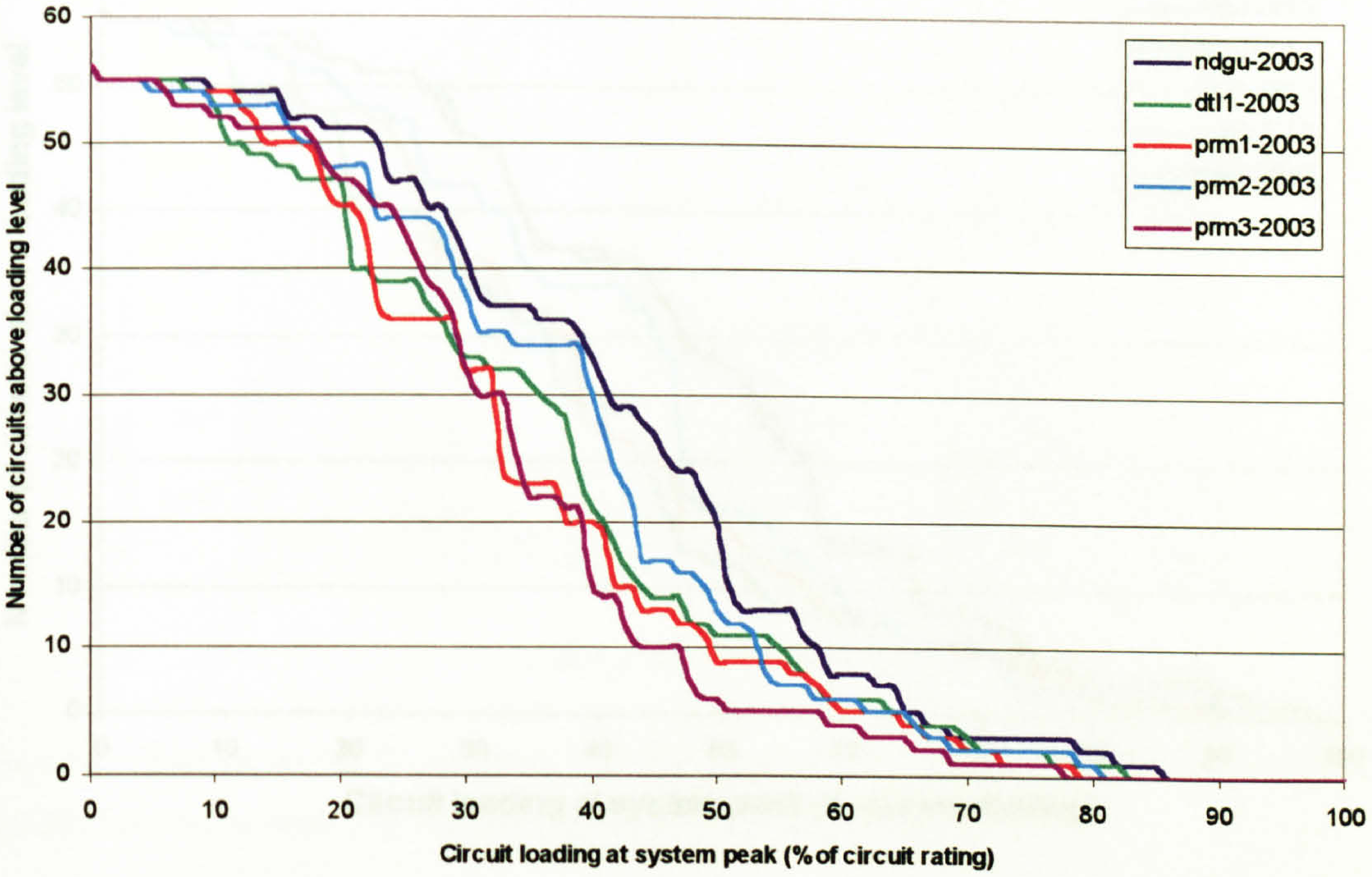

Figure 7-21: Utilisation of network capacity - Network 1 (2003).

The circuit utilisation curves seem to indicate that there is, in general, up to ten percent reduction in the utilisation of each circuit due to distributed generation located nearer to load points (Figure 7-21).

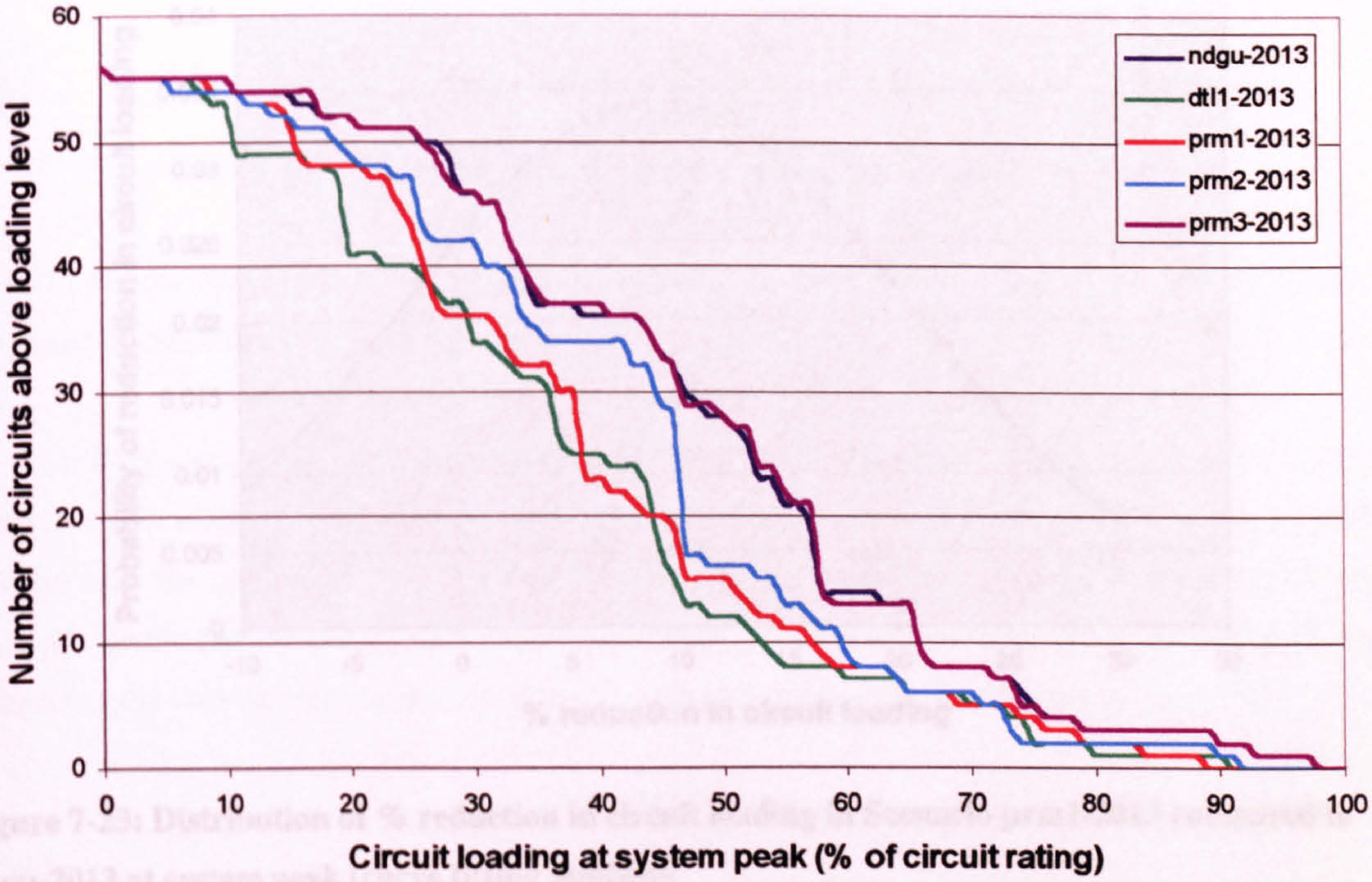

Figure 7-22: Utilisation of network capacity - Network 1 (2013).

Once more, up to a ten percent reduction in circuit utilisation is evident for the year 2013 (Figure 7-22). Scenario dtl1 has more generation capacity than the three 'prm' scenarios in the year 2013 and provides the greatest reduction in circuit utilisation. It is interesting to note that the ten percent reduction is spread across more circuits rather than the percentage reduction becoming larger on a small number of circuits. This results from the tendency to spread new generation units across the network in later years, thus reducing the load on more circuits.

The change in individual circuit loading at system peak for Network 1 is illustrated in Figure 7-23 below. The characteristic is produced for the differential in circuit loading for scenario prm1 compared to scenario *ndgu* in year 2013. The average reduction in circuit loading is 9.11% and the standard deviation is 11.6%.

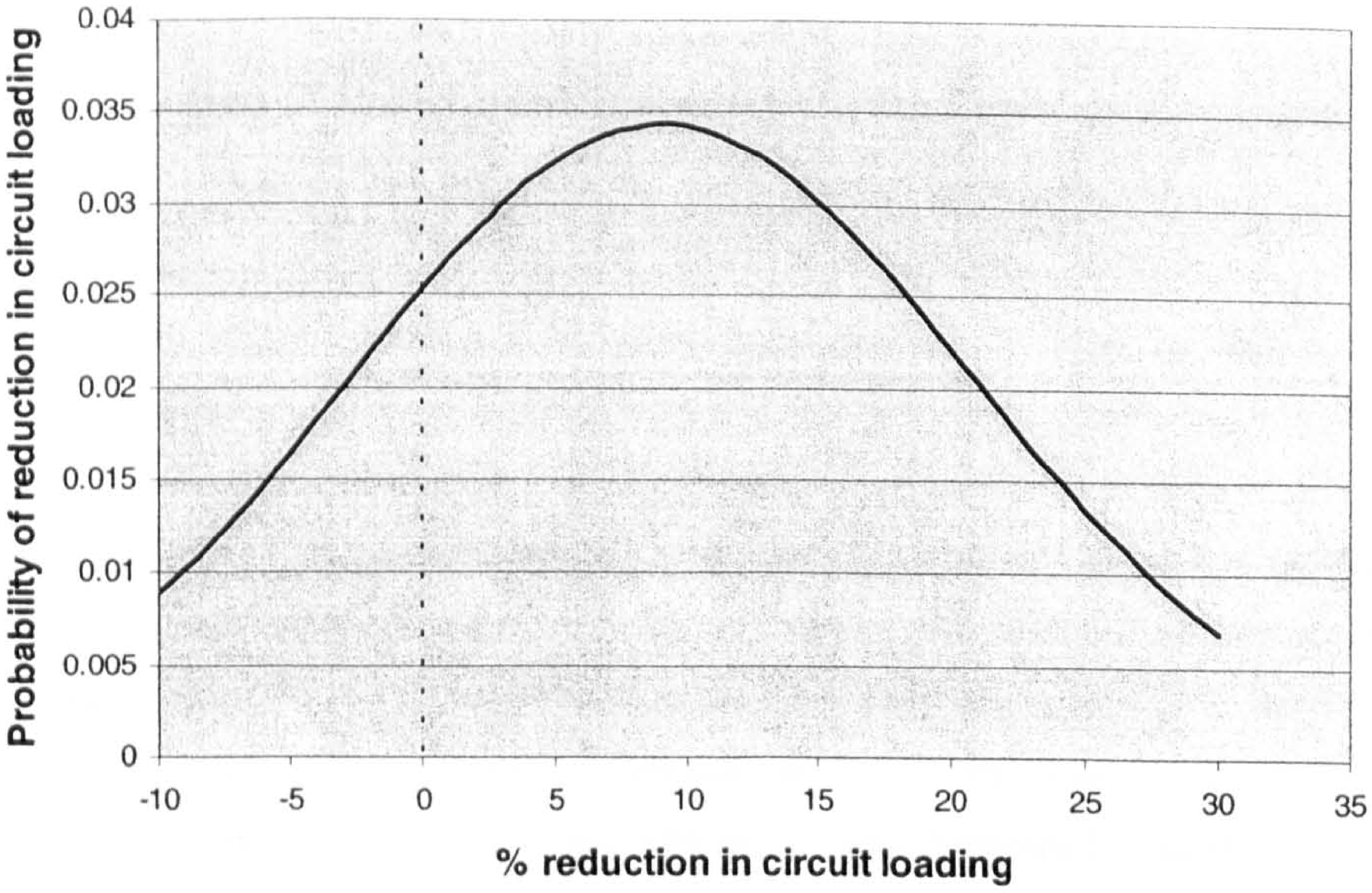

Figure 7-23: Distribution of % reduction in circuit loading in Scenario prm1-2013 compared to ndgu-2013 at system peak (curve fitting applied).

The maximum reduction in circuit loading was 42% (from 57% to 15%) on a 33kV circuit. The minimum reduction was –7.6% (thus the maximum increase in circuit loading was 7.6%).

In addition to the general reduction in circuit loading, the reduction in peak loading level below a reinforcement requirement threshold is a key output from this module. In addition to the general levels of circuit utilisation the reduction of loading on circuits which are loaded at close to full capacity can free circuit capacity for further load growth without upgrade. If the general level of 10% reduction in circuit loading was applied to a peak constrained circuit, upgrading of the circuit could be deferred by around seven years based on load growth of 1.2% per annum.

The results of these savings are incorporated directly into the financial analysis described in section 7.7.

7.4.1.2 Utilisation of transformer capacity ('transflows' analysis module)

Selected results from analysis conducted according to the process described in section 6.3.3.2 are presented in this section.

To simplify the analysis of transformer capacity utilisation (and also due to the low number of bulk supply transformers and the problems of drawing any meaningful conclusions from such a small sample) only the primary 33/11kV transformers in the case study networks will be assessed. Figure 7-24 illustrates the effects of distributed generation on transformer loading at system peak by comparing the loading level on the transformers with and without distributed generation.

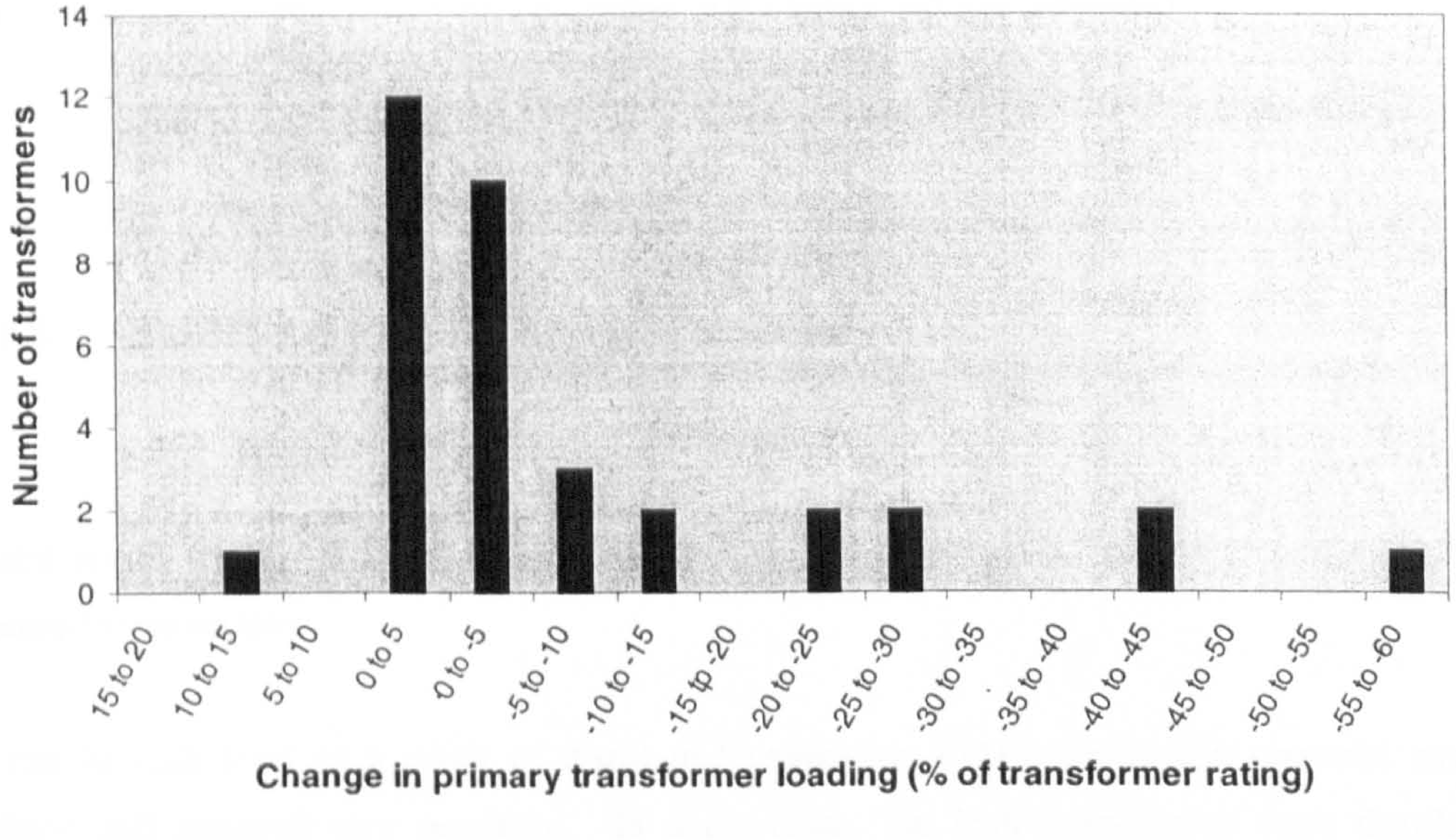

Figure 7-24: Change in primary transformer loading at system peak between scenario prm3-2008 and ndgu-2008 in Network 1.

Several points can be made from this result. The majority of the primary transformers in Network 1 experience little change in their peak loading level from cases with (*prm3*) and without (*ndgu*) distributed generation. Figure 7-24 shows that the majority of transformers experience a change in loading in the '0% to 5%' and '0% to –5%' ranges. Inspection of the data reveals that many of the transformers experience no change in loading as a result of distributed generation. The power flow through a primary transformer only changes from scenario to scenario if generation is located on the low voltage side of the transformer. This highly localised effect is different from the 33kV and 132kV circuit loading effects where the general loading levels change on most circuits due to interconnection of circuits.

The high reductions in transformer loading for a small number of transformers also arise from the substation specific effect of generation. The reduction in transformer loading can be directly attributed to particular generation units located on the low voltage side of the transformer. This specificity of effect is also illustrated in the pairings of transformers in Figure 7-24 (seen in the '-10% to –15%', '-20% to –25%' and '-40% to –45%' bars) which represent pairs of transformers at the same primary substations.

These issues are interesting from the point of view of classifying the effects of distributed generation into *asset specific effect* (e.g. the reduced loading on a particular transformer) and *general network effect* (e.g. the spread reduction in circuit loading in the higher voltage networks).

7.4.1.3 Fault level ('faults' analysis module)

Selected results from analysis conducted according to the process described in section 6.3.3.3 are presented in this section.

The rise in fault level as a result of distributed generation within distribution networks can be simulated and assessed very precisely. In some cases, the fault contribution from distributed generation can push fault levels beyond the withstand rating of distribution plant. The simulations herein have concentrated on the effect of fault level changes on switchgear. Fault levels have been estimated from simulations in each scenario for each year. Where the fault level exceeds the withstand rating of switchgear, this is flagged as an area for operational changes or upgrading of the switchgear plant. Upgrading requirements for switchgear are dealt with in the utility financial analysis module (section 7.7).

Figure 7-25 illustrates the number of 33kV switchgear units in Network 1 where the fault withstand rating has been exceeded in the simulation. Scenarios *ndgu*, *prm1* and *dtl1* are charted.

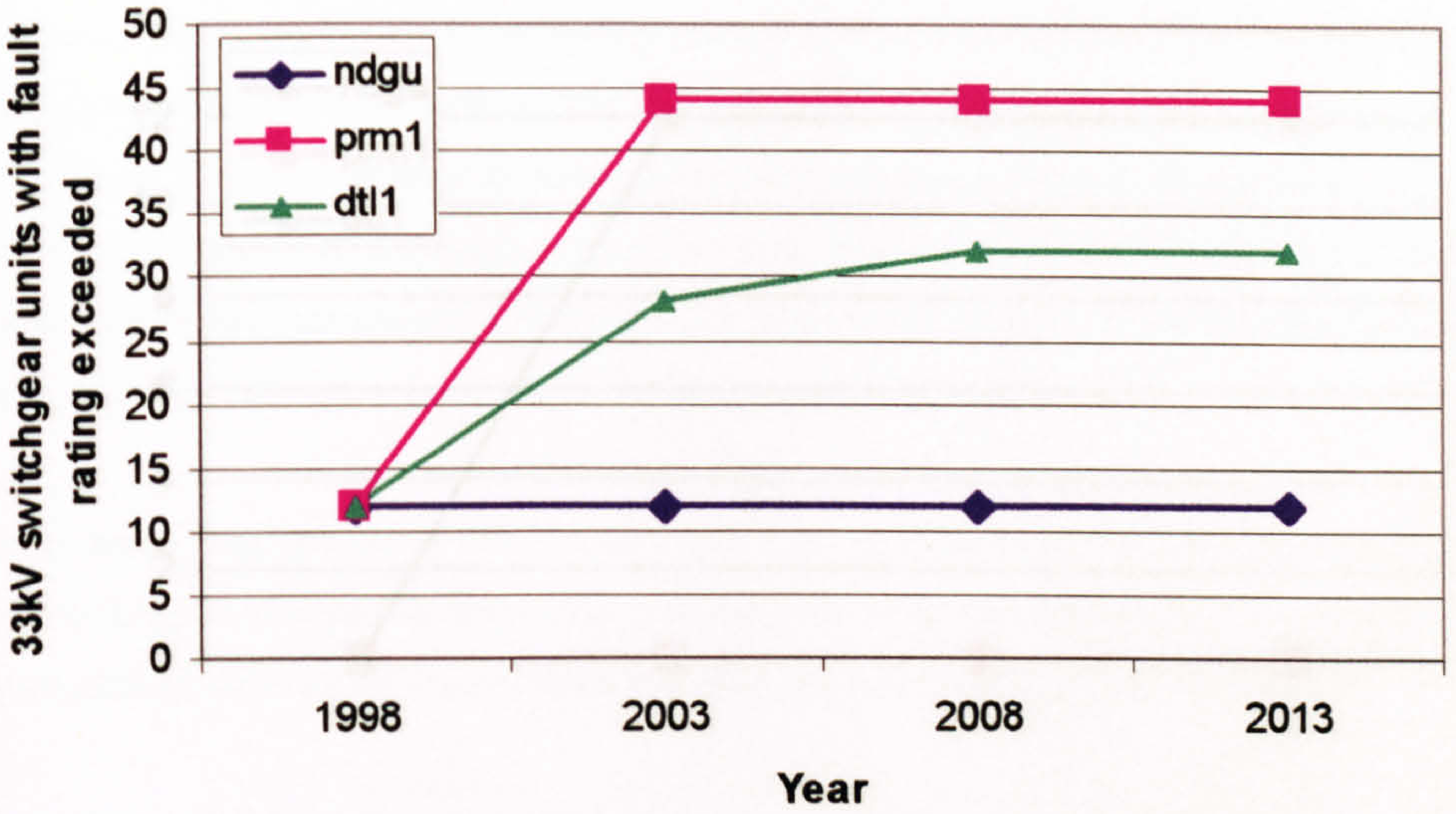

Figure 7-25: Network 1 fault rating constrained 33kV switchgear units.

In this case the number of 33kV switchgear units constrained by fault rating for scenarios *prm2* and *prm3* are identical to *ndgu*. There are 89 units of 33kV switchgear in Network 1. The results for 132kV and 11kV switchgear are less illustrative of the effects of distributed generation on fault level.

The curve of fault level exceeded switchgear units for scenario *dtl1* illustrates an interesting effect. While the installed capacity of generation increases more or less linearly through the four years analysed, the curve for switchgear units requiring upgrading grows quickly to begin with and then flattens off. The initial incline is illustrative of the fact that no generation is assumed in year 1998 while in fact there is a residual capacity in the network in this year. However, the interesting point is the flattening of the curve between 2003 and 2008 but particularly between 2008 and 2013. This characteristic is evident in both Figure 7-25 and Figure 7-26 and suggests that, beyond a certain capacity of distributed generation within the network, the problem of having to replace switchgear due to fault level increases may ease off.

Figure 7-26 shows the results for 33kV switchgear for Network 2.

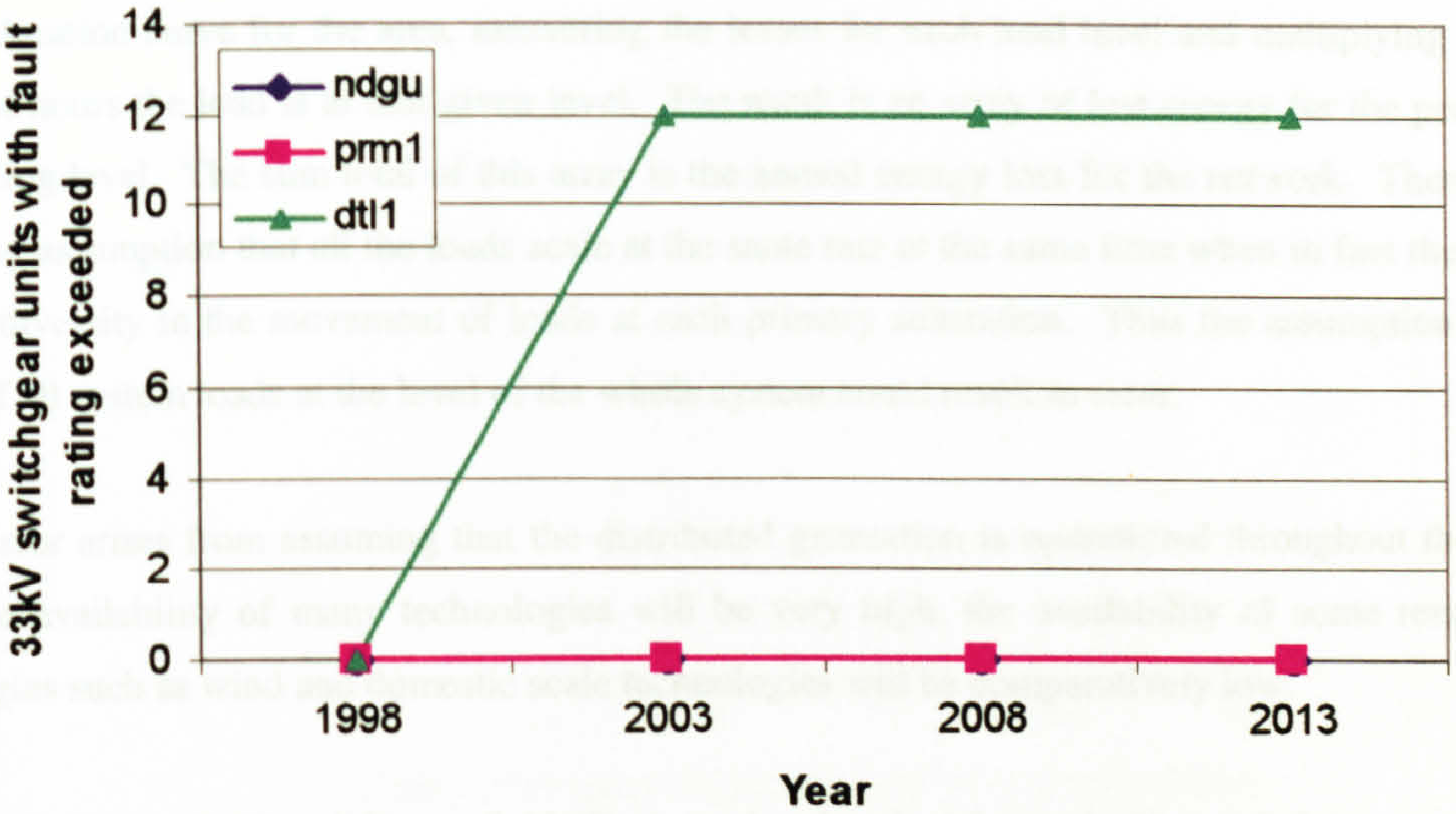

Figure 7-26: Network 2 fault rating constrained 33kV switchgear units.

There are 22 units of 33kV switchgear in Network 2. The result for scenario *ndgu* is identical to *prm1* and is hidden in the view in Figure 7-26.

It is acknowledged that distribution companies try to keep fault levels at higher levels as there are benefits for customer power quality in doing so. As a result of this, it may be possible to reduce the number of fault rating constrained switchgear units by reversing any operational measures put in place to raise fault level before the possibility of distributed generation connection arose.

7.4.1.4 Electrical losses changes ('losses' analysis module)

Selected results from analysis conducted according to the process described in section 6.3.3.4 are presented in this section.

The annual electrical losses in the system are simulated through scaling the loads in accordance with the load duration curve for the area, measuring the losses for each load level and multiplying by the number of hours the load is at that given level. The result is an array of lost energy for the period of each loading level. The sum total of this array is the annual energy loss for the network. There is an underlying assumption that all the loads scale at the same rate at the same time when in fact there will be some diversity in the movement of loads at each primary substation. Thus the assumption of the scaling of all system loads at the level of the whole system could result in error.

Further error arises from assuming that the distributed generation is operational throughout the year. While the availability of many technologies will be very high, the availability of some renewable technologies such as wind and domestic scale technologies will be comparatively low.

Figure 7-27, Figure 7-28 and Figure 7-29 illustrate the electrical losses in Network 2 in years 2003, 2008 and 2013 respectively. The scenarios presented are *ndgu*, *prm2*, *prm3*, *prm1* and *dtl1* in order of increasing magnitude of distributed generation capacity.

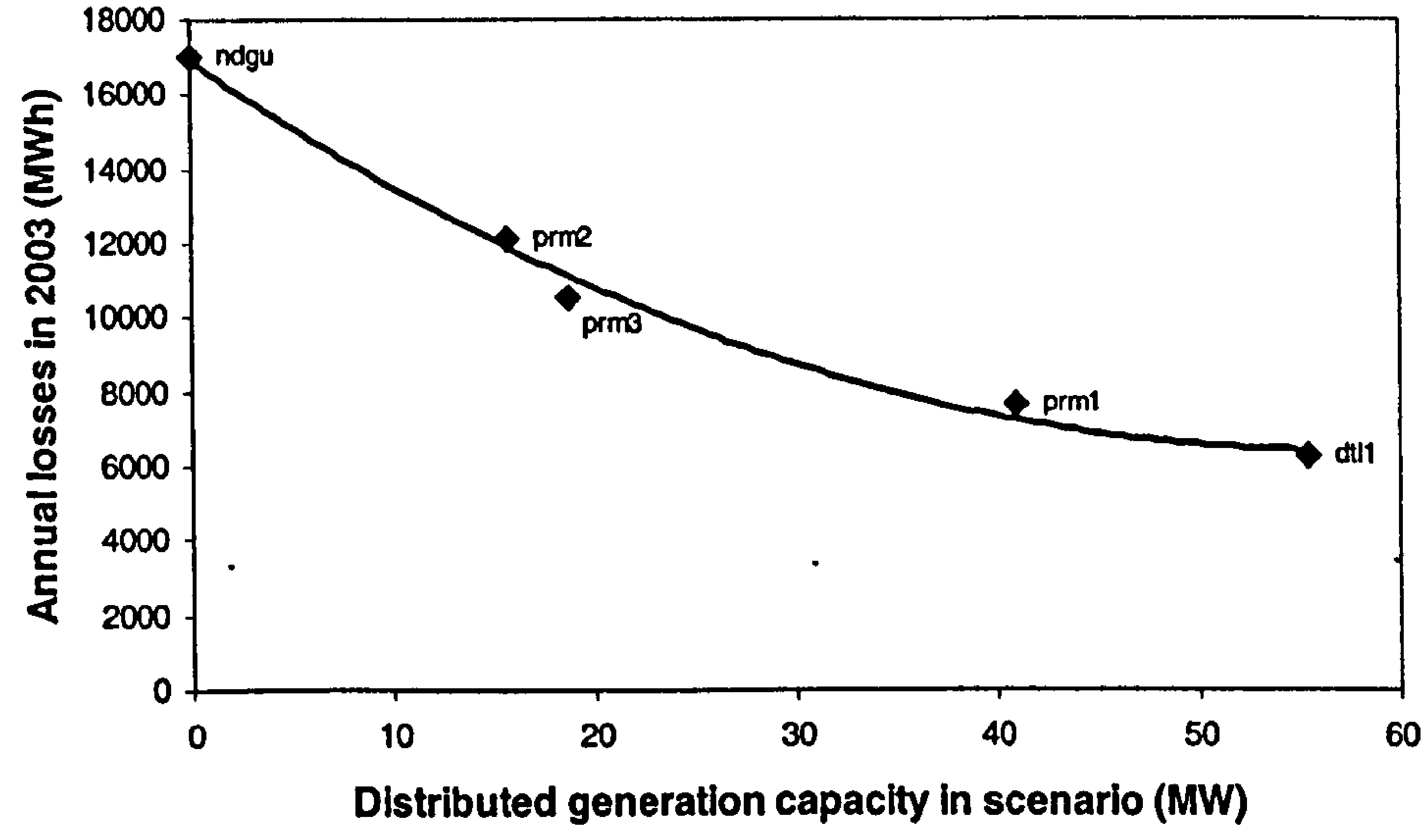

Figure 7-27: Annual energy losses for Network 2 in 2003 under various scenarios.

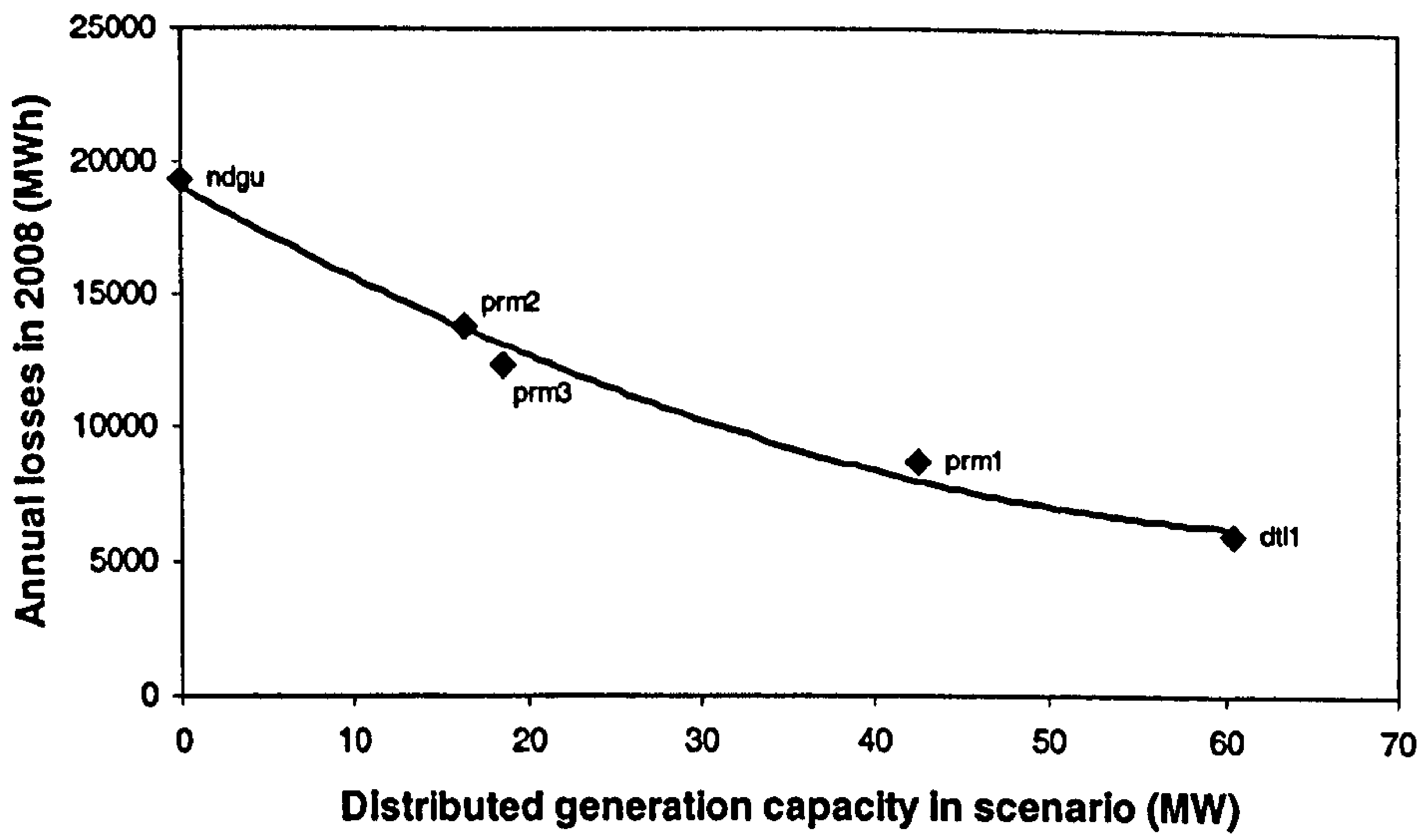

Figure 7-28: Annual energy losses for Network 2 in 2008 under various scenarios.

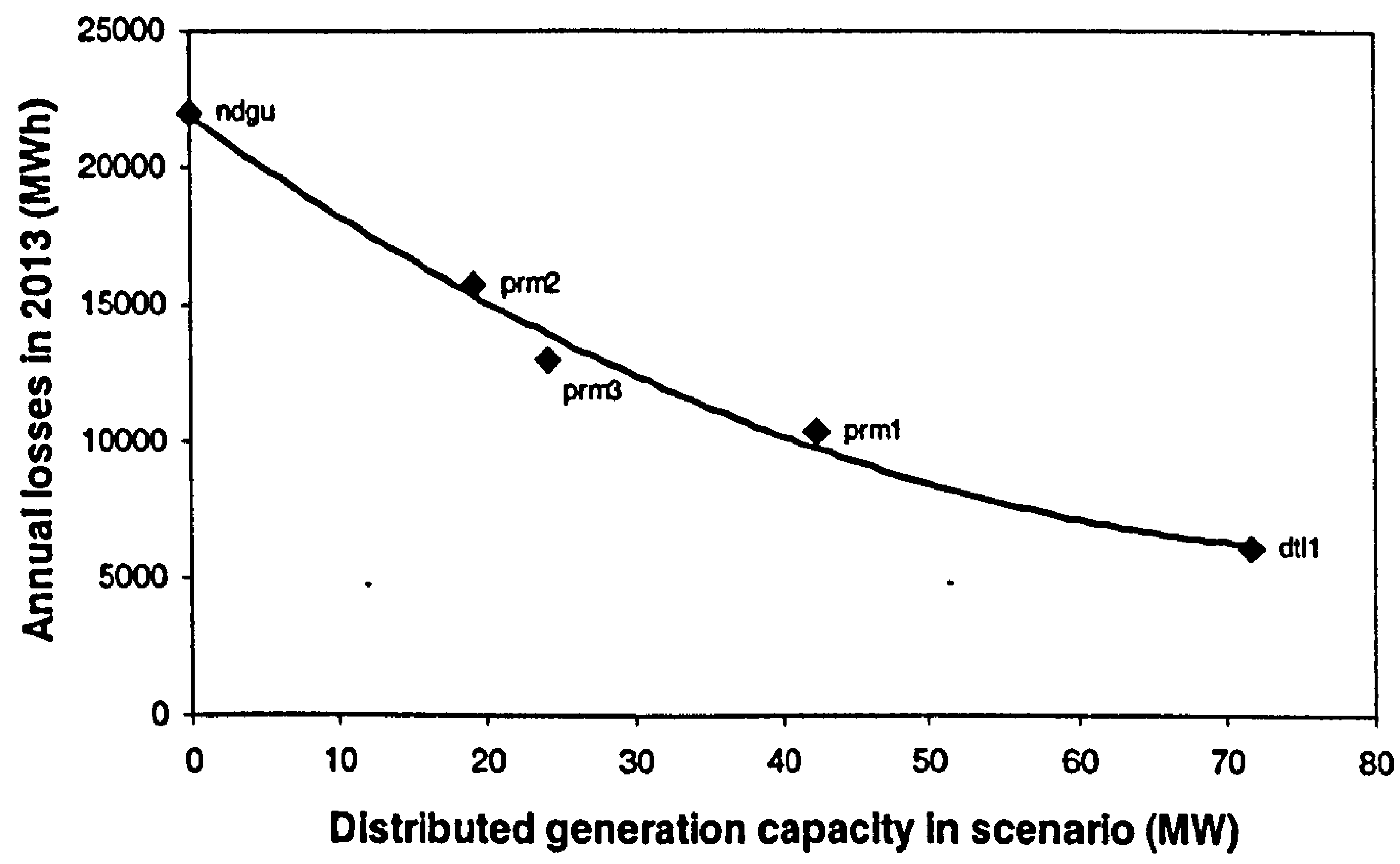

Figure 7-29: Annual energy losses for Network 2 in 2013 under various scenarios.

A second order polynomial trend line (to represent the square rule for losses) has been overlaid on each chart to illustrate the general trend in electrical losses. It is clear that the simulated losses in Network 2 decrease with increasing levels of distributed generation. The magnitudes of the reductions in losses on each chart for Network 2 (and for Network 1) are substantial. If the reduction in losses across each of the scenarios is taken as being in the range 5000 MWh to 10,000 MWh then the value of the losses at the prevailing average annual Electricity Pool price (around 25 £/MWh) values the reduction in losses as £125,000 to £250,000 per year. The distribution company does not pick up this benefit in its entirety but rather is allowed to collect more revenue from distribution system users in line with increasing system efficiency. The precise method of incentives for electrical losses is described in section 3.3.6.7 while the benefit from losses reduction is developed in Table H-5 and Table H-6.

A similar picture emerges for Network 1. Figure 7-30, Figure 7-31 and Figure 7-32 show the annual losses for each distributed generation scenario in the years 2003, 2008 and 2013 respectively.

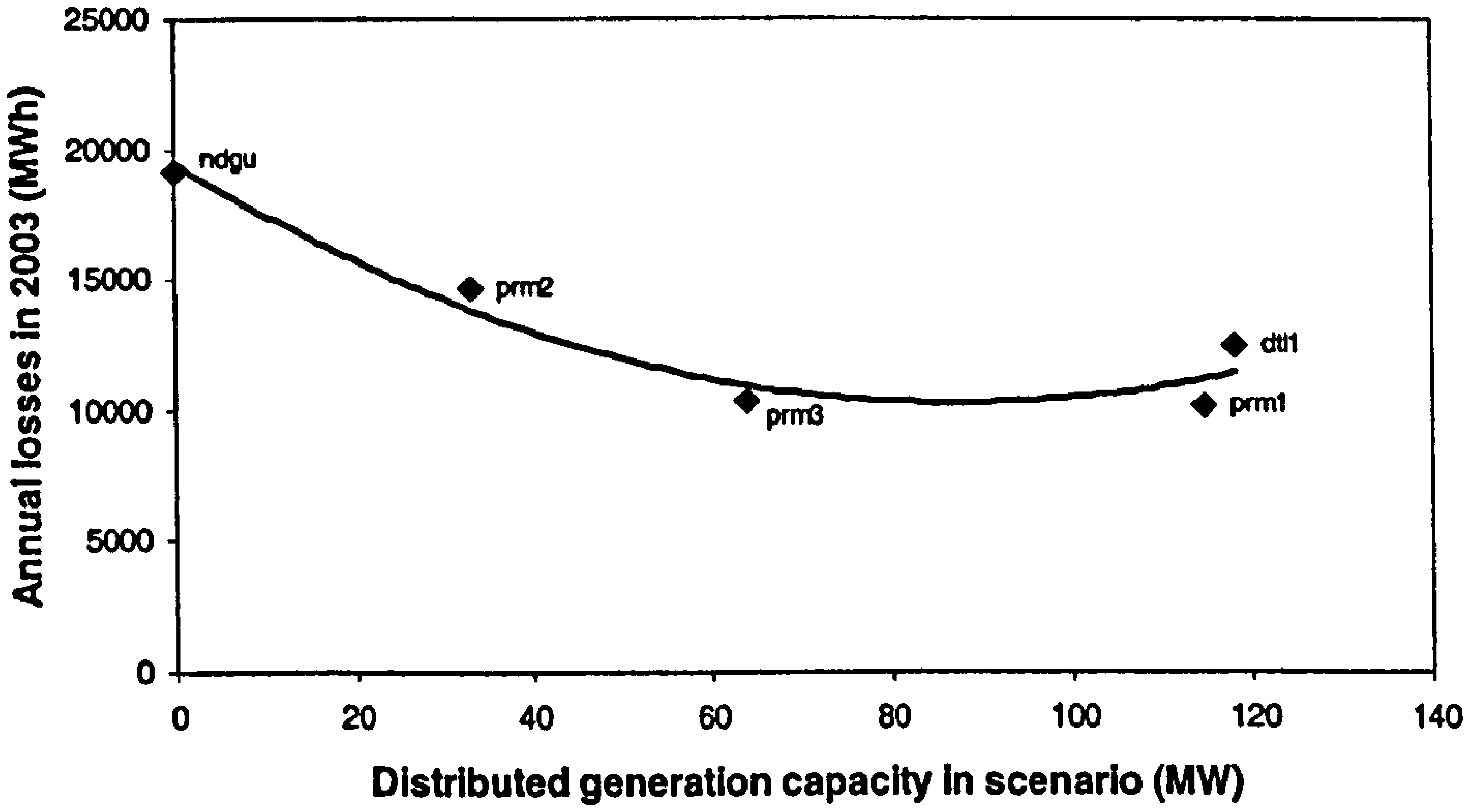

Figure 7-30: Annual energy losses for Network 1 in 2003 under various scenarios.

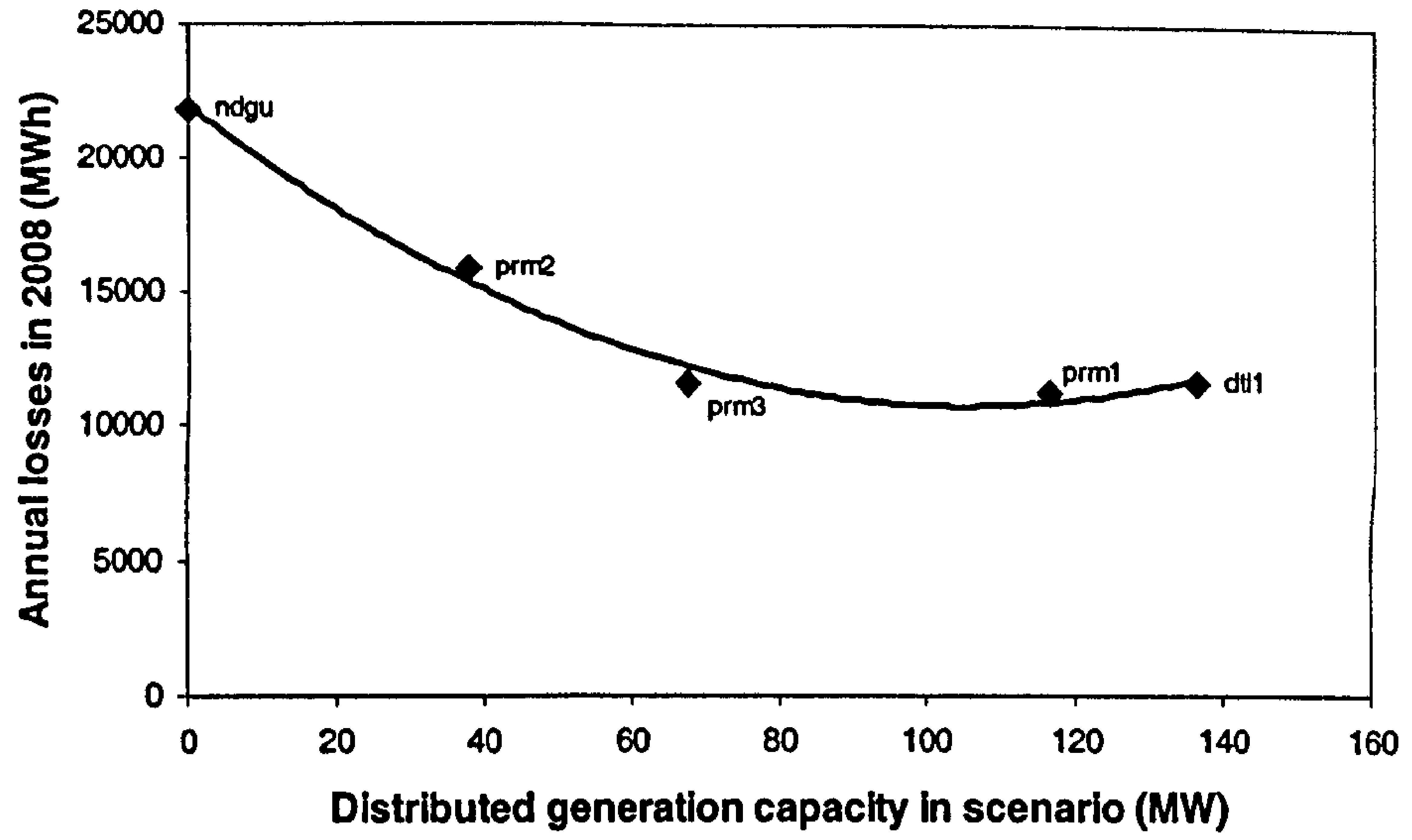

Figure 7-31: Annual energy losses for Network 1 in 2008 under various scenarios.

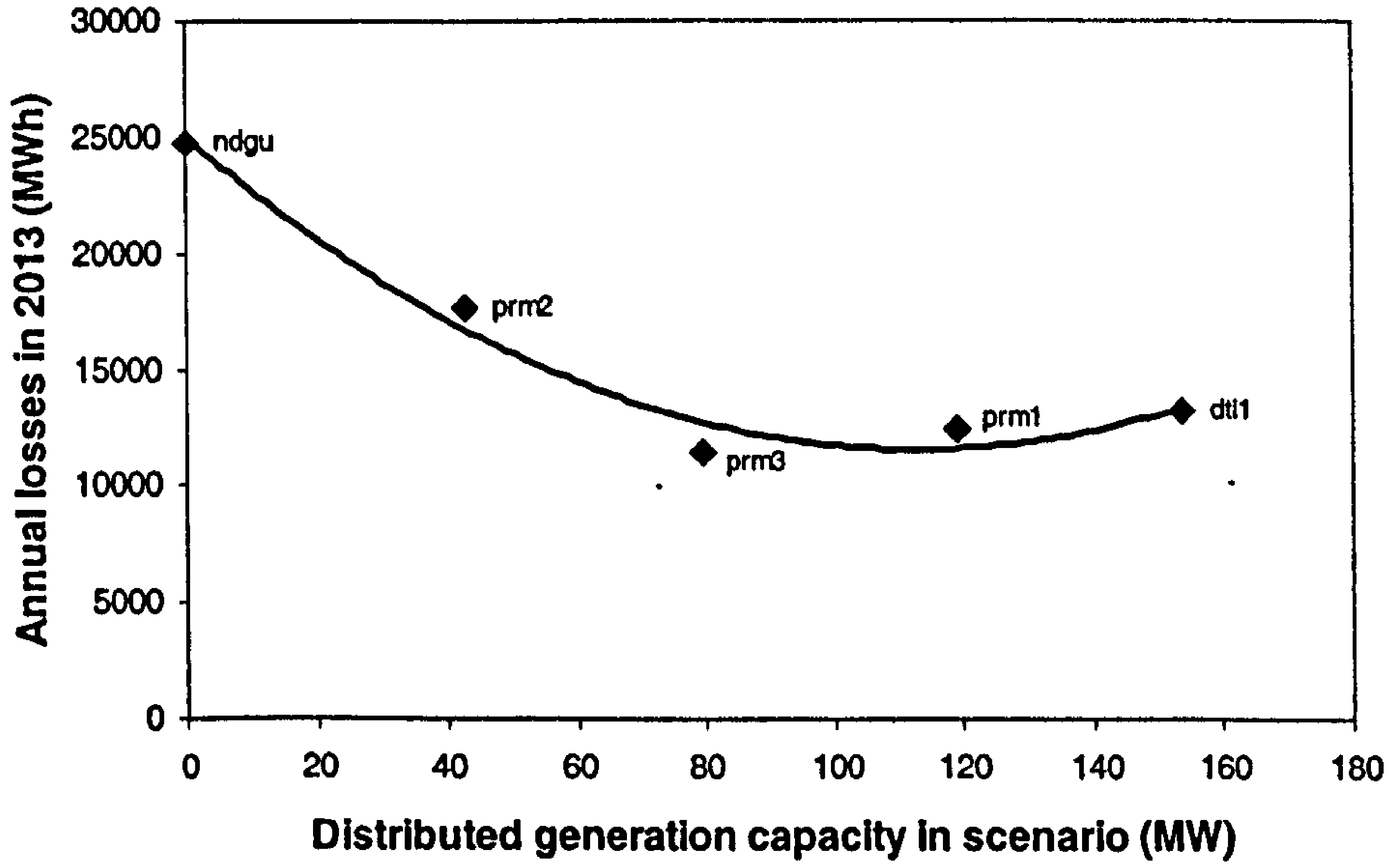

Figure 7-32: Annual energy losses for Network 1 in 2013 under various scenarios.

The effects of distributed generation on overall distribution system losses are evident from the results outlined above. The annual losses in the distribution system decrease with increasing distributed generation capacity for smaller penetrations of distributed generation. The trend lines show that system losses increase with increasing distributed generation capacity beyond a certain threshold capacity of distributed generation. The relationship between distributed generation capacity and losses is not as simple as these charts suggest. However, there is a clear relationship of decreasing losses throughout the system with increasing distributed generation capacity up to a threshold.

The position of the threshold (beyond which any increase in distributed generation capacity results in an increase in system losses) depends on generation location, network topology and design characteristics, generation operational profile and generation connection design. Some of these parameters are subject to simplifications within this study and therefore the true influences on the position of the threshold can not be identified definitively. However, the general position of the breakpoint is a general characteristic of the network as indicated by the results presented in Figure 7-27 to Figure 7-32 above. The threshold for case study network 1 lies at a distributed generation penetration of around 35% of system peak capacity while the threshold for case study network 2 lies beyond 50% (the actual threshold not attained in any of the scenarios simulated). The characteristics of the networks and the likely connection points for distributed generation leading to these threshold values are important considerations in the formation of distribution planning, operations and charging policies.

7.4.2 Power system analysis results summary

The summaries of the physical impact of distributed generation on the case study networks (Table H-1 and Table H-2 in Appendix F) must be viewed with reference to the characteristics of the case study distribution networks which are outlined in Table 7-12 and Table 7-14 for Network 1 and Network 2 respectively.

For example, the total length of 33kV underground cable in Network 1 is 161.1km. Against this we can see that circuit length where the power flow has exceeded the security rating of the cable in 1998 is 20.32km and for scenario *ndgu-2013*, 75.63km. For the scenario *dtl1-2013*, the length of 33kV underground circuit where the power flow has exceeded the security rating of the cables is 37.83km. This brief summary of results tells us that the secure capacity criteria used in this analysis could be different from that used by the asset manager of this network since 20.32km of 33kV underground circuit had exceeded the rating in 1998 which is the base year for this model. A second point to note is the scale of the potential saving in reinforcement of the network. In the year 2013, the 33kV underground cable length which has exceeded its secure limit is 75.63km with no distributed generation and 37.83km where the maximum scenario (*dtl1-2013*) for distributed generation is assumed. While there are many factors in play, some of which have been simplified in this analysis, the magnitude of the potential savings are evident. In this case, 75.63 minus 37.83 yields a deferred capacity need in the 33kV underground network of 37.8km. Such comparative analysis between scenarios and between years is described in section 7.5.

7.5 Comparative analysis of power system analysis results

Comparisons of the impact of distributed generation from year to year and from scenario to scenario are provided in Table H-3 and Table H-4 for Network 1 and Network 2 respectively.

The method of comparison varies slightly for each category of results to reflect the basis on which value accrues from the effect of distributed generation on the network. In circuits and transformers, the saving from a deferral of reinforcement is made each year in reduced capital costs. Hence, the reinforcement required with distributed generation is compared to the reinforcement requirement in the same year without distributed generation. When new switchgear is required as a result of distributed generation, its installation is permanent and, so, the comparison is made between the volume of switchgear in one study year and the previous period for the same scenario.

The power (P) losses value for any year and scenario is compared with the P losses in the base year, 1998. This reflects, the value which accrues from P losses in regulated revenue for the distribution company. The value of reduced losses lasts for 10 years before being counted into the baseline for further electricity loss comparisons. The value of losses reduction actually declines each year within a ten-year period as the allowable losses (against which the actual annual losses are compared) takes the average value of losses over the preceding ten years on a rolling ten year basis. This additional complexity has not been factored into this analysis.

7.6 Interpretation of impact of distributed generation on network performance

Four areas of the impact of distributed generation on the distribution network have been simulated using generation scenarios, power network models and power system simulation software. The key results have been outlined in section 7.4.1.

In summary:

- Distributed generation results in generally lower utilisation of installed circuit capacity.
- Distributed generation results in generally lower circuit loading at peak demand periods.
- Transformer loading generally decreases with increasing levels of distributed generation.
- Specific circuits and transformers experience large changes (mainly reductions) in loading level due to distributed generation.
- Fault level increases in 33kV networks can result in large numbers of switchgear rating violations producing the need for plant upgrades.
- Switchgear rating violations appear to have generation capacity thresholds beyond which a comparatively large number of switchgear upgrades are required.
- System annual energy losses decrease for generation penetration capacities up to between one third to one half of system peak demand.
- System losses increase when distributed generation capacity in a network rises above a threshold which equates to between one third and one half of system peak demand.
- Reactive power losses benefit from the presence of distributed generation in a similar manner to active power losses but are not investigated further in this analysis.
- Each of the results for loading levels, fault levels and losses are subject to aggregated network-wide effects and plant specific effects.
- Aggregate effects produce a benefit or cost across the whole system resulting from the sum effect of all or part of the distributed generation portfolio.
- Plant specific effects result in benefits or costs linked to specific plant items.
- Specific effects have a more pronounced effect on distribution plant with changes of tens of percent in operating point due to single generating units.
- Aggregate effects result in changes of a few percent in operating point due to the relatively small capacity of individual generating units compared to the whole system.

The effects from these physical phenomena on distribution utility finances are investigated in section 7.7.

7.7 Financial Analysis of Distributed Generation Scenarios

The following set of results has been developed utilising the distributed generation value function specified in section 5.5.3. The results are based on the distributed generation scenarios detailed in section 7.2 with their corresponding power system impact as described in section 7.4.

7.7.1 Analysis of results with distributed generation value function

The monetary value of the physical effects of distributed generation are derived using the unit costs from Table 6-4 and are presented in Table H-5 and Table H-6 for Network 1 and Network 2 respectively.

The figures presented in Table H-5 and Table H-6 are not particularly meaningful in their own right. Further analysis is required to ascertain the true magnitude of the impact of distributed generation on distribution utility finances. Table H-5 and Table H-6 do show that the value associated with distributed generation is quite variable across different scenarios and in different years. The results for Network 2 show limited impact in some areas where a larger impact is evident for Network 1. For example, 132kV overhead line and 33kV underground cable reinforcement deferral have associated large values in Network1 while not appearing in the analysis for Network 2. These effects have as much to do with the characteristics of the network as with the effect of distributed generation. Table H-6 shows that for Network 2, the effect of the switchgear requirement at £1,200,000 far outweighs any other effect for scenario *dtl1* in 2003.

7.7.2 Financial impact of distributed generation

The individual values of the impact of distributed generation on the distribution network are allocated to the primary budget items for a typical distribution company. These budget allocations are presented in Table H-7 and Table H-8 for Network 1 and Network 2 respectively.

Figure 7-33 and Figure 7-34 have been extracted from the lower row of Table H-7 and Table H-8 respectively. These charts show the changes in value arising from distributed generation through the four study periods from 1998 to 2013.

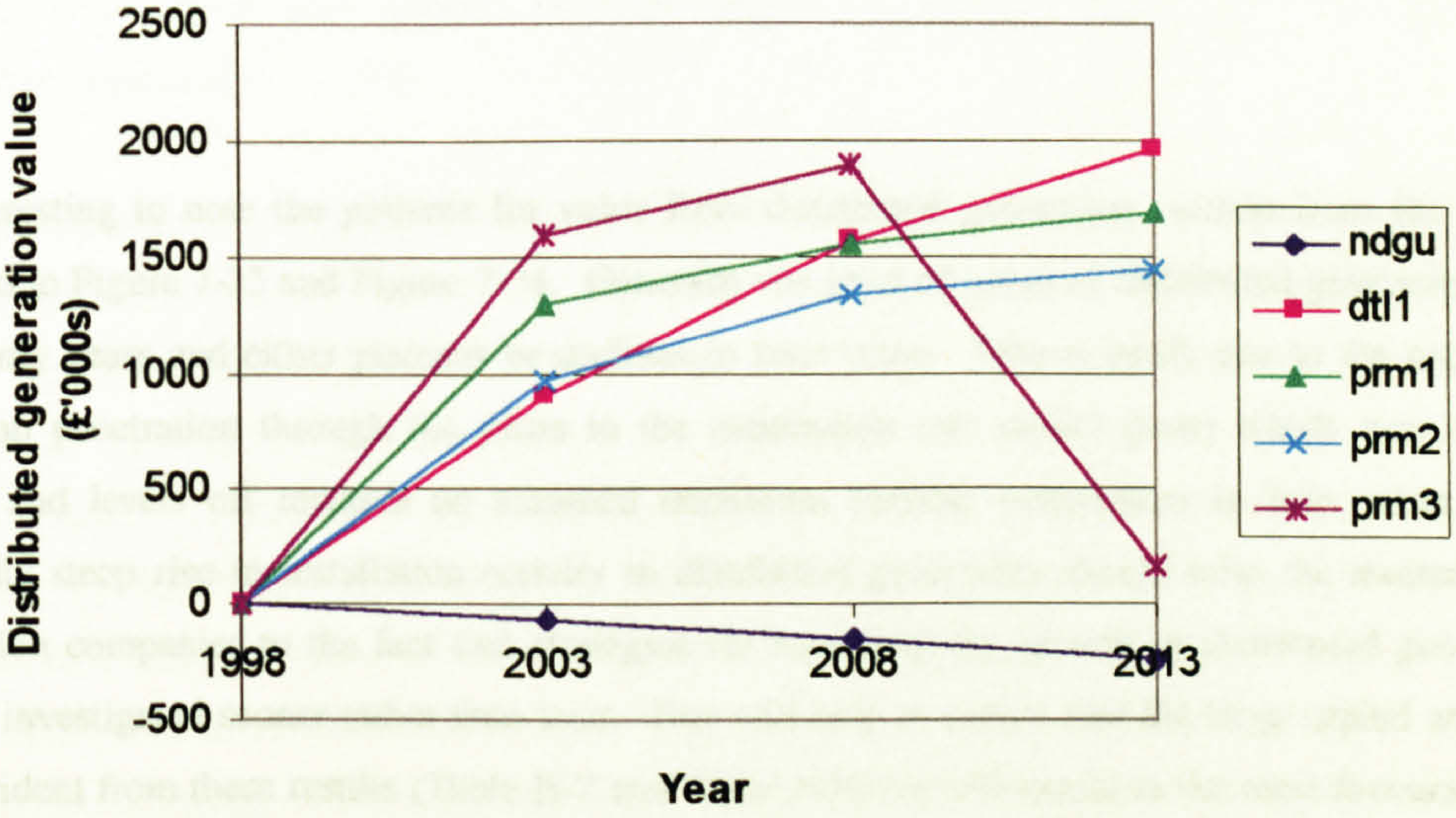

Figure 7-33: Distributed generation value for case study network 1 (£'000s).

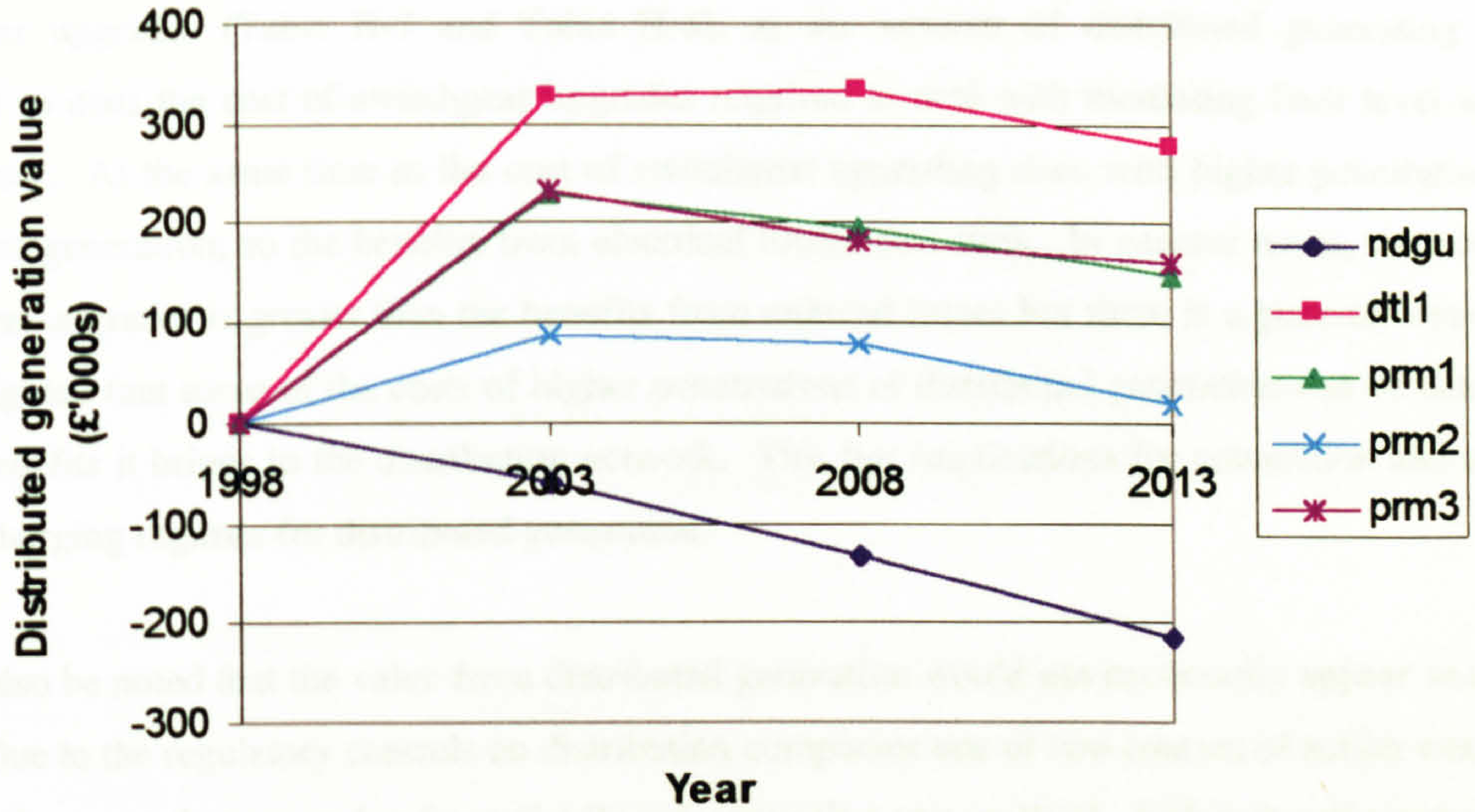

Figure 7-34: Distributed generation value for case study network 2 (£'000s).

It is interesting to note the patterns for value from distributed generation evident from the results presented in Figure 7-33 and Figure 7-34. Generally the level of value of distributed generation rises in the early years and either plateaus or declines in later years. This is partly due to the pattern of generation penetration through the years in the penetration rate model (*prm*) which rises steeply initially and levels off towards an assumed maximum feasible penetration in later years. The potentially steep rise in installation activity in distributed generation should raise the awareness of distribution companies to the fact that strategies for managing the growth in distributed generation must be investigated sooner rather than later. This will help to ensure that the large capital and cash flows evident from these results (Table H-7 and Table H-8) are influenced to the most favourable (or least detrimental) position.

It should be noted that the switchgear upgrading value appears twice in each column: once as a capital expenditure cost and once as a connection revenue receipt. This reflects the treatment of generation connection costs which are fully charged to the generation developer.

The load related reinforcement ($\Delta C_{C.LRRt}$) item in Network 1 reduces to zero for *prm3* in the year 2013. The potential benefits of load reinforcement deferral from distributed generation experienced in earlier years have been outstripped by load growth by 2013.

It is interesting to note that, although the benefit of reduced losses does not equate to the cost of switchgear upgrades (Table H-7 and Table H-8), as the number of distributed generating units increases so does the cost of switchgear upgrades required to deal with increasing fault level within the network. At the same time as the cost of switchgear upgrading rises with higher penetrations of distributed generation, so the benefits from electrical losses also rises. In general terms, the costs of switchgear upgrades is greater than the benefits from reduced losses but there is a general concept to be highlighted that some of the costs of higher penetrations of distributed generation can be balanced by the benefits it brings to the distribution network. This has implications for connection and use of system charging regimes for distributed generation.

It must also be noted that the value from distributed generation would not necessarily appear as utility profit. Due to the regulatory controls on distribution companies one of two courses of action would be taken in the event that any value from distributed generation was realised. Either the allowed annual expenditure would be reduced to reflect the savings arising from distributed generation or the excess expenditure would have to be channelled into other projects. Either way, the benefits of distributed generation would feed into greater economic efficiency through lower prices or improved performance respectively.

In the specific case of electrical losses, any efficiencies in the delivery of electricity arising from distributed generation would not only be rolled into the regulatory price control considerations but also into the loss adjustment factors (LAF) calculations. Supply companies must purchase a larger volume of energy at the entry point to the distribution network to ensure adequate energy delivery at customer load points (exit points) net of electrical losses. These loss adjustment factors are calculated periodically by distribution companies with reference to historical data on network losses. The recalculation of loss adjustment factors in response to efficiencies arising from distributed generation would redistributed the benefits from distributed generation among distribution companies, supply companies and ultimately consuming customers. Thus the sharing of benefits from reduced electrical losses arising from distributed generation will be influenced by the regulator in the medium to long term with opportunities for the distribution company to benefit in the short term.

7.8 Assessment of Distributed Generation Strategic Analysis Framework

The features of an effective planning framework were discussed in chapter 4 and a shortened list of the most important features for a distributed generation strategic analysis framework were listed in chapter 6 to define what the implementation of the strategic analysis framework should prove. The characteristics required for a strategic analysis framework are (section 6.2.2):

- deals with multiple criteria
- provides modular analytical framework
- integrates analytical modules
- provides insight to the planning problem and solutions
- deals with uncertainties
- provides a decision focused planning framework
- provides flexibility and robustness in the planning process

In addition, the case studies utilising the strategic analysis framework are intended to provide useful strategic information regarding the impact of distributed generation. In chapter 5 (section 5.2) the four key strategic issues with distributed generation for a distribution company were noted as:

- how much distributed generation will appear in the distribution networks?
- what effect will the distributed generation have on the technical performance of the network?
- what effect will the distributed generation have on the financial performance of the utility?
- what changes in technical design or commercial practice will be effective within a distribution utility distributed generation strategy?

This section discusses the performance of the implementation of the strategic analysis framework and the analysis of case studies with reference to these two lists of objectives.

The first three planning characteristics (multiple criteria, modular and integrated) could all be said to be found in the distributed generation strategic analysis framework. The implementation of the strategic analysis framework has only concentrated on a small number of the major issues (e.g. generation technologies and location, network capacity requirements, losses and fault levels, impact on distribution revenues, etc.) but this has not ruled out the incorporation of many more issues into the analysis framework. Analytical modules have been created in each stage of the framework (energy market, power system and utility financial) and integrated using the custom programming features of the analytical software packages.

While the initial programming of the modules and their integration takes some time to complete, the process of creating a scenario, analysing the scenario and producing results of the effects of the distributed generation scenario on the distribution network and business is relatively quick. The models can be reused once created and the scenarios altered to investigate numerous variations to core input assumptions such as the trajectories for generation costs, the unit costs of distribution plant or the value of losses within the distribution price control formula.

The insight gained on the behaviour of the system when subjected to various distributed generation scenarios has been mixed. In part this is due to the lack of graphical and tabulated data output screens for the user to view (in turn due to the reduced set of objectives of the implementation). However, useful insights have been gained on:

- the sensitivity of some areas of the system to generation connections
- distribution components most likely to suffer from problems under a wide range of scenarios
- distribution components most likely to benefit under a wide range of scenarios
- general trends in system performance with growing numbers of distributed generators.

Insights such as these will support the utility strategy development process and guide the formation of specific tactics in relation to distributed generation.

The strategic analysis framework deals with uncertainty in distributed generation penetration and location through the use of scenarios. This is probably the most effective way of incorporating uncertainty into the distribution strategic planning process. The number of scenarios should ideally be greater than the numbers simulated in these case studies. More scenarios would enable more substantive evidence of the general effects of distributed generation to be gauged and subsequently would provide greater assurance to decision makers in forming strategy. The confidence that a decision maker has in the output from analytical tools is a key concern for analysts. The use of standard industry tools and data sets usually raise the level of confidence but discussions always arise over the input data, tools used and the subsequent quality of output. Keeping debate on these issues to a minimum amongst decision makers is essential to enable a clear focus on the major issues arising in distributed generation.

With only a certain amount of public domain and utility network data available to construct the analytical framework and build the case studies the results produced have been comprehensive (within the areas studied). This shows a measure of flexibility in the framework to the availability of planning resources such as analytical tools, data and personnel time. More than ever, these resources are scarce within utility companies who are subject to tight price control regulation. However, results have been produced in a relatively short period of time which, if validated and extended, could form a basis for strategy formation. The strategies produced could subsequently be tested within the strategic analysis framework to sift the better performing strategies and make refinements to make them more robust.

The general methodology for assessing distributed generation has been designed to produce the information required for decision making. While the decision making elements of the methodology have not been implemented for use with the case studies, it can be seen that multiple criteria decision making techniques could be incorporated after utility financial analysis by keeping the impacts from distributed generation as separate items (rather than aggregating into the distributed generation value function). Many parameters could be incorporated in the decision making framework such as:

- financial effect of distributed generation on the distribution utility (revenue and expenditure)
- distribution network performance parameters (such as losses)
- customer quality of supply (such as power quality and availability)
- external measures representing the value of diversity and sustainability of generation fuel sources or environmental effects.

The three main analytical modules have been used successfully to tackle the first three of the key issues with distributed generation. The Energy Market Analysis module has used economic modelling techniques to produce scenarios of plausible penetrations of distributed generation. Only the penetration rate method was used to create distributed generation scenarios (excluding the DTI forecasts) but other methods could have been used in parallel to produce a more diverse range of scenarios which could be beneficial.

Distributed generation scenarios have been analysed in four power system analysis modules to gauge the physical effect that these scenarios have on the distribution network. Other power system analysis modules could have been implemented to provide a fuller picture of the impact of distributed generation but in general the concept of integrating analytical modules to provide an overall impact of distributed generation has been shown through the use of the four power system analysis modules selected. The four power system analysis modules were selected partly for reasons of available software and data but also as the capacity, fault level and losses effects have been gauged to be among the most important (Driver, 2000).

The physical effects of distributed generation on distribution networks have been interpreted in the Utility Financial Analysis module by means of a distributed generation value function. This function assesses the effect of distributed generation on specific areas of distribution revenue and expenditure and seeks to provide an overall picture of the effects of distributed generation scenarios on the financial health of the utility. Equally, the effects of distribution utility strategies could be gauged through analysis with each of the distributed generation scenarios. In this way, more effective scenarios could be developed and the best performing scenarios selected according to whatever decision making method is desired (multiple criteria or otherwise). The distributed generation value function has proved to be a useful way of assessing the financial effects of distributed generation in the case studies presented here. It readily provides an interpretation of the effects of a scenario to inform planners and decision makers. The distributed generation value function may suffer from focusing on distributed generation in isolation, where distribution strategic planners may wish to assess distributed generation along with other key issues. This myopia (to other non-distributed generation issues) is a potential drawback of the framework as a whole. While planning frameworks should deal with all the issues at hand this could be interpreted as meaning all the issues external to distributed generation also.

7.9 Simulation of Distribution Utility Policy Options

The simulation of utility policy options has not been attempted as part of this proof of the strategic analysis framework idea. There are a number of policy options open to distribution companies to deal with the growing number of distributed generation units appearing and likely to appear in their distribution networks. A selection of distribution utility options are listed and discussed below (Ault et al, 1999):

- use of system charging structure changes (including location incentives)
- connection charging structure changes
- regional reactive power market inception
- power islanding introduction
- ancillary services market introduction
- integrated load/generation management schemes for industrial on-site generators
- dispatch and control of embedded generation

- lobby regulator for reflection of distributed generation in price control mechanism
- highly standardised and re-usable distributed generator connection designs
- co-operative ventures with generators and energy traders

Changes to the use of system charging structure would enable a more cost reflective, and hence more economically efficient, approach to the charging distributed generators for the use of the distribution system. At present the generators are not charged for use of the distribution system if their export is contracted and consumed within the local area (defined by the transmission grid supply point under which the generator operates). While this is generally favourable to generators it does not reflect the spatially differentiated value of the generator in such areas as network support and losses. Such a change of charging structure would enable the distribution company to reward generators with positive contributions to the whole system while penalising generators incurring wider costs.

The connection charging structure could be altered in much the same way as the use of system charging structure to provide signals to generators of the best locations for new generation schemes. The combination of location differentiated charging mechanisms would enable the value of generation connections and operations to be signalled in both the generation planning and operational phases.

One of the potential benefits of distributed generation is the provision of a distributed source of reactive power. If the distribution utility were interested in supporting the operation of the network through reactive power then a regional market in reactive power could enable the distribution company to purchase reactive services in a competitive manner. The sale of reactive power would enable some distributed generators to augment their revenue stream with income from reactive power sales.

The investigation and then introduction of a power island operating mode would enable distribution companies to improve the continuity or availability of supply in some cases. Technical, commercial and legal implications would have to be overcome to enable standard operations of groups of demand and generation disconnected from the rest of the distribution system. Such measures would also enable the generator to have both a greater volume of sales (since the generator would normally automatically disconnect on detection of a power island) and income from the distribution company for provision of the service. This measure may also allay some fears among distribution companies that they may be held liable for loss of earnings to distributed generators due to network constraints.

In addition to reactive power and island operation, there may be other ancillary services which could be offered by distributed generators for the benefit of the system. For example, the dispatch of distributed generation under emergency conditions could be a useful option for a distribution company when managing emergency situations on the distribution network. The terms of such an arrangement would have to be carefully designed to be acceptable to both distribution company and distributed generator while the remuneration of the distributed generator may need to be based on some sort of capability element plus a usage element to ensure that the facility was available when required. However, the distribution company would need to be covered for the situation where an essential emergency service became unavailable since the distribution companies have licence obligations which must be met regardless of distributed generation.

One potential aspect of ancillary services could be load control for sites with generation and load. The distribution company may benefit from the ability to ask for and receive reduced (or even in some cases increased) demand. The ability of a customer to provide such a service may be enhanced through a combined generation and load control scheme. Co-operation may provide benefits for the distribution company in terms of indirect control over demand on the network while the generator may benefit from the ability to control load and thus manage energy purchase costs. Similar to this arrangement for load control could be a prior agreement for the distribution company to dispatch generation on a regular basis. This would provide the distribution company with additional operational flexibility which could be used to manage the stresses placed on the network. The distributed generation owner would cede a large degree of autonomy to provide this flexibility to the distribution company but would expect a return from the distribution company for the service.

The distribution company may opt to lobby the electricity regulator to take specific account of the costs and benefits of distributed generation in the price control review process. The regulator normally balances the requirements for operational and capital expenditure and profit to produce an allowed revenue target for each distribution company. If distributed generation substantially alters the current distribution financial model, as large penetrations of generation may do, it may be best to incorporate the effects in the price control process to give specific signals to distribution companies regarding what strategies to adopt in relation to distributed generation.

A significant effort is required from distribution companies to design individual distribution network connections for distributed generation projects. The process could be streamlined through novel planning techniques or the development of standard designs and procedures. This measure could be particularly effective for smaller generation units where the impact of individual generation units is less sensitive to connection design and also the relative cost of designing the connection to the distribution network is higher.

Many of these strategic options for distribution companies involve some degree of co-operation with distributed generator owners. At present, such co-operation does not seem to exist to a great level.

The possibilities for co-operative ventures between distribution company, distributed generator and even energy traders or supply companies are numerous. Investigation of the possibilities would seem to be prudent while the testing of any ideas with the regulator would also avoid expensive regulatory opposition to such ventures at implementation stage.

7.10 Review of Chapter 7

Two case studies have been introduced in this chapter to demonstrate the performance of the distributed generation strategic analysis framework. The results show that a number of distributed generation issues have been successfully analysed. The power system impact and utility financial impact of distributed generation scenarios have been presented and thoroughly discussed. The significance of the results has been identified through the potential magnitude of the effect of distributed generation on distribution utility finances.

The distributed generation strategic analysis framework having been specified and implemented has been used from beginning to end to produce distributed generation scenarios and analyse those scenarios. The framework has a number of strong features including:

- scenario approach to the uncertainty presented by distributed generation
- modular approach to the analytical framework structure
- multiple issue foundation for the framework
- incorporation of multiple issues in a common distributed generation value function within the utility financial analysis module.

The strategic analysis framework has produced answers to three of the four key issues of distributed generation for the distribution utility:

- how much distributed generation will appear in the distribution networks?
- what effect will the distributed generation have on the technical performance of the network?
- what effect will the distributed generation have on the financial performance of the utility?

The development, simulation and selection of strategies to enable a distribution utility to manage the costs and benefits of distributed generation can be facilitated by the general strategic planning methodology and through the use of the analytical capability of the DG strategic analysis framework.

7.11 Chapter 7 References

Ault, G.W., Cruden, A., and McDonald, J.R. (1999) "Assessing the impact the expected increase in embedded generation will have on the planning and operation of distribution systems". Conference Documentation: IIR 2nd Industry Forum on 'Preparing for the impact of RETA and Current Government Reviews on Embedded Generation', London, 1st December 1999.

Baker, P. (1999) "Embedded Generation in the UK Power System (Department of Trade and Industry - UK)". UMIST Power System Club Seminar on 'Challenges and Opportunities for Embedded Generation', September 1999.

Department of Trade and Industry (1999) "New and Renewable Energy: Prospects for the 21st Century - Supporting Analysis". Department of Trade and Industry, 1999.

Driver, R. (2000) "Embedded Generation - Realising the potential for network benefits. Seminar 1: Content & outcomes". Econnect Report: February 2000.

Hossack, J. (1999) *Modelling the Impact of Embedded Generation* [MEng Thesis], University of Strathclyde, Glasgow.

National Grid Company plc (1997) "NGC Seven Year Statement for the years 1997/98 to 2003/04". April 1997.

Chapter 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This chapter draws together the main conclusions arising from the research project leading to the thesis presented herein and also identifies routes to develop this work further. The conclusions are split into two sections. The first section relates to the general concept of a distributed generation strategic analysis framework and its implementation while the second section discusses the results produced with the strategic analysis framework in terms of the effects of distributed generation on distribution networks and distribution companies in the UK. The principal contributions of this work are drawn from these conclusions.

8.1.1 Distributed Generation Strategic Analysis Framework

- The case studies have illustrated that the proposed framework for analysing the impact of distribution generation on the networks and business of the UK distribution utility companies is effective in a number of ways. First, the framework is based on the understanding of a comprehensive set of issues in the field of distributed generation. Dealing with each of the important issues and understanding the criteria by which the impact of distributed generation can be measured is the first step in designing an analytical framework for assessing distributed generation.

- The distribution utility perspective of distributed generation has been selected since the issues seem to be particularly numerous and complex from that perspective. Distribution utilities own and operate networks into which independent generation developers can seek connection and subsequently operate with minimal recourse to the distribution company other than following the statutory regulations already in place. The distribution companies have not had to deal with any single development in their networks since privatisation which has such a large prospective impact and which they have so little control over. Thus, the planning problem for distribution companies is particularly challenging and it is to tackle this problem that research has been conducted leading to this thesis.

- The strategic analysis framework for distributed generation incorporates many desirable features of modern planning methodologies. It has already been stated that the strategic analysis framework deals with multiple issues and multiple criteria for measuring the impact of distributed generation on the distribution network. The strategic analysis framework has also been designed in a modular fashion such that analytical modules have been integrated into a core analysis environment and commands and data are passed from the core environment while result data sets are passed back to the core. The power system analysis functions within the implementation of the framework are self contained and called as necessary from the core.

- The distributed generation strategic analysis framework is also flexible to available data and analytical resources. The implementation of the framework has focused on a select number of analytical modules (power flow and fault analysis). The number of integrated analytical modules utilised does not affect the operation of the whole framework. In addition, the distributed generation scenarios have been created using only one method (the penetration rate model) but additional scenarios have been easily created using data from other sources. In each of these cases the framework could be made to produce information from the utility financial analysis module relating to the impact of the distributed generation scenarios on the distribution company finances.

- One core requirement of the framework is that it must deal with the uncertainties relating to distributed generation and other utility considerations. The use of a method based on scenarios has been used effectively to enable multiple scenarios to be investigated with the only limitation being the ability of a planner to keep mental track of the scenarios modelled. The volume, technology and location of distributed generation have been the chief uncertainties incorporated into the case studies since these were believed to be the main factors affecting the overall impact of distributed generation on the distribution network. Uncertainties relating to the regulatory environment, fuel security or longer term availability of generation could equally well have been incorporated into the case study as uncertainties. The use of probabilistic or unknown-but-bounded parameters to represent uncertainty have not been used extensively in the implementation of the strategic analysis framework described in this thesis. The structure of the strategic analysis framework does not rule out the use of these representations of uncertainty in any way. The ability to run simulations in batch processes offers the prospect of generating many more scenarios than have been developed in the case studies in order to make use of probabilistic or unknown but bounded parameters to gauge the sensitivity of the results to further uncertainties in the input data.

- The specification of the DG strategic analysis framework has been based on a definition of best practice in modern power system planning. The survey of power system planning methodologies yielded the following list of desirable characteristics:

    - has the ability to deal with multiple criteria
    - enables consideration of multiple and diverse solutions
    - provides whole system solutions
    - is modular in nature
    - provides means of integrating analytical modules and interfacing with other applications
    - is automated and interactive as appropriate
    - provides bulk data handling facilities
    - enhances planner productivity
    - provides flexibility in the planning process
    - is robust to limited planning resources
    - provides insight to the planning problem and solutions
    - makes appropriate use of simulation/optimisation
    - deals with uncertainty
    - deals explicitly in terms of risk
    - provides leverage to future activities
    - is decision focused
    - uses appropriate time scales
    - makes appropriate use of graphical/mathematical decision techniques
    - enables data and model reuse
    - provides auditable planning records
    - enables reuse of the solutions
    - facilitates re-use of planning rationale

While not all these features have been implemented and tested on the case studies, it is believed that none has been ruled out by the structure of the framework. The flexibility offered by the modular nature of the strategic analysis framework opens many avenues for analysis of distributed generation. The strategic analysis framework is a general concept for distributed generation planning which facilitates the use of these desirable characteristics of modern planning techniques to deal with the issues of distributed generation.

8.1.2 Impact of Distributed Generation on Distribution Networks and Distribution Businesses

Two case studies have been developed to test the general concept of a strategic analysis framework for distributed generation which can incorporate the best characteristics of modern planning techniques. The results of simulations of distributed generation scenarios superimposed on the two case study distribution networks have shown the potential impact of distributed generation not only on distribution networks but on distribution businesses also. The detailed results have been presented in chapter 7 and the main conclusions are discussed here.

The economics of distributed generation have been shown to be very positive for natural gas fired, wind and some waste-to-energy generation technologies. For other technologies such as fuel cells and energy crops, the prospects are less promising, without significant reductions in capital costs and fuel costs respectively. Some developments in these underlying costs are likely in the future and, along with government support measures and associated legislation such as obligations on supply companies to buy 'green' energy and a climate change levy, the future for distributed generation in the UK looks very promising.

Large savings have been identified in the capital budgets of the utility companies relating to reinforcement of the network for growth in load demand. This conclusion shows the potential for capital expenditure reductions for reinforcing the distribution network. Having identified that there is the potential for gain in this area, a number of other factors come into play. It is likely that the price control regulation review process would identify this saving and either mark down the allowed distribution revenues due to this efficiency or request that the capital saving be diverted to other projects. The distribution company may take a risk in deferring capital expenditure as a result of favourable generation siting but the reward may be thus removed through the regulatory framework. Clearly the regulatory structure would have to take account of the changing circumstances under which the distribution companies operate and promote such efficiencies through appropriate regulatory mechanisms. In addition, the statutory guidelines on security of supply (standard P2/5) may inhibit any move towards acknowledging a security contribution from distributed generation to reduce load related reinforcement costs.

Large benefits for regulated distribution revenues due to the reduction in annual energy losses have been identified. The inclusion of an energy efficiency factor in the distribution regulated revenue formulation provides an incentive for distribution companies to reduce their losses. The evidence from the scenario simulations conducted in this research shows that there is great potential for reduced electrical losses where distributed generation continues to grow. In the UK context, the regulatory formula progressively reduces the benefit from loss reductions over a ten year period which gives the distribution companies the opportunity to gain over a relatively long period. In any case, when the financial rewards to the distribution company have dwindled, the fact will still remain that the distribution networks produce less lost energy than when no distributed generation existed and this is an unquestionable economic welfare gain.

The requirements for switchgear upgrades due to fault level increases are very large and may act as a substantial barrier to the development of distributed generation under the current mechanisms of generation connection charging (again in the UK context). The distributed generator is liable to any upgrade costs as a result of the connection of the new generation unit. The potentially high costs of switchgear upgrades will prevent many distributed generation schemes from achieving a financially feasible status which may result in the loss of opportunity to yield other distributed generation benefits. Some novel approach to connection and use of system charging could enable the additional costs of the connection to be offset by the recognition of the benefits of the generation scheme. This would result in the distributed generation schemes being evaluated over the full set of costs and benefits which would facilitate generation schemes which are genuinely beneficial while blocking those which have little benefit for the network as a whole. Network benefits are not the only set of criteria against which the generation will be evaluated (e.g. energy sale costs and emissions reductions) but providing a transparent system of generation evaluation could yield substantial economic benefits.

The conclusions reported here are based on simulations carried out under an accompanying set of assumptions. Assumptions have been made that relate to generation location, generation operating mode, load factor and fuel prices amongst many others. Model input data can always be questioned and a different set of assumptions strongly supported, so these conclusions on the impact of distributed generation have been deliberately presented as 'potential' costs and benefits. The results and conclusions provide an indicative profile of the likely impact of distributed generation and have been produced in the process of proving the general concept of a strategic analysis framework for distributed generation.

While it is claimed that the general framework for analysing distributed generation has been proved valid and beneficial, some development is required for the modelling methods and techniques used within the framework. Greater effort has not been devoted to the detail of data and industry processes since these are not essential for proof of the strategic planning concept proposed.

This thesis has not detailed the effects of distribution utility strategies for harnessing the benefits of distributed generation. A limited number of simulations have been conducted and the results show dependencies on the location of the distributed generating units. Alternative generating unit locations have been simulated for each scenario with widely varying results emerging from the simulations. From the quantitative evidence gathered from many simulations of distributed generation integrated in distribution networks there appear to be many potential benefits for distribution companies from having effective distributed generation strategies in place and in a timely manner.

8.1.3 Contribution

- This thesis has identified, categorised and analysed a comprehensive list of distributed generation issues and structured these issues in such a way as to support the development of a framework for strategic analysis of distributed generation which takes account of multiple issues and multiple criteria.

- A general methodology for evaluating the impact of distributed generation on utility networks and businesses and for assessing distribution utility strategies for managing distributed generation has been proposed, investigated and developed. The general methodology can be represented by the following simplified flow diagram (Figure 8-1) which illustrates three main analytical modules (energy market, power system and utility financial analysis modules) with decision making supported by the information generated in the analytical modules. Distribution strategic options can be modelled through the input data blocks.

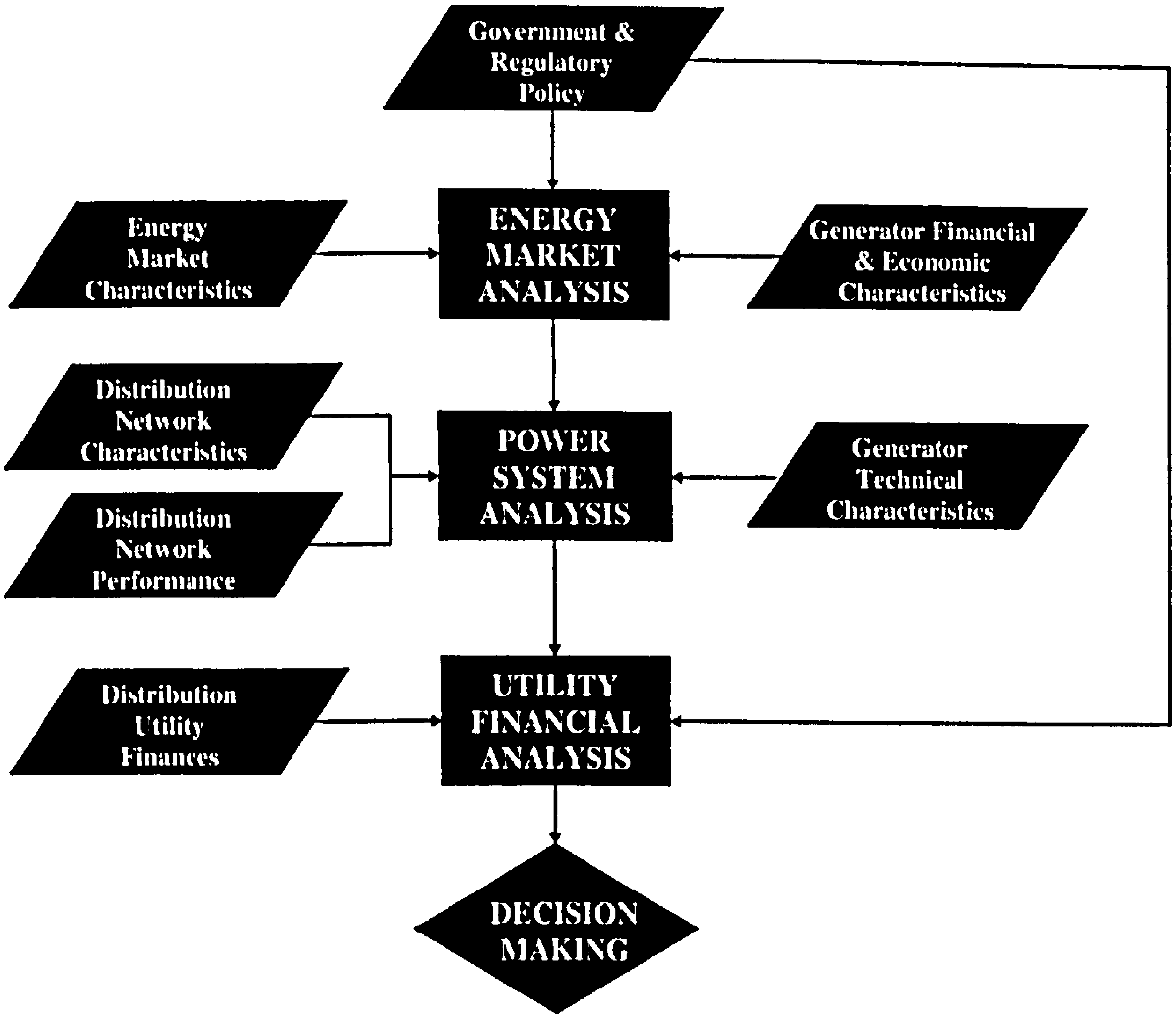

Figure 8-1: General structure of Distributed Generation Strategic Analysis Framework.

- A specification has been developed for a distributed generation strategic analysis framework including the integration of sophisticated market, power system and utility financial models. The distributed generation strategic analysis framework is based on the best features of modern planning methods. The framework provides an environment to model and simulate the effects on distribution networks and businesses of many possible distributed generation scenarios.

- Financial, economic and technical models relating to distributed generation and distribution utilities have been developed and integrated into the DG strategic analysis framework. These models facilitate the analysis of key distributed generation issues as required by distribution utilities facing growing numbers of distributed generating units in their networks.

- A series of simulations of distributed generation scenarios has enabled the quantification and interpretation of the impact of distributed generation on distribution utility networks and businesses. This analysis is based on an implementation of the distributed generation strategic analysis framework which includes the integration of detailed economic, technical and financial models as proposed in the general methodology for distributed generation analysis (Figure 8-1). Financial analysis is based on the effects of distributed generation on each of the distribution utility budgets.

- The construction and subsequent utilisation of the distributed generation strategic analysis framework has demonstrated the effectiveness of the proposed methodology in dealing with the uncertainties faced by distribution utilities with regard to distributed generation.

8.2 Future Work

This thesis has focused on the planning problems associated with distributed generation as viewed from a distribution company viewpoint. A number of interesting avenues have arisen from this work and these ideas are discussed below.

8.2.1 Extension of scope of strategic analysis framework

The first possibility is an extension of the DG strategic analysis framework which has been proposed in this thesis. The list of characteristics for modern planning methodologies could be fully implemented within the framework. The framework could incorporate a graphical and interactive user interface which could be highly valuable for scenario based analysis and planning. Risk measures could be incorporated in the framework to provide the distribution strategic planner with some quantification of the level of risk faced through commitment to one strategy or another. To enable more accurate investigation of the effects of distributed generation on the distribution network assets in the area surrounding the generation connection point, the strategic analysis framework could be integrated with distribution asset management databases. This would enable a view to be taken on the remaining life of assets in the vicinity of the generation and thus more informed decisions could be made with respect to the maintenance, replacement or reinforcement of those assets with respect to distributed generation connection and operation. The effects on the life of the network assets from unusual generation export profiles could also be investigated in the operational time frame rather than the planning time frame.

The integration of further analytical modules into the core framework could serve to prove, to a greater extent, the idea of a modular and flexible planning methodology. Of particular interest would be the integration of stand alone power system analysis modules (now appearing in the market) which are primarily intended to be embedded within other software applications. These modules could be used to create more fluidity in the integrated approach to analysis and enable multiple applications to be run from the core framework thus enhancing the productivity and insight of system planners as the framework takes on a true 'what if' analysis functionality. In more general terms, the analysis of other effects of distributed generation on the distribution network and the costs of benefits of these effects would make the implementation of the framework more comprehensive. For example, integrating the analysis of dynamics, harmonics and other power quality effects would be more challenging and also include more potentially negative aspects of distributed generation into the distributed generation value function.

8.2.2 Integration of strategic analysis framework with 'traditional' distribution expansion planning

One clear objective for further work would be to marry the scenario based distributed generation strategic planning framework with more traditional distribution system expansion planning techniques (Ault et al, 1999). Such a combination would enable the distribution network operator to assess the network expansion plans with a view to potential generation developments and thus avoid unnecessary or stranded investment in the distribution network. For example, the siting of new substations and the routing of new circuits could be made with reference, not only to load and 'wayleaves' but also, to generation locations. This would be particularly effective for small commercial and domestic sized generation units which may grow according to similar trends found in load growth and may also be analysed using the energy device penetration curves of section 5.5.1.3. In addition, the investigation of the power system effects of multiple miniature scale generating units connected to the domestic voltage mains is an activity presently desired by many distribution companies.

8.2.3 Distribution utility policy analysis and decision making

More extensive use of the strategic analysis framework could be made in a number of ways. The exhaustive combination of penetration capacities, generation technologies and locations could be used with multiple attribute tradeoff techniques to inform better decision making for distribution system strategies. In general, the development of the decision making functionality of the framework is necessary since the analytical processes described in this thesis exist primarily to inform strategic decision making. The development of decision making techniques for distribution utilities is a topic of continuing interest and one where many benefits have been demonstrated (Espie et al, 1999; Espie et al, 2000).

The modelling of distribution utility strategic options was an area not covered in this research but of obvious interest to distribution companies. Some distribution strategy options have been listed and discussed in section 7.9 and others could also be identified and investigated. The development of novel strategies for distributed generation could place a distribution network operator in a very favourable position to exploit the growth of distributed generation.

8.2.4 Distribution system management and control infrastructure

The final suggested area for future investigation in relation to distributed generation is control, management and communication systems for distributed generation. Many of the benefits of distributed generation for the distribution company arise from better co-ordination and co-operation with the generation owner-operator. Formalising the communication links would enable the distribution company to more effectively manage the whole distributed generation resource in their franchise area. It may be possible to implement this degree of management through existing communication and control systems for substations (i.e. RTU/SCADA/DMS systems). One of the major risks faced from the distributed generator viewpoint, is the introduction of the new electricity trading arrangements in November 2000. Effective communications for trading purposes and especially to co-ordinate aggregated sales (with other distributed generators and market aggregators such as risk management service providers) in the market may be beneficial for many distributed generators. This area of further research could really be summarised as the management of more active distribution networks in the future.

8.3 Chapter 8 References

Ault, G.W., Cruden, A., and McDonald, J.R. (1999) "Assessing the impact the expected increase in embedded generation will have on the planning and operation of distribution systems". Conference Documentation: IIR 2nd Industry Forum on 'Preparing for the impact of RETA and Current Government Reviews on Embedded Generation', London, 1st December 1999.

Espie, P., Ault, G.W., and McDonald, J.R. (1999) "Multi-Criteria Decision Making methods for Distribution Utility Embedded Generation Strategy Development", *Proceedings of the 34th Universities Power Engineering Conference, Leicester, UK* vol. 2, pp. 551-555, 1999.

Espie, P., Ault, G.W., and McDonald, J.R. (2000) "Multiple Criteria Decision Making in Distribution Utility Investment Planning", *Proceedings: Electric Utility Deregulation and Restructuring, and Power Technologies Conference, DRPT2000, London,* 2000.

APPENDICES

APPENDIX A: EGEAS Gas Turbine Model

The following EGEAS model of the Rolls-Royce Industrial Trent Gas Turbine should be read in conjunction with the EGEAS User Manual referenced from the main text.

```
*
*
*         ROLLS-ROYCE INDUSTRIAL TRENT AERODERIVATIVE GAS TURBINE ECONOMIC PLANT
MODEL
*
*
*
*         *********     TRENT SIMPLE CYCLE MODEL      *********
*
*
 EBPA300  RR-TRENT         THRM I G GAS  SYSA      100.             30 30
 EBPB300  48.6  1.0   1.0799      0.05  8580.              90.   1.0
 EBPC300  500.      450.      10.   25.0  0.5                  2
 EBPD300   50 55 56 57 50 50 58    59 50      50    50  5 58 35
*
*         == MAINTENANCE CYCLES ==
*
*
*          Y YBO ----NUMBER OF WEEKS (W) AND STARTING WEEK (S)----
*          I RAP   1    2    3    4    5    6    7    8    9   10
*          N PST  W S  W S  W S  W S  W S  W S  W S  W S  W S  W S
*          ++--+- ++-- ++-- ++-- ++-- ++-- ++-- ++-- ++-- ++-- ++--
 EMC  50   3 300  2    2    4
*
*
*         == FUEL TYPES ==
*
*              MASS    HEAT    AVAILABLE    FUEL    AV CS AV
*         NAME UNIT  CONTENT     FUEL       COST    TJ TJ SM
*         ---- ++++ ----------+++++++++----------++----+++
 EFL  50  GASN KG   0.042      -1        2.25          85
*
*
*
*         == TRAJECTORIES ==
*
*          T B
*          Y A  N YEAR RATE  YEAR RATE  YEAR RATE  YEAR RATE  YEAR RATE
*          - + -- ++++------ ++++------ ++++------ ++++------ ++++------
*
*         TRAJECTORIES FOR HEAT RATES
 ETJ  35 1 2 2  3    2  1.03    3   1.05   5  1.10
*         TRAJECTORY FOR CAPITAL COST
 ETJ  50 1 1 1  1 1997 -5.0
*         TRAJECTORY FOR FIXED O+M COST
 ETJ  55 1 1 1  1 1997  2.0
*         TRAJECTORY FOR VARIABLE O+M COST
 ETJ  56 1 1 1  1 1997  2.0
*         TRAJECTORY FOR FORCED OUTAGE RATE
 ETJ  57 1 1 2  1    1 -5.0
```

```
*         TRAJECTORY FOR CAPACITIES
 ETJ  58 1 1 2  1    1  0.0
*         TRAJECTORY FOR DESIGN CAPACITY FACTOR
 ETJ  59 1 1 2  1    1  0.0

*         TRAJECTORY FOR FUEL TYPES
 ETJ  85 1 1 1  1 1997  4.0
*         TRAJECTORY FOR EMISSION PRODUCTION
 ETJ 100 1 1 2  1    1   1.0
*         TRAJECTORY FOR EMISSION (PENALTY) COST
 ETJ 101 1 1 1  1 1997  2.0
*         TRAJECTORY FOR UNIT EMISSION LIMIT
 ETJ 102 1 2 1 1  1997  1.0
*
*         == LOADING BLOCK DATA SETS ==
*
*           -CAP(A), HT RATE(B), FOR(C) MULTIPLIERS-
*         N   1       2       3       4       5
*         - +++++++--------+++++++--------++++++++
 ELBA 50  4 0.25    0.25    0.25    0.25
 ELBB 50    1.589   1.238   1.047   1.0
 ELBC 50    1.0     1.0     1.0     1.0
*
*
*         == EMISSIONS TYPES ==
*               ---NAME (A), UNIT OF MASS (B), CLASS (C) FOR TYPE----
*         N      1      2      3      4      5      6      7      8
*         -     ++++   ----   ++++   ----   ++++   ----   ++++   ----
 EEMA     3     SO2    NOX    CO
 EEMB           TONN   TONN   TONN
 EEMC           OUTP   OUTP   OUTP
*
*
*         == ENVIRONMENTAL PLANT DATA ==
*          PROD. 2ND-FL TJ SM  LIMIT TJ SM  COST  TJ CREDIT TJ
*         -------++++++---+++-------+++---+++++++---++++++++---
 EEP  50 2 0.237       100   -1.0   102 0 10.0   101  1.0  101
 EEP  50 3 0.552       100   -1.0   102 0  1.0   101  0.1  101
*
*
*         == GENERIC SITES ==
*               -----------SITE EMISSIONS LIMITATION FOR TYPE-----------
*                  1      2      3      4      5      6      7      8
*               +++++++-------+++++++-------+++++++-------+++++++-------
 EESA  5           -1.0   -1.0   -1.0
*
*
*         == SEGMENT MULTIPLIER TABLES ==
*          T. -----------------MULTIPLIERS FOR SEGMENT---------------- .
*          Y    1       2       3       4       5       6       7
*          -  +++++++--------+++++++--------+++++++--------+++++++
 ESM  50 1 1  1.101   1.101   1.067   1.034   1.0     1.0     0.953
 ESM  50 2 1  0.953   1.0     1.034   1.067   1.101
*
*END==============================================================
*
```

APPENDIX B: Circuit Flows Power System Analysis Module

The program and batch file listings for the circuit flows power system analysis module as described in section 6.3.3.1 are presented below.

startcircuitflows.idv

```
MENU,OFF
EXEC, "c:\gwa\model\work\circuitflows.IRF"
STOP
@END
```

circuitflows.ipl

```
PROGRAM CIRCUITFLOWS

/* Declare variables
*/
STRING networkrawdatafile
STRING circuitflowsfinishfile
STRING circuitflowsoutputfile
STRING ICKT
REAL V
REAL P
REAL Q
REAL RATIO
REAL ANGLE
REAL percentrating(2000)
REAL mvaflow(2000)
REAL rating(2000)
REAL realpower(2000)
REAL reactpower(2000)
REAL ratingtemp
REAL mvaflowtemp
INTEGER IERR
INTEGER IBUS
INTEGER JBUS
INTEGER LIST
INTEGER busfrom(2000)
INTEGER busto(2000)
INTEGER b
INTEGER c
INTEGER d
INTEGER branchcount
STRING STRNG
```

```
/* Read passed data from VB
*/
OPEN 'c:\gwa\model\work\iplinput\circuitflowsinput.txt' ON 1 FOR 'R'
READ 1; networkrawdatafile
READ 1; circuitflowsoutputfile
READ 1; circuitflowsfinishfile
CLOSE 1


/* Call core program procedures
*/
PERFORM REDIRECT
PERFORM READRAW
PERFORM SOLVEIT
PERFORM GETCALCDATA
PERFORM WRITEOUTPUT


/* Let VB macros know that PSSE is complete
*/
PUSH ''
OPEN circuitflowsfinishfile ON 5 FOR 'W'
WRITE 5; ''
CLOSE 5
END


/* REDIRECT pushes the normal on-screen simulation progress reports into background
*/
PROCEDURE REDIRECT
PUSH 'PDEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\circuitprogressfile1.tmp'
PUSH 'ODEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\circuitprogressfile2.tmp'
END


/* READRAW reads the network-scenario data file prepared in VB
*/
PROCEDURE READRAW
PUSH 'READ,ALL '
PUSH networkrawdatafile
END


/* SOLVEIT conducts a Gauss-Siedel followed by a Newton-Raphson
*/
PROCEDURE SOLVEIT
PUSH '@INPUT c:\gwa\model\work\idv\solve'
PAUSE UNTIL 'TEXT SOLUTION'
PUSH '@END'
END


/* GETCALCDATA retrieves data from PSSE memory to enable calculations to be made
*/
PROCEDURE GETCALCDATA
IBUS = 0
CALL INIBUS(IBUS,IERR)
IERR = 0
branchcount = 0
LOOP b=1,2000
        CALL NXTBUS(IBUS,STRNG,IERR)
        IF (IERR<>0) THEN GOTO LABEL5
        ELSE
        LIST = 1
```

```
        CALL INIBRN(IBUS,LIST,IERR)
        LOOP c=1,20
                CALL NXTBRN(IBUS,JBUS,ICKT,IERR)
                IF (IERR<>0) THEN GOTO LABEL6
                ELSE
                        CALL TRNDAT(IBUS,JBUS,ICKT,RATIO,ANGLE,IERR)
                        IF (IERR>=3) THEN
                                CALL BRNFLO(IBUS,JBUS,ICKT,P,Q,IERR)
                                mvaflowtemp = SQRT(P*P+Q*Q)
                                IF (mvaflowtemp>=0.001) THEN
                                        STRNG = 'RATEA'
                                        CALL BRNDAT(IBUS,JBUS,ICKT,STRNG,V,IERR)
                                        ratingtemp = V
                                                IF (ratingtemp<=4500.0) THEN
                                                        branchcount = branchcount + 1
                                                        busfrom(branchcount) = IBUS
                                                        busto(branchcount) = JBUS
                                                        realpower(branchcount) = P
                                                        reactpower(branchcount) = Q
                                                        mvaflow(branchcount) =
mvaflowtemp

                                                        rating(branchcount) = ratingtemp
                                                        percentrating(branchcount) =
(mvaflow(branchcount)*100.0)/(rating(branchcount))
                                                ENDIF
                                ENDIF
                        ENDIF
                ENDIF
        ENDLOOP
        ENDIF
        LABEL6:
ENDLOOP
LABEL5:
END


/* WRITEOUTPUT writes the calculation output to file for retrieval by VB
*/
PROCEDURE WRITEOUTPUT
OPEN circuitflowsoutputfile ON 2 FOR 'W'
WRITE 2; 'Total Number of Circuits:     ',branchcount
WRITE 2; ''
WRITE 2;
'FROM_BUS',TAB(15),'TO_BUS',TAB(30),'MVA_FLOW',TAB(45),'CIRCUIT_RATING',TAB(60),'%_RA
TING',TAB(75),'P',TAB(90),'Q'
LOOP d=1,branchcount
        WRITE 2;
busfrom(d),TAB(15),busto(d),TAB(30),mvaflow(d),TAB(45),rating(d),TAB(60),percentratin
g(d),TAB(75),realpower(d),TAB(90),reactpower(d)
ENDLOOP
CLOSE 2
END
```

solve.idv

```
MENU,OFF        /* FORCE MENU TO CORRECT STATUS
CHNG
7
Y
,,,,150
Y
,,50
Y
,,
```

```
Y
,,,,,
0            / TO EXIT CHNG
SOLV,OPT
1,0,0,0,0,0
FNSL,OPT
1,0,0,0,0,0
99
TEXT SOLUTION
@END
```

APPENDIX C: Transformer flows power system analysis module

The program and batch file listings for the circuit flows power system analysis module as described in section 6.3.3.2 are presented below.

starttransflows.idv

```
MENU,OFF
EXEC, "c:\gwa\model\work\transflows.IRF"
STOP
@END
```

transflows.ipl

```
PROGRAM TRANSFLOWS

/* Declare variables
*/
STRING networkrawdatafile
STRING transflowsfinishfile
STRING transflowsoutputfile
STRING ICKT
REAL V
REAL P
REAL Q
REAL RATIO
REAL ANGLE
REAL percentrating(2000)
REAL mvaflow(2000)
REAL rating(2000)
REAL realpower(2000)
REAL reactpower(2000)
REAL ratingtemp
REAL mvaflowtemp
INTEGER IERR
INTEGER IBUS
INTEGER JBUS
INTEGER LIST
INTEGER busfrom(2000)
INTEGER busto(2000)
INTEGER b
INTEGER c
INTEGER d
INTEGER branchcount
STRING STRNG
```

```
/* Read passed data from VB
*/
OPEN 'c:\gwa\model\work\iplinput\transflowsinput.txt' ON 1 FOR 'R'
READ 1; networkrawdatafile
READ 1; transflowsoutputfile
READ 1; transflowsfinishfile
CLOSE 1


/* Call core program procedures
*/
PERFORM REDIRECT
PERFORM READRAW
PERFORM SOLVEIT
PERFORM GETCALCDATA
PERFORM WRITEOUTPUT


/* Let VB macros know that PSSE is complete
*/
PUSH ''
OPEN transflowsfinishfile ON 5 FOR 'W'
WRITE 5; ''
CLOSE 5
END


/* REDIRECT pushes the normal on-screen simulation progress reports into background
*/
PROCEDURE REDIRECT
PUSH 'PDEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\transprogressfile1.tmp'
PUSH 'ODEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\transprogressfile2.tmp'
END


/* READRAW reads the network-scenario data file prepared in VB
*/
PROCEDURE READRAW
PUSH 'READ,ALL '
PUSH networkrawdatafile
END


/* SOLVEIT conducts a Gauss-Siedel followed by a Newton-Raphson
*/
PROCEDURE SOLVEIT
PUSH '@INPUT c:\gwa\model\work\idv\solve'
PAUSE UNTIL 'TEXT SOLUTION'
PUSH '@END'
END


/* GETCALCDATA retrieves data from PSSE memory to enable calculations to be made
*/
PROCEDURE GETCALCDATA
IBUS = 0
CALL INIBUS(IBUS,IERR)
IERR = 0
branchcount = 0
LOOP b=1,2000
        CALL NXTBUS(IBUS,STRNG,IERR)
        IF (IERR<>0) THEN GOTO LABEL5
        ELSE
        LIST = 1
```

```
        CALL INIBRN(IBUS,LIST,IERR)
        LOOP c=1,20
                CALL NXTBRN(IBUS,JBUS,ICKT,IERR)
                IF (IERR<>0) THEN GOTO LABEL6
                ELSE
                        CALL TRNDAT(IBUS,JBUS,ICKT,RATIO,ANGLE,IERR)
                        IF (IERR<=2) THEN
                                CALL BRNFLO(IBUS,JBUS,ICKT,P,Q,IERR)
                                mvaflowtemp = SQRT(P*P+Q*Q)
                                IF (mvaflowtemp>=0.001) THEN
                                        STRNG = 'RATEA'
                                        CALL BRNDAT(IBUS,JBUS,ICKT,STRNG,V,IERR)
                                        ratingtemp = V
                                                IF (ratingtemp<=4500.0) THEN
                                                        branchcount = branchcount + 1
                                                        busfrom(branchcount) = IBUS
                                                        busto(branchcount) = JBUS
                                                        realpower(branchcount) = P
                                                        reactpower(branchcount) = Q
                                                        mvaflow(branchcount) =
mvaflowtemp

                                                        rating(branchcount) = ratingtemp
                                                        percentrating(branchcount) =
(mvaflow(branchcount)*100.0)/(rating(branchcount))
                                                ENDIF
                                ENDIF
                        ENDIF
                ENDIF
        ENDLOOP
        ENDIF
        LABEL6:
ENDLOOP
LABEL5:
END


/* WRITEOUTPUT writes the calculation output to file for retrieval by VB
*/
PROCEDURE WRITEOUTPUT
OPEN transflowsoutputfile ON 2 FOR 'W'
WRITE 2; 'Total Number of Transformers:     ',branchcount
WRITE 2; ''
WRITE 2;
'FROM_BUS',TAB(15),'TO_BUS',TAB(30),'MVA_FLOW',TAB(45),'TRANS_RATING',TAB(60),'%_RATI
NG',TAB(75),'P',TAB(90),'Q'
LOOP d=1,branchcount
        WRITE 2;
busfrom(d),TAB(15),busto(d),TAB(30),mvaflow(d),TAB(45),rating(d),TAB(60),percentratin
g(d),TAB(75),realpower(d),TAB(90),reactpower(d)
ENDLOOP
CLOSE 2
END
```

APPENDIX D: Fault analysis power system analysis module

The program and batch file listings for the circuit flows power system analysis module as described in Section 6.3.3.3 are presented below.

startfaults.idv

```
MENU,OFF
EXEC, "c:\gwa\model\work\faults.IRF"
STOP
@END
```

faults.ipl

```
PROGRAM FAULTS

/* Declare variables
*/
STRING networkrawdatafile
STRING faultsbusesfile
STRING faultsoutputfile
STRING faultstempfile
STRING faultsfinishfile
INTEGER busnumber(500)
INTEGER fb
REAL faultcurrent(500)
REAL basevolt(500)
STRING blank(50)
STRING busname(500)
STRING STRNG
REAL V
INTEGER IERR
INTEGER IBUS
INTEGER i


/* Main part of the program - Read in passed parameters and call procedures to read
in data, calculate fault level and write results to file.
*/

PERFORM REDIRECT
```

```
/* Read passed data from VB
*/
OPEN 'c:\gwa\model\work\iplinput\faultsinput.txt' ON 4 FOR 'R'
READ 4; networkrawdatafile
READ 4; faultsbusesfile
READ 4; faultsoutputfile
READ 4; faultstempfile
READ 4; faultsfinishfile
CLOSE 4


PERFORM READRAW
PERFORM FAULTSIM


OPEN faultstempfile ON 1 FOR 'R'
LOOP i=1,7
        READ 1; blank(i)
ENDLOOP

/* Prepare output file for data write
*/
OPEN faultsoutputfile ON 2 FOR 'W'
WRITE 2; 'BUS',TAB(15),'BASE_VOLT',TAB(30),'FAULT_MVA',TAB(45),'BUS_NAME'


/* For each network bus: retrieve PSSE direct and file written data and write output
*/
LOOP fb=1,500
        PERFORM READSIMDATA
                ON EOF (1) GOTO endtempfile
        PERFORM CALLPSSEDATA
        PERFORM WRITEOUTPUT
ENDLOOP
endtempfile: CLOSE 1


CLOSE 2


/* Let VB macros know that PSSE is complete
*/
PUSH ''
OPEN faultsfinishfile ON 3 FOR 'W'
WRITE 3; ''
CLOSE 3
END


/* REDIRECT pushes the normal on-screen simulation progress reports into background
*/
PROCEDURE REDIRECT
PUSH 'PDEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\faultsprogressfile1.tmp'
PUSH 'ODEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\faultsprogressfile12.tmp'
END


/* READRAW reads the network-scenario data file prepared in VB
*/
PROCEDURE READRAW
PUSH 'READ,ALL '
PUSH networkrawdatafile
END
```

```
/* FAULTSIM conducts the 3-phase fault simulation
*/
PROCEDURE FAULTSIM
PUSH '@INPUT c:\gwa\model\work\idv\faults,',faultstempfile
PAUSE UNTIL 'TEXT FAULTMVA'
PUSH '@END'
END


/* READSIMDATA retrieves the pertinent simulation data from a PSSE file
*/
PROCEDURE READSIMDATA
READ 1; busnumber(fb),TAB(26),faultcurrent(fb)
END


/* CALLPSSEDATA retrives auxiliary data direct from PSSE memory
*/
PROCEDURE CALLPSSEDATA
IBUS = busnumber(fb)
STRNG = 'BASE'
CALL BUSDAT(IBUS,STRNG,V,IERR)
basevolt(fb) = V
CALL NOTONA(IBUS,STRNG,IERR)
busname(fb) = STRNG
END


/* WRITEOUTPUT writes the output data to file for retrieval by VB
*/
PROCEDURE WRITEOUTPUT
IF (busnumber(fb)<>0) THEN
       WRITE 2; busnumber(fb),TAB(15),basevolt(fb),TAB(30),SQRT(3.0) * basevolt(fb) *
faultcurrent(fb) * 0.001,TAB(45),busname(fb)
ENDIF
END
```

faults.idv

```
MENU,OFF       /* FORCE MENU TO CORRECT STATUS
OPEN
2
%1%
OPTN
7
1
8
1
22
20
24
400
25
400
0
TRSQ
q
BAT_BSYS 0 0 11.000 400.000
1 1
0
0
0
```

```
BAT_ASCC 0 0 0 0 0 0 0 3 0 0 0 0
• •
• •
CLOS
OPTN
7
0
8
0
22
60
24
58
25
60
0
TEXT FAULTMVA
@END
```

APPENDIX E: Losses analysis power system analysis module

The program and batch file listings for the circuit flows power system analysis module as described in Section 6.3.3.4 are presented below.

startlosses.idv

```
MENU,OFF
EXEC, "c:\gwa\model\work\losses.IRF"
STOP
@END
```

losses.ipl

```
PROGRAM LOSSES

/* Declare variables
*/
STRING networkrawdatafile
STRING lossesoutputfile
STRING loadpointfile
STRING lossesfinishfile
STRING STRNG
REAL P
REAL Q
INTEGER s
INTEGER scalenumber
INTEGER IERR
REAL scale(200)
REAL pssscale(200)
REAL hours(200)
REAL lostenergy(200)
REAL lostpower(200)
REAL lostqpower(200)
REAL lostqenergy(200)
REAL totallostenergy
REAL totallostqenergy



PERFORM REDIRECT


/* Read passed data from VB
*/
```

```
OPEN 'c:\gwa\model\work\iplinput\lossesinput.txt' ON 1 FOR 'R'
READ 1; networkrawdatafile
READ 1; lossesoutputfile
READ 1; loadpointfile
READ 1; lossesfinishfile
CLOSE 1


PERFORM GETDATA


/* perform core procedures for each load scaling level
*/
LOOP s=1,scalenumber
        PERFORM READRAW
        PERFORM SCALE
        PERFORM SOLVEIT
        PERFORM LOSSES
ENDLOOP



PERFORM TOTAL
PERFORM OUTPUT


/* Let VB macros know that PSSE is complete
*/
PUSH ''
OPEN lossesfinishfile ON 1 FOR 'W'
WRITE 1; ''
CLOSE 1
END


/* REDIRECT pushes the normal on-screen simulation progress reports into background
*/
PROCEDURE REDIRECT
PUSH 'PDEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\lossesprogressfile1.tmp'
PUSH 'ODEV'
PUSH '2'
PUSH 'c:\gwa\model\work\temp\lossesprogressfile2.tmp'
END


/* GETDATA retrieves the load scaling data from a file created by VB and stores to
array
*/
PROCEDURE GETDATA
OPEN loadpointfile ON 1 FOR 'R'
scalenumber = 0
LOOP s=1,200
        READ 1; scale(s),hours(s)
        ON EOF (1) GOTO LABEL1
        scalenumber = scalenumber + 1
ENDLOOP
LABEL1:
CLOSE 1
LOOP s=1,scalenumber
        pssscale(s) = scale(s) - 100.0
ENDLOOP
END


/* READRAW reads the network-scenario data file prepared in VB
*/
PROCEDURE READRAW
```

```
PUSH 'READ,ALL '
PUSH networkrawdatafile
END


/* SCALE scales the peak load network data file to predetermined level
*/
PROCEDURE SCALE
PUSH '@INPUT c:\gwa\model\work\idv\scaleloads,',pssscale(s)
PAUSE UNTIL 'TEXT SCALED'
PUSH '@END'
END


/* SOLVEIT conducts a Gauss-Siedel followed by a Newton-Raphson
*/
PROCEDURE SOLVEIT
PUSH '@INPUT c:\gwa\model\work\idv\solve'
PAUSE UNTIL 'TEXT SOLUTION'
PUSH '@END'
END


/* LOSSES retrieves power loss data from PSSE and calculates energy loss
*/
PROCEDURE LOSSES
STRNG = 'LOSS'
CALL SYSTOT(STRNG,P,Q,IERR)
lostpower(s) = P
lostenergy(s) = lostpower(s)*hours(s)
lostqpower(s) = Q
lostqenergy(s) = lostqpower(s) *hours(s)
END


/* TOTAL totals the lost active and reactive energy over a year
*/
PROCEDURE TOTAL
totallostenergy = 0.0
LOOP s=1,scalenumber
        totallostenergy = totallostenergy + lostenergy(s)
ENDLOOP
totallostqenergy = 0.0
LOOP s=1,scalenumber
        totallostqenergy = totallostqenergy + lostqenergy(s)
ENDLOOP
END


/* OUTPUT writes the lost power and energy for each loading level and totals to file
PROCEDURE OUTPUT
OPEN lossesoutputfile ON 1 FOR 'W'
WRITE 1; 'TOTAL ENERGY LOSSES (MWh) =',TAB(30),totallostenergy
WRITE 1; 'TOTAL REACTIVE LOSSES (MVARh) =',TAB(30),totallostqenergy
WRITE 1; ''
WRITE 1;
'SCALE(%SMD)',TAB(15),'MW_LOSSES',TAB(30),'MWh_LOSSES',TAB(45),'MVAR_LOSSES',TAB(60),
'MVARh_LOSSES'
LOOP s=1,scalenumber
        WRITE 1;
scale(s),TAB(15),lostpower(s),TAB(30),lostenergy(s),TAB(45),lostqpower(s),TAB(60),los
tqenergy(s)
ENDLOOP
CLOSE 1
END
```

scaleloads.idv

```
MENU,OFF
BAT_SCAL 0 1 1 0 0 0 0
      0.00       0.00       0.00       0.00       0.00       0.00       0.00
BAT_SCAL 0 1 2 2 0 1 0
    %1%       0.00       0.00       0.00       0.00       0.00       0.00
TEXT SCALED
@END
```

APPENDIX F: Detailed distributed generation scenarios for case studies

Table F-1 details the national generation capacity derived for scenario dtl1.

Generator Type	Capacity (MWe)	1998 Capacity (MW)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0.25	0	83.3	166.7	250.0
Wind (Onshore)	1.5	0	1291.7	2583.3	3875.0
Municipal Waste	25	0	654.2	1308.3	1962.5
Energy Crop	17.5	0	250.0	500.0	750.0
Gas Turbine (Large)	50	0	1458.3	2916.7	4375.0
CHP Gas Engine	1.8	0	833.3	1666.7	2500.0
CHP Gas Turbine	6.1	0	1250.0	2500.0	3750.0

Table F-1: National capacity for distributed generation scenario DTL1.

Table F-2 details the national generation capacity derived for scenario prm1.

Generator Type	Capacity (MWe)	1998 Capacity (MW)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0.25	0	0	0	0
Wind (Onshore)	1.5	0	1708	2171	2627
Municipal Waste	25	0	105	145	188
Energy Crop	17.5	0	0	0	0
Gas Turbine (Large)	50	0	1189	1248	1299
CHP Gas Engine	1.8	0	1795	1898	1955
CHP Gas Turbine	6.1	0	2489	2592	2680

Table F-2: National capacity for distributed generation scenario PRM1.

Table F-3 details the national generation capacity derived for scenario prm2.

Generator Type	Capacity (MWe)	1998 Capacity (MW)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0.25	0	0	248	908
Wind (Onshore)	1.5	0	2371	2,624	2864
Municipal Waste	25	0	189	205	219
Energy Crop	17.5	0	0	-	0
Gas Turbine (Large)	50	0	911	939	966
CHP Gas Engine	1.8	0	1283	1,373	1458
CHP Gas Turbine	6.1	0	1816	1,871	1926

Table F-3: National capacity for distributed generation scenario PRM2.

Table F-4 details the national generation capacity derived for scenario prm3.

Generator Type	Capacity (MWe)	1998 Capacity (MW)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0.25	0	0	0	1762
Wind (Onshore)	1.5	0	3617	3946	4263
Municipal Waste	25	0	795	883	966
Energy Crop	17.5	0	0	0	0
Gas Turbine (Large)	50	0	956	991	1025
CHP Gas Engine	1.8	0	1360	1470	1569
CHP Gas Turbine	6.1	0	1905	1975	2043

Table F-4: National capacity for distributed generation scenario PRM3.

Table F-5 details the number of generation units of each technology type and also the total generation capacity for scenario dtl1 in case study Network 1.

Generator Type	No. Units (2003)	No. Units (2008)	No. Units (2013)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	2	4	6	0.5	1	1.5
Wind (Onshore)	5	10	14	7.5	15	21
Municipal Waste	1	1	1	25	25	25
Energy Crop	1	1	1	17.5	17.5	17.5
Gas Turbine (Large)	1	1	1	50	50	50
CHP Gas Engine	3	5	8	5.4	9	14.4
CHP Gas Turbine	2	3	4	12.2	18.3	24.4
Total				118.1	135.8	153.8

Table F-5: Case Study Network 1 – DTL1 distributed generation scenario.

Table F-6 details the number of generation units of each technology type and also the total generation capacity for scenario prm1 in case study Network 1.

Generator Type	No. Units (2003)	No. Units (2008)	No. Units (2013)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0	0	0	0	0	0
Wind (Onshore)	7	8	10	10.5	12	15
Municipal Waste	1	1	1	25	25	25
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	1	1	1	50	50	50
CHP Gas Engine	6	6	6	10.8	10.8	10.8
CHP Gas Turbine	3	3	3	18.3	18.3	18.3
Total				114.6	116.1	119.1

Table F-6: Case Study Network 1 – PRM1 distributed generation scenario.

Table F-7 details the number of generation units of each technology type and also the total generation capacity for scenario prm2 in case study Network 1.

Generator Type	**No. Units (2003)**	**No. Units (2008)**	**No. Units (2013)**	**2003 Capacity (MW)**	**2008 Capacity (MW)**	**2013 Capacity (MW)**
Fuel Cell	0	6	20	0	1.5	5
Wind (Onshore)	9	10	11	13.5	15	16.5
Municipal Waste	0	0	0	0	0	0
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	4	5	5	7.2	9	9
CHP Gas Turbine	2	2	2	12.2	12.2	12.2
Total				32.9	37.7	42.7

Table F-7: Case Study Network 1 – PRM2 distributed generation scenario.

Table F-8 details the number of generation units of each technology type and also the total generation capacity for scenario prm3 in case study Network 1.

Generator Type	**No. Units (2003)**	**No. Units (2008)**	**No. Units (2013)**	**2003 Capacity (MW)**	**2008 Capacity (MW)**	**2013 Capacity (MW)**
Fuel Cell	0	0	38	0	0	9.5
Wind (Onshore)	13.	14	16	19.5.	21	24
Municipal Waste	1	1	1	25	25	25
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	4	5	5	7.2	9	9
CHP Gas Turbine	2	2	2	12.2	12.2	12.2
Total				63.9	67.2	79.7

Table F-8: Case Study Network 1 – PRM3 distributed generation scenario.

Table F-9 details the number of generation units of each technology type and also the total generation capacity for scenario dtl1 in case study Network 2.

Generator Type	No. Units (2003)	No. Units (2008)	No. Units (2013)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	1	2	3	0.25	0.5	0.75
Wind (Onshore)	2	4	6	3	6	9
Municipal Waste	1	1	1	25	25	25
Energy Crop	1	1	1	17.5	17.5	17.5
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	2	3	4	3.6	5.4	7.2
CHP Gas Turbine	1	1	2	6.1	6.1	12.2
Total				55.45	60.5	71.65

Table F-9: Case Study Network 2 – DTL1 distributed generation scenario.

Table F-10 details the number of generation units of each technology type and also the total generation capacity for scenario prm1 in case study Network 2.

Generator Type	No. Units (2003)	No. Units (2008)	No. Units (2013)	2003 Capacity (MW)	2008 Capacity (MW)	2013 Capacity (MW)
Fuel Cell	0	0	0	0	0	0
Wind (Onshore)	3	4	4	4.5	6	6
Municipal Waste	1	1	1	25	25	25
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	3	3	3	5.4	5.4	5.4
CHP Gas Turbine	1	1	1	6.1	6.1	6.1
Total				41	42.5	42.5

Table F-10: Case Study Network 2 – PRM1 distributed generation scenario.

Table F-11 details the number of generation units of each technology type and also the total generation capacity for scenario prm2 in case study Network 2.

Generator Type	**No. Units (2003)**	**No. Units (2008)**	**No. Units (2013)**	**2003 Capacity (MW)**	**2008 Capacity (MW)**	**2013 Capacity (MW)**
Fuel Cell	0	3	8	0	0.75	2
Wind (Onshore)	4	4	5	6	6	7.5
Municipal Waste	0	0	0	0	0	0
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	2	2	2	3.6	3.6	3.6
CHP Gas Turbine	1	1	1	6.1	6.1	6.1
Total				15.7	16.45	19.2

Table F-11: Case Study Network 2 – PRM2 distributed generation scenario.

Table F-12 details the number of generation units of each technology type and also the total generation capacity for scenario prm3 in case study Network 2.

Generator Type	**No. Units (2003)**	**No. Units (2008)**	**No. Units (2013)**	**2003 Capacity (MW)**	**2008 Capacity (MW)**	**2013 Capacity (MW)**
Fuel Cell	0	0	16	0	0	4
Wind (Onshore)	6	6	7	9	9	10.5
Municipal Waste	0	0	0	0	0	0
Energy Crop	0	0	0	0	0	0
Gas Turbine (Large)	0	0	0	0	0	0
CHP Gas Engine	2	2	2	3.6	3.6	3.6
CHP Gas Turbine	1	1	1	6.1	6.1	6.1
Total				18.7	18.7	24.2

Table F-12: Case Study Network 2 – PRM3 distributed generation scenario.

APPENDIX G: Supplementary data for Case Studies

This supplementary table of data (Table G-1) illustrates the urban to rural split applied to each node in case study Network 1 for the purposes of locating generation within the network during the scenario building process. A full description of the generation locating process is provided in section 7.2.7.

Bus Number	Reference Name	Name	Voltage	Urban	Rural
1701	'TAY1'	TAY	132	50%	50%
3701	'LOMOND1'	LOMOND	33	0%	100%
3703	'TAY1'	TAY	33	50%	50%
3705	'MORAR1'	MORAR	33	80%	20%
3710	'NEVIS1'	NEVIS	33	90%	10%
3712	'NEVIS3'	NEVIS	33	90%	10%
3714	'DUICH1'	DUICH	33	70%	30%
3721	'BROOM1'	BROOM	33	80%	20%
11701	'TAY4'	TAY	11	50%	50%
11703	'LEVEN1'	LEVEN	11	0%	100%
11704	'VOIL1'	VOIL	11	40%	60%
11706	'ARKLET1'	ARKLET	11	30%	70%
11708	'AWE1'	AWE	11	90%	10%
11710	'MORAR1'	MORAR	11	80%	20%
11712	'ERICHT1'	ERICHT	11	50%	50%
11714	'CARRON1'	CARRON	11	70%	30%
11715	'LOCHAY1'	LOCHAY	11	40%	60%
11717	'OICH1'	OICH	11	0%	100%
11719	'NESS1'	NESS	11	30%	70%
11721	'LOMOND1'	LOMOND	11	0%	100%
11723	'ACHRAY1'	ACHRAY	11	0%	100%
11725	'ETIVE1'	ETIVE	11	40%	60%
11727	'HOURN1'	HOURN	11	50%	50%
11729	'NEVIS1'	NEVIS	11	90%	10%
11731	'ARD1'	ARD	11	60%	40%
11733	'BROOM1'	BROOM	11	80%	20%

Table G-1: Distributed generation connection point characteristics.

APPENDIX H: Detailed Results from Distributed Generation Strategic Analysis Framework

The core results from the power system simulations are detailed in Table H-1 and Table H-2 for case study Network 1 and Network 2 respectively.

Table H-3 and Table H-4 show comparisons of the results with the no distributed generation scenario (*ndgu*) or the same scenario in the previous period as appropriate. The results are presented for Network 1 and Network 2 respectively.

Table H-5 and Table H-6 illustrate the value of the changes in distributed generation impact across the scenarios for Network 1 and Network 2 respectively.

Table H-7 and Table H-8 summate and allocate each of the financial effects into the typical distribution utility budget items as discussed in section 5.5.3.2. The results are presented for Network 1 and Network 2 respectively.

Circuit capacity analysis	ndgu-1998	ndgu-2003	prm1-2003	dtl1-2003	prm2-2003	prm3-2003	ndgu-2008	prm1-2008	dtl1-2008	prm2-2008	prm3-2008	ndgu-2013	prm1-2013	dtl1-2013	prm2-2013	prm3-2013
33kV OH length replacement due (km)	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	0.00	6.03	6.03	6.03	6.03	6.03	6.03	6.03
33kV UG length replacement due (km)	20.32	29.44	16.44	29.50	31.37	8.84	55.08	36.07	31.15	26.61	26.31	75.63	56.81	37.83	46.10	75.63
132kV OH length replacement due (km)	19.34	34.78	0.00	0.00	0.00	0.00	35.52	0.00	0.00	19.34	0.00	47.18	0.00	0.00	19.34	47.18
132kV UG length replacement due (km)	0.05	0.05	0.00	0.00	0.05	0.00	0.05	0.00	0.00	0.05	0.05	0.05	0.00	0.00	0.05	0.05
Transformer capacity analysis																
400kV transformers required	2	2	0	0	2	2	2	0	0	2	2	2	2	0	2	2
132kV transformers required	0	2	0	0	0	0	4	0	0	0	0	4	0	0	0	4
33kV transformers required	18	21	17	20	16	12	24	20	22	18	15	24	20	20	19	24
Swicthgear rating analysis																
132kV Switchgear count	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33kV Switchgear count	12	12	44	28	12	12	12	44	32	12	12	12	44	32	12	12
11kV Switchgear count	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0
Energy Losses																
Active energy losses (MWh)	16,863	19,169	10,199	12,466	14,678	10,386	21,806	11,325	11,685	15,916	11,569	24,775	12,431	13,151	17,624	11,454
Reactive energy losses (MVArh)	359,247	408,149	160,649	182,583	295,540	213,141	464,032	183,407	185,283	321,170	237,840	526,379	207,565	194,910	351,081	233,654

Table H-1: Power system analysis summary for case study network 1.

Circuit capacity analysis	ndgu-em-1998	ndgu-em-2003	prm1-em-2003	dtl1-em-2003	prm2-em-2003	prm3-em-2003	ndgu-em-2008	prm1-em-2008	dtl1-em-2008	prm2-em-2008	prm3-em-2008	ndgu-em-2013	prm1-em-2013	dtl1-em-2013	prm2-em-2013	prm3-em-2013
33kV OH length replacement due (km)	18.6	18.6	17.8	7	18.6	7	26.5	25.7	14.9	26.5	14.9	26.5	25.7	25.7	26.5	14.9
33kV UG length replacement due (km)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132kV OH length replacement due (km)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132kV UG length replacement due (km)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transformer capacity analysis																
400kV transformers required	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132kV transformers required	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33kV transformers required	1	1	1	1	1	0	2	2	2	1	1	3	3	3	2	2
Swicthgear rating analysis																
132kV Switchgear count	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33kV Switchgear count	0	0	0	12	0	0	0	0	12	0	0	0	0	12	0	0
11kV Switchgear count	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy Losses																
Active energy losses (MWh)	15,014	17,010	7,641	6,238	12,127	10,579	19,349	8,765	6,006	13,744	12,275	22,010	10,320	6,088	15,737	12,986
Reactive energy losses (MVArh)	91,793	103,452	51,639	44,019	74,930	68,957	117,197	59,915	45,669	84,942	79,280	132,724	69,253	46,001	98,328	86,871

Table H-2: Power system analysis summary for case study network 2.

Circuit capacity analysis	ndgu-1998	ndgu-2003	prm1-2003	dtl1-2003	prm2-2003	prm3-2003	ndgu-2008	prm1-2008	dtl1-2008	prm2-2008	prm3-2008	ndgu-2013	prm1-2013	dtl1-2013	prm2-2013	prm3-2013
33kV OH km reduction from ndgu in same year	-	-	-	-	-	-	-	-	6.0	-	-	-	-	-	-	-
33kV UG km reduction from ndgu in same year	-	-	13.0	(0.1)	(1.9)	20.6	-	19.0	23.9	28.5	28.8	-	18.8	37.8	29.5	-
132kV OH km reduction from ndgu in same year	-	-	34.8	34.8	34.8	34.8	-	35.5	35.5	16.2	35.5	-	47.2	47.2	27.8	-
132kV UG km reduction from ndgu in same year	-	-	0.1	0.1	-	0.1	-	0.1	0.1	-	-	-	0.1	0.1	-	-
Transformer capacity analysis																
400kV primary reduction from ndgu in same year	-	-	2	2	-	-	-	2	2	-	-	-	-	2	-	-
132kV primary reduction from ndgu in same year	-	-	2	2	2	2	-	4	4	4	4	-	4	4	4	-
33kV primary reduction from ndgu in same year	-	-	4	1	5	9	-	4	2	6	9	-	4	4	5	-
Swicthgear rating analysis																
132kV additional switchgear requirement in scenario	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33kV additional switchgear requirement in scenario	-	-	32	16	-	-	-	-	4	-	-	-	-	-	-	-
11kV additional switchgear requirement in scenario	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	(2)
Energy Losses																
P losses reduction to ndgu-1998(GWh)	-	-2.3	6.7	4.4	2.2	6.5	-4.9	5.5	5.2	0.9	5.3	-7.9	4.4	3.7	-0.8	5.4
Q losses reduction to ndgu-1998 (GVArh)	-	-48.9	198.6	176.7	63.7	146.1	-104.8	175.8	174.0	38.1	121.4	-167.1	151.7	164.3	8.2	125.6

Table H-3: Comparative analysis of case study network 1 power system analysis results.

Circuit capacity analysis	ndgu-em-1998	ndgu-em-2003	prm1-em-2003	dtl1-em-2003	prm2-em-2003	prm3-em-2003	ndgu-em-2008	prm1-em-2008	dtl1-em-2008	prm2-em-2008	prm3-em-2008	ndgu-em-2013	prm1-em-2013	dtl1-em-2013	prm2-em-2013	prm3-em-2013
33kV OH km reduction from ndgu in same year	-	-	0.8	11.6	-	11.6	-	0.8	11.6	-	11.6	-	0.8	0.8	-	11.6
33kV UG km reduction from ndgu in same year	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
132kV OH km reduction from ndgu in same year	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
132kV UG km reduction from ndgu in same year	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Transformer capacity analysis																
400kV primary reduction from ndgu in same year	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
132kV primary reduction from ndgu in same year	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33kV primary reduction from ndgu in same year	-	-	-	-	-	1	-	-	-	1	1	-	-	-	1	1
Swicthgear rating analysis																
132kV additional switchgear requirement in scenario	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33kV additional switchgear requirement in scenario	-	-	-	12	-	-	-	-	-	-	-	-	-	-	-	-
11kV additional switchgear requirement in scenario	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Energy Losses																
P losses reduction to ndgu-1998(GWh)	-	(2.0)	7.4	8.8	2.9	4.4	(4.3)	6.2	9.0	1.3	2.7	(7.0)	4.7	8.9	(0.7)	2.0
Q losses reduction to ndgu-1998 (GVArh)	-	(11.7)	40.2	47.8	16.9	22.8	(25.4)	31.9	46.1	6.9	12.5	(40.9)	22.5	45.8	(6.5)	4.9

Table H-4: Comparative analysis of case study network 2 power system analysis results.

Circuit capacity requirements (£'000s)	ndgu-1998	ndgu-2003	prm1-2003	dtl1-2003	prm2-2003	prm3-2003	ndgu-2008	prm1-2008	dtl1-2008	prm2-2008	prm3-2008	ndgu-2013	prm1-2013	dtl1-2013	prm2-2013	prm3-2013
Value of 33kV OH km requirement change	-	-	-	-	-	-	-	-	30	-	-	-	-	-	-	-
Value of 33kV UG km requirement change	-	-	195	(1)	(29)	309	-	285	359	427	432	-	282	567	443	-
Value of 132kV OH km requirement change	-	-	522	522	522	522	-	533	533	243	533	-	708	708	418	-
Value of 132kV UG km requirement change	-	-	5	5	-	5	-	5	5	-	-	-	5	5	-	-
Transformer capacity requirements (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 400kV transformers change		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV transformers change	-	-	200	200	200	200	-	400	400	400	400	-	400	400	400	-
Value of 33kV transformers change	-	-	160	40	200	360	-	160	80	240	360	-	160	160	200	-
Swicthgear requirements (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV switchgear requirement	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 33kV switchgear requirement	-	-	3,200	1,600	-	-	-	-	400	-	-	-	-	-	-	-
Value of 11kV switchgear requirement	-	-	-	-	-	50	-	-	-	-	-	-	-	-	-	(50)
Energy Losses (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of P losses reduction	-	(71)	204	135	67	199	(152)	170	159	29	162	(243)	136	114	(23)	166
Value of Q losses reduction	-	(12)	50	44	16	37	(26)	44	43	10	30	(42)	38	41	2	31

Table H-5: Evaluation of distributed generation scenarios impact on case study network 1 in £'000s.

Circuit capacity requirements (£'000s)	ndgu-em-1998	ndgu-em-2003	prm1-em-2003	dtl1-em-2003	prm2-em-2003	prm3-em-2003	ndgu-em-2008	prm1-em-2008	dtl1-em-2008	prm2-em-2008	prm3-em-2008	ndgu-em-2013	prm1-em-2013	dtl1-em-2013	prm2-em-2013	prm3-em-2013
Value of 33kV OH km requirement change	-	-	4	58	-	58	-	4	58	-	58	-	4	4	-	58
Value of 33kV UG km requirement change	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV OH km requirement change	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV UG km requirement change	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Transformer capacity requirements (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 400kV transformers change		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV transformers change	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 33kV transformers change	-	-	-	-	-	40	-	-	-	40	40	-	-	-	40	40
Swicthgear requirements (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 132kV switchgear requirement	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of 33kV switchgear requirement	-	-	-	1,200	-	-	-	-	-	-	-	-	-	-	-	-
Value of 11kV switchgear requirement	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Energy Losses (£'000s)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Value of P losses reduction	-	(61)	226	269	88	136	(133)	192	276	39	84	(214)	144	274	(22)	62
Value of Q losses reduction	-	(3)	10	12	4	6	(6)	8	12	2	3	(10)	6	11	(2)	1

Table H-6: Evaluation of distributed generation scenarios impact on case study network 2 in £'000s.

Units: £'000s	ndgu-1998	ndgu-2003	prm1-2003	dtl1-2003	prm2-2003	prm3-2003	ndgu-2008	prm1-2008	dtl1-2008	prm2-2008	prm3-2008	ndgu-2013	prm1-2013	dtl1-2013	prm2-2013	prm3-2013
ΔRRUSt	-	(71)	204	135	67	199	(152)	170	159	29	162	(243)	136	114	(23)	166
ΔRCONt	-	-	3,200	1,600	-	50	-	-	400	-	-	-	-	-	-	(50)
ΔRRWt																
ΔREXUSt																
ΔCC.GRRt																
ΔCC.LRRt	-	-	(1,082)	(766)	(893)	(1,396)	-	(1,383)	(1,407)	(1,310)	(1,724)	-	(1,555)	(1,840)	(1,460)	-
ΔCC.EHSt																
ΔCC.NCt	-	-	3,200	1,600	-	50	-	-	400	-	-	-	-	-	-	(50)
ΔCC.PIt																
ΔCC.PQIt																
ΔCC.ARt																
ΔCO.PERt																
ΔCO.REPt																
ΔCO.MNTt																
ΔCO.ITt																
FDGt	-	(71)	1,286	901	960	1,594	(152)	1,553	1,566	1,339	1,887	(243)	1,691	1,954	1,437	166

Table H-7: Distributed generation value function components for case study network 1 in £'000s.

	ndgu-em-1998	ndgu-em-2003	prm1-em-2003	dtl1-em-2003	prm2-em-2003	prm3-em-2003	ndgu-em-2008	prm1-em-2008	dtl1-em-2008	prm2-em-2008	prm3-em-2008	ndgu-em-2013	prm1-em-2013	dtl1-em-2013	prm2-em-2013	prm3-em-2013
ΔRRUSt	-	(61)	226	269	88	136	(133)	192	276	39	84	(214)	144	274	(22)	62
ΔRCONt	-	-	-	1,200	-	-	-	-	-	-	-	-	-	-	-	-
ΔRRWt																
ΔREXUSt																
ΔCC.GRRt																
ΔCC.LRRt	-	-	(4)	(58)	-	(98)	-	(4)	(58)	(40)	(98)	-	(4)	(4)	(40)	(98)
ΔCC.EHSt																
ΔCC.NCt	-	-	-	1,200	-	-	-	-	-	-	-	-	-	-	-	-
ΔCC.PIt																
ΔCC.PQIt																
ΔCC.ARt																
ΔCO.PERt																
ΔCO.REPt																
ΔCO.MNTt																
ΔCO.ITt																
FDGt	-	(61)	230	327	88	234	(133)	196	334	79	182	(214)	148	278	18	160

Table H-8: Distributed generation value function components for case study network 2 in £'000s.