Decision Support for New and Renewable Energy Systems Deployment

By Nicola Anne Visocchi Smith

A Thesis for the degree of Doctor
of Philosophy

University of Strathclyde
Department of Mechanical Engineering
Energy Systems Research Unit

2002

Abstract

The global requirement for sustainable energy provision will become increasingly important over the next fifty years as the environmental effects of fossil fuel use become apparent. Therefore, the issues surrounding integration of renewable energy supplies need to be considered carefully. The focus of this work was the development of a decision support framework that will aid the design of sustainable energy systems for the supply of electricity, heat, hot water and fuel for transportation.

Issues requiring consideration in high percentage renewable energy systems include the reliability of the supply when intermittent sources of electricity are being used, and the subsequent necessity for storage and back-up generation. In order to allow the modelling of realistic integrated systems that supply the total energy needs of an area, the production of fuels derived from biomass and waste and their use in a variety of different plant types (e.g. vehicles, engines, turbines, fuel cells, electrolysers, heating and hot water storage systems) is an important consideration. The temporal nature of both intermittent electricity and derived fuel supplies must be taken into account in any analysis.

Existing demand and supply matching software has been enhanced to allow the full analysis described. Generic algorithms have been developed to allow the behaviour of a comprehensive list of plant types and methods for producing derived fuels to be modelled, which require only available process and manufacturers' data. The program is flexible, generic and easy to use, allowing a variety of supply strategies to be analysed. This has been shown through the study of a small Scottish island, which highlights the importance of derived fuel production and use.

This work has succeeded in developing a more complete tool for analysing the feasibility of integrated renewable energy systems. This will allow informed decisions to be made about the technical feasibility of supply mix and control strategies, plant type and sizing, suitable fuel production, and fuel and energy storage sizing, for any given area and range of supply options.

Acknowledgements

I would like to express my sincere gratitude to all the people and organisations who provided help and support to me throughout this project.

Particular thanks go to Professor Joe Clarke for his guidance and advice, to Doctor Francesca Born for providing a good basis on which to build my work, and to Cameron Johnstone and Lori McElroy for their help and encouragement. My gratitude also goes to the rest of the ESRU team for their support, and to the EPSRC for funding this work.

My thanks go to my parents for their encouragement, and to my mother for her efficient back up and archiving services.

Finally, and most importantly, I would like to thank my husband Chris for his practical and emotional support, without which this project would never have been started or finished.

CONTENTS

FIGURES

1 Energy Systems for Sustainable Living

Sustainable design can be described as that which enhances ecological, social and economic well being, both now and in the future [1]. The global requirement for sustainable energy provision will become increasingly important over the next fifty years as the environmental effects of fossil fuel use become apparent. As new and renewable energy supply technologies become more cost-effective and attractive, a greater level of both small-scale and large-scale deployment of these technologies will become evident. This chapter discusses the problem of increasing global energy use, potential sustainable energy supply system options, and the various complex integration issues that are inherent in the design of sustainable energy supply systems that are both reliable and efficient. The creation of a decision support framework is proposed that will aid the technical design of sustainable energy systems, in order to encourage and support planning for future development.

Since the discovery of fire, and the harnessing of animal power, mankind has captured and used energy in various forms for different pruposes. This has included the use of fire, fuelled by wood, biomass and other waste for cooking, heating and the melting of metals, the use of windmills, waterwheels and animals to produce mechanical work, and the use of animals for transportation. However, it was not until the industrial revolution that humans began to rely heavily on energy utilisation for everyday life. With the development and exploitation of electricity, the discovery of abundant reserves of fossil fuels with higher energy densities than biomass fuels, and the rapid expansion of energy intensive industrial processes and vehicles, the use of energy in industrialised countries increased at an incredible rate, with no concern for energy conservation as fuels were inexpensive and plentiful. In fact, machines that were originally designed to run on biomass derived fuels (e.g. Rudolf Diesel's first engine ran on peanut oil [2] and the Model T Ford was designed to run on alcohol [3]), were redesigned to run on fossil fuel derived fuels as these were abundant and cheap. From this beginning, the development of machines, processes and methods for generating electricity and heat have continued to rely on the use of fossil fuels, energy demand has continued to grow, and energy use, particularly in the forms of electricity and transportation fuel, has become a vital part of our technological society.

Around two hundred years later, an increased understanding of the environmental effects of burning fossil fuels has led to stringent international agreements, policies and legislation regarding the control of the harmful emissions related to their use [4]. Despite this knowledge, global energy consumption continues to increase due to rapid population growth and increased global industrialisation. In order to meet the targets laid down, a greater awareness of energy efficiency among domestic and industrial users throughout the world will be required, and domestic, commercial and industrial buildings, industrial processes, and vehicles will need to be designed to keep energy use at a minimum. Increased energy efficiency and improved design, however, will not be enough on their own.

If emission targets are to be met, various measures must be taken. The current reliance on fossil fuels for electricity generation, heating and transport must be greatly reduced, and alternative generation methods and fuels for heating and transport must be developed and used. Alternatively fuelled vehicles, and the refuelling infrastructure to support them, also require to be developed, and the use of these vehicles must be encouraged. The implementation of these changes over the next fifty to one hundred years will significantly change the way in which energy is currently produced, distributed and used worldwide, and well considered forward planning and research into suitable supply options will be crucial to the effective future deployment of sustainable energy supply systems.

1.1 Energy Use in the United Kingdom

Figure 1.1 shows the final use for the overall energy consumed in the UK between 1970 and 2000 [5]. From this it can be seen that the energy use in all sectors, except the industrial sector, has increased during this period. Importantly, the energy use for transport has almost doubled in this 30-year period, and continues to grow, representing over a third of the overall primary energy use in 2000. Similar patterns can be seen in other industrialised and developing nations, showing energy use for transport to be a significant and increasing problem [6]. The reduction in energy use in industry, which has levelled off within the last decade, is due to both the general decline in the industrial sector in the UK over this time, and the adoption of energy efficient practices. Despite this, there has been a 10% increase in the overall annual energy use in the UK since 1970.

Figure 1.2 shows the contribution of the main primary energy carriers to the total energy consumption in the UK in 2000 [5]. It can be seen that the use of fossil fuels (coal, oil and gas) accounted for 90% of the total UK energy supply in 2000, which is an increase of 1% on the previous year.

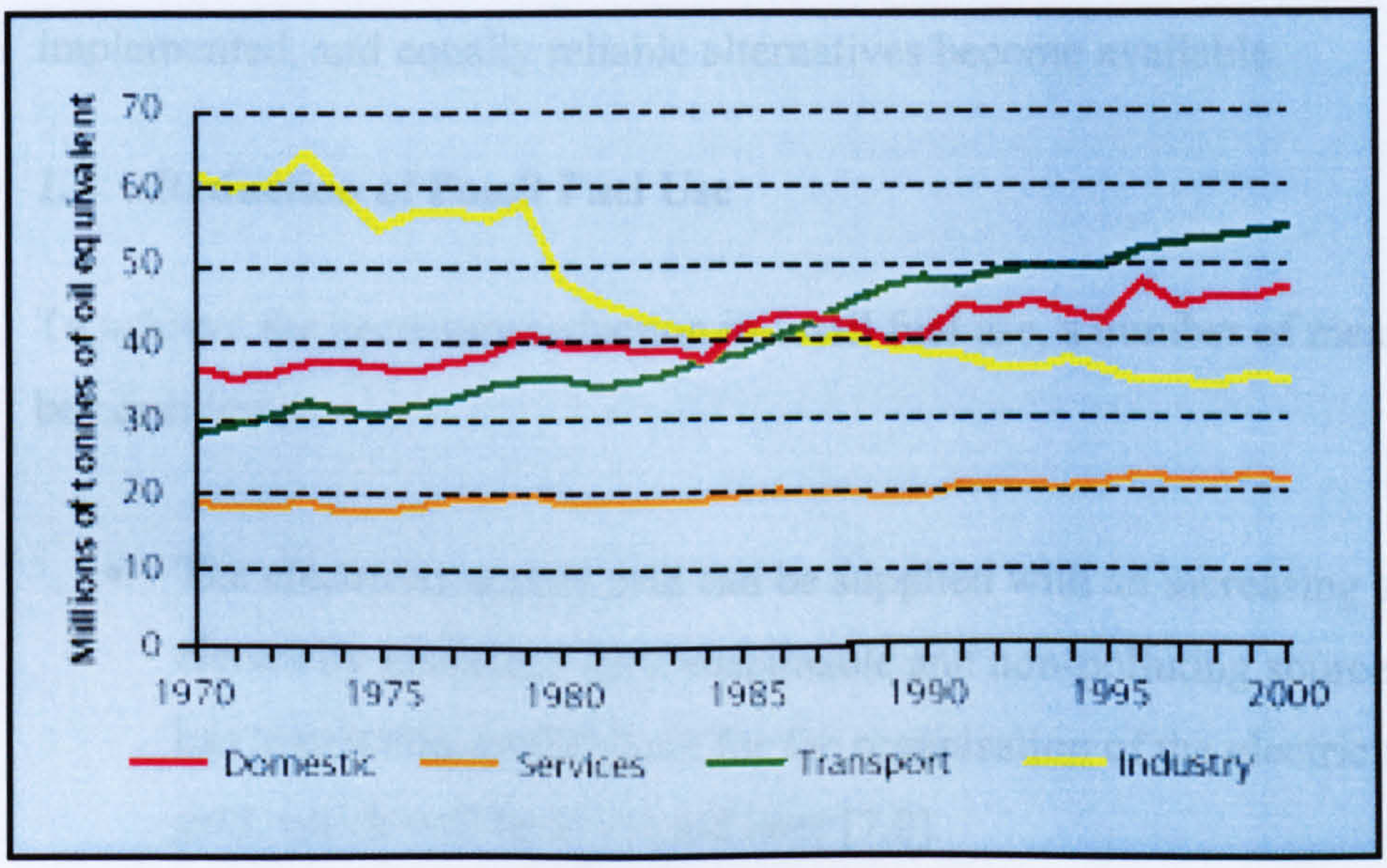


Figure 1.1 Final Energy Consumption 1970 to 2000 [5]

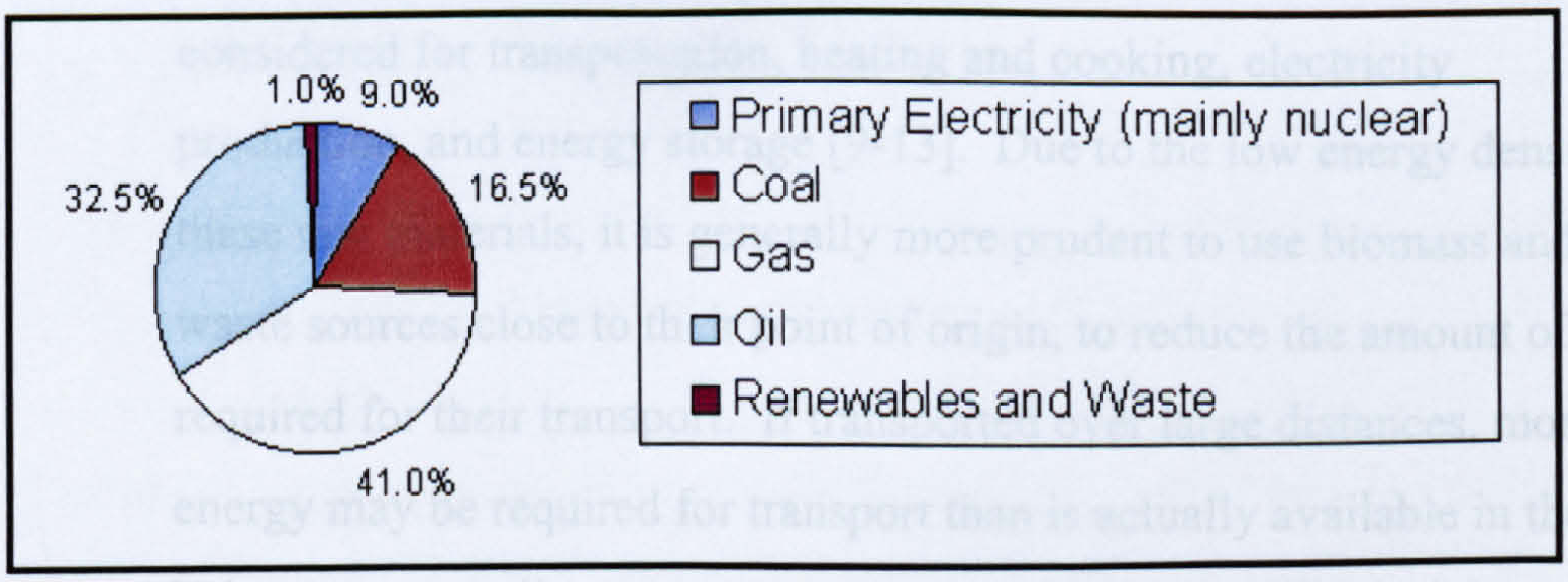


Figure 1.2 UK Primary Energy Consumption in 2000 [5]

The general increase in energy consumption and overall reliance on fossil fuels shown here are not unique to the United Kingdom. Global energy consumption is increasing, and this is particularly noticeable in the developing nations as they move towards industrialisation [6]. It is therefore important that, where new energy demands are created, these are met, where possible, by sustainable and non-polluting means, in order to stop the escalation of the already visible environmental effects of fossil fuel use. This alone, however, will not be enough to meet emissions targets, and reduce the environmental threat posed by the production of carbon dioxide and other pollutants. To achieve this, the current reliance on fossil fuels for all energy uses must be reduced, and, eventually, eliminated. Consequently, it will be necessary to re-evaluate the way in which energy is produced, distributed and used in the UK and worldwide. This, however, will not happen until less expensive, easily implemented, and equally reliable alternatives become available.

1.2 Reduction of Fossil Fuel Use

To achieve the necessary reduction in fossil fuel use, a number of measures can be considered: -

- The electricity supply grid can be supplied with an increasing amount of electricity generated from sustainable and non-polluting sources. This has interesting implications for the organisation of the electricity supply grid, which will be discussed later [7,8].

- The use of waste and biomass, or fuels derived from these, can be considered for transportation, heating and cooking, electricity production, and energy storage [9-13]. Due to the low energy density of these raw materials, it is generally more prudent to use biomass and waste sources close to their point of origin, to reduce the amount of fuel required for their transport. If transported over large distances, more energy may be required for transport than is actually available in the fuel being transported!

- The use of combined heat and power (CHP), where the waste heat from electricity production is used for space and water heating or cooling (increasing fuel utilisation often by a factor of two or more), and the use of efficient district heating schemes, powered either by CHP or heat only plant, could be encouraged [8-13]. These could be fuelled by waste, biomass or derived fuels. This type of system has become popular in hospitals and hotels where there is a large electricity and heat demand [14], and is also being used to provide electricity and air conditioning for buildings that house multiple internet servers, as a way to reduce costs and secure a vital uninterrupted supply [15].

- Due to the availability of efficient small scale renewable energy generating plant, it can be worthwhile for many users (e.g. individual buildings, hospitals, farms, small communities) to consider on-site electricity, heat, hot water and transportation fuel generation for their own use, especially where there are exploitable local resources (e.g. a source of biomass or waste fuel, and/or a local wind or solar resource) [9-13]. This would significantly benefit areas where the import of fuel by pipeline, electricity grid or transport is difficult or expensive (e.g. on islands or in other remote areas), and may benefit many other areas or buildings, regardless of location, due to reduced energy costs, improved reliability, and the possible reduction of waste disposal needs.

- Alternative forms of transport, alternatively fuelled vehicles, and the refuelling infrastructure to support these could be developed and encouraged [3,10].

- Alternatives to the direct use of natural gas and other fossil fuels for heating and cooking could be encouraged [9,10].

The use of local resources to supply the local area (whether that be a building, small community or entire country) has definite economic, political and environmental advantages. Reliance on other areas or countries for energy supply is reduced or eliminated, lowering costs, and providing security of supply and self-sufficiency. The need for transportation of fuels by ship, pipeline, grid or other means is also reduced, lessening the fuel use or energy loss associated with these activities, and the environmental effects of accidents.

The types of primary energy used, generation of other energy carriers (e.g. electricity or biofuels), and distribution methods used in different areas will vary with the available local resources and the patterns of demand for electricity, heat, hot water and transport. It will, therefore, be necessary to look at the overall energy resources and requirements for different individual areas, and to find the best match between the total energy requirements for a specific area and the available resources.

1.3 Electricity Generation From Renewable Energy Sources

One of the main demands for energy is in the form of electricity, and electricity supply grids are well established in most areas of the developed world. However, the methods for generating electricity from renewable sources, and the siting of the generating plants, can be quite different from the conventional methods for electricity generation from fossil fuels. This has interesting implications for the future design of these grids, particularly if an increasing percentage of the electricity is supplied from renewable sources. In order to describe these differences, electricity generators can be classed in three main categories – capacity limited, energy limited and intermittent [7], and these are described below.

1.3.1 Traditional Thermal Plants

Coal-fired, gas-fired, oil-fired and nuclear power plants, which supply almost all of the electricity to the national grid in the UK, can be classed as capacity limited. In this type of plant the amount of electricity that can be generated is limited by the physical capacity of the plant and availability constraints such as required time for maintenance and any unplanned outages. Traditional plants tend to have large generating capacities, requiring expensive heavy-duty transmission lines and conversion equipment. Electricity is transmitted from these central points, splitting off again and again like the branches of a tree to supply electricity to both cities and remote areas. These large generating plants are interlinked to create a large supply grid, and are often situated far from the point of use of the electricity, which leads to significant losses in the transmission lines (on average 2.5% per 100km, depending on the capacity of the line [16]). This can be seen in Figure 1.3, which shows a schematic of the electricity supply grid in England and Wales [16] - this whole area being served by around forty power stations. Nuclear power stations, though not fed by fossil fuels, have other environmental and safety concerns, including radioactive waste disposal, contamination of surrounding land and water, and the possibility of minor and major accidents.

1.3.2 Renewable Energy Generators

Energy limited plants are limited by the amount of energy or fuel available to them at a certain time from a certain area (e.g. rainfall, waste, seasonal energy crop yields) and cannot always run at their rated capacity. Examples of this type of plant would be hydropower with reservoirs, and biomass, landfill gas or waste fuelled generators. Energy limited generators have an inbuilt storage capacity that is not available with intermittent sources, and the storage capacity available depends on the size of reservoir for hydroelectric schemes and the size of storage facilities and length of time the fuel can be stored without significantly degrading for the other types of plant. The storage capacity and generally fast response of these types of plant allows them to act as spinning reserve in a network, providing electricity at peak times to help match supply with demand. Currently, only hydroelectric plants are common in the UK, though an increasing number of small capacity biomass and waste plants are being considered and built. This type of plant tends to have a much lower rated capacity than the traditional thermal plant due to limited local resources, and the low energy density of the fuels making transportation of the fuel difficult and expensive in energy terms.

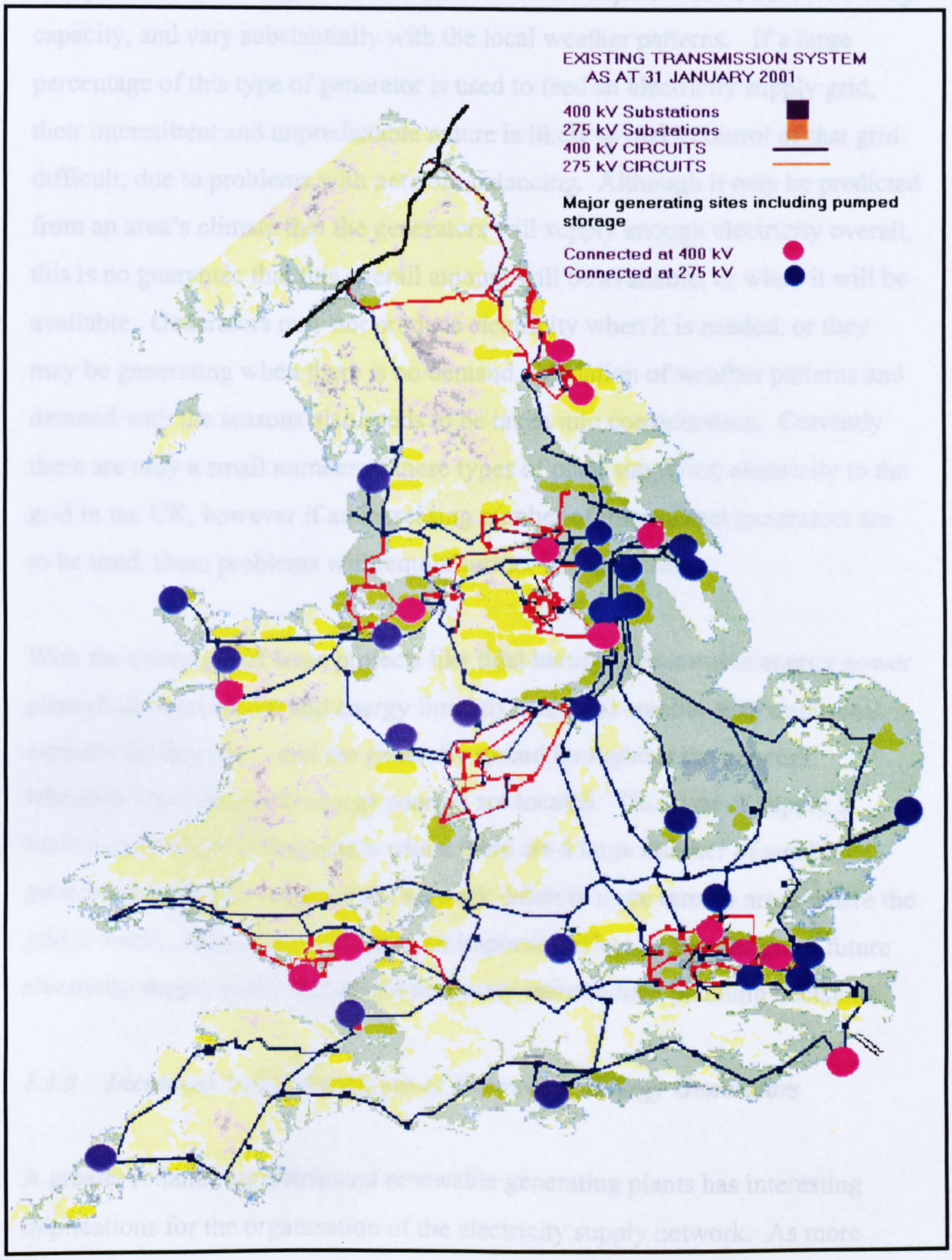


Figure 1.3 The Electricity Supply Grid for England and Wales [15]

The other main class of renewable energy sources are those that are intermittent in nature (e.g. wind, wave, solar, tidal, run-of-the-river hydro). With the exception of tidal energy, intermittent sources are unpredictable, have no storage capacity, and vary substantially with the local weather patterns. If a large percentage of this type of generator is used to feed an electricity supply grid, their intermittent and unpredictable nature is likely to make control of that grid difficult, due to problems with network balancing. Although it may be predicted from an area's climate that the generators will supply enough electricity overall, this is no guarantee that this overall amount will be available, or when it will be available. Generators may not produce electricity when it is needed, or they may be generating when there is no demand. Variation of weather patterns and demand with the seasons also needs to be taken into consideration. Currently there are only a small number of these types of plant supplying electricity to the grid in the UK, however if an increasing number of intermittent generators are to be used, these problems will require further investigation.

With the exception of large projects like tidal barrages, renewable energy power plant (both intermittent and energy limited) tend to be smaller than traditional capacity limited plant, and are generally spread throughout the network wherever the exploitable energy sources are located. This type of supply is known as distributed generation where there are a large number of smaller generators located throughout the network, often in more remote areas where the grid is weak. This, again, will have an important effect on the design of future electricity supply grids, and on the necessary intermediate planning decisions.

1.3.3 Increased Grid Penetration of Renewable Energy Generators

A greater reliance on distributed renewable generating plants has interesting implications for the organisation of the electricity supply network. As more distributed sources start to be utilised, a more interconnected network should emerge. Having a larger number of minor generators throughout the network should allow many smaller areas of that network to become mainly self-sufficient, with the rest of the grid there only for backup. These areas will rely on different generation mixes depending on the type of area, suitable sites, and available local resources.

Distributed generation will also bring a number of other benefits. If electricity is generated closer to the end user by smaller plants it will not need to be transmitted as far, and at such large power densities. Transmission line and conversion losses will therefore be reduced, though remote networks containing generators may need to be upgraded. Also, if power transmission densities are reduced, it may allow more overhead lines to be economically replaced with underground cables, alleviating the health, safety and visual disturbance issues relating to overhead cables [11]. Although the exact effects need to be investigated, distributed generation should help strengthen the grid, and allow greater autonomy and a better security of supply, particularly in remote areas.

Inevitably, the way the electricity supply grid is organised will change radically with the inclusion of increasing amounts of distributed renewable electricity generation. The situation will gradually change as individual thermal power plants reach the end of their lives and are replaced by increasing numbers of distributed renewable generators. Unfortunately, the intermittent nature of the most easily exploited sources (wind and solar) is likely to cause problems as ever-increasing amounts of these intermittent sources are used to supply the electricity network. This has implications for the management of this transitional period as the balance between supply and demand must be maintained as efficiently and reliably as possible while the system moves towards the ultimate goal of a 100% renewable energy supply over the next fifty to one hundred years.

Opinion is divided as to the effect that a significant amount of intermittent electricity sources would have if integrated into a larger-scale electricity supply network. McLarnon and Cairns [8] state that energy storage is critical to systems supplied with intermittent energy, while Grubb [7] states that it should be possible to have large systems with well over half of their power from intermittent sources, provided that there is a large amount of fossil fuelled spinning reserve. This reserve, however, could be supplied by plant run on fuels derived from biomass and waste. These issues must be resolved in order to design reliable renewable energy systems. There is, however, no one solution, and the situation will vary substantially with the size, type, location and climate of the area being considered, and with the available local resources and energy demand patterns.

As the grid moves towards greater reliance on intermittent renewable sources, it would be useful for utilities, local authorities and other decision makers to be able to determine how renewable electricity generation could be maximised given the various attributes, constraints, potentials, and other energy requirements (for heat and transport) of specific areas. This would allow decisions to be made to aid the transition between the current situation and a future, mostly renewable, electricity supply network with a substantial amount of distributed generation, and largely self-sufficient network areas.

1.4 High Renewable Energy Penetration in Small Areas

The most significant developments currently taking place in high percentage or 100% renewable energy supply are in small-scale projects, particularly on islands and in remote areas, where the import of energy sources via transport, pipeline or electricity grid is difficult or expensive [17,18]. Individual buildings, industries and farms are also looking to the possibility of energy self-sufficiency to reduce fuel bills, and make good use of waste materials which are becoming increasingly difficult and expensive to dispose of [19]. It is through this type of autonomous application that the main developments in renewable energy use are currently taking place. This is because renewable energy systems are becoming increasingly cost competitive in these situations due to the greater comparative cost of conventional energy supplies, and increasing waste disposal costs. Valuable lessons will be learned from these applications, which may be applied to other energy supply systems as further experience, research, increased manufacture, and economies of scale make such systems more reliable and economically desirable.

Various studies have been carried out into the extensive use of new and renewable resources, to generate electricity, on a small scale, for rural communities, grid-isolated islands and individual farms [17-25]. These studies have generally been for autonomous systems, though some have used a grid connection as a backup. Although the studies have different emphases, they all recognise a few common and important points.

- To allow security of supply when considering intermittent sources, demand and supply must be as well matched as possible, and this is generally a function of climate. For example, in warm climates like that of California, high demands are recorded during the day as air conditioning units are run, and this matches the available solar energy resource. The UK is not so fortunate, with little correlation between the two main intermittent sources (wind and solar) and energy demand. A further problem for the UK is the increased demand during the winter months, mainly for heating, with a small increase in wind power and a large reduction in solar power to meet that demand. Therefore, all available supply sources should be considered in order to find the best possible correlation between demand and supply.

- To allow security of supply, it is prudent to use as diverse a mix of generation methods as is available, allowing the variable and unpredictable nature of individual sources to be partially compensated for.

- Where possible, energy limited sources should be used as spinning reserve for times when the intermittent supply does not meet the demand. If this type of spinning reserve is not available, the need for adequate electricity storage was shown to be an important consideration, especially in smaller scale projects. For some climates it may be important to consider the need for inter-seasonal fuel storage or increased generating capacity during the winter months.

These studies are, however, only concerned with electricity supply. The important issues of energy demand for transportation, hot water and heat have not been addressed, and any full analysis of the energy needs of an area must also consider these.

1.5 Decision Support Framework

Although various studies have been carried out to find the best supply mix for given areas, results from specific studies cannot be easily applied to other situations due to area-specific resources and energy-use profiles. This is because the ideal way to organise an energy supply system, with a large percentage of renewable resources, will vary substantially with the size and type of area (rural, urban), climate, location, typical demand profiles, and available renewable resource mix. Therefore, a decision support framework is required in order to aid the design of future renewable energy supply systems (both large and small), effectively manage transitional periods, and encourage and advance state-of-the-art deployment as systems become more economically desirable. This system model will concentrate on the technical feasibility of possible renewable energy supply systems, although the ultimate decision will also be affected by wider economic and political issues.

The proposed decision support framework will allow possible supply scenarios to be quickly and easily tried, to see how well the demands for electricity, heat and transport for any given area can be matched with the outputs of a wide variety of possible generation methods. These generation methods will include the generation of electricity from intermittent sources, the production of fuels derived from waste and biomass and their use in CHP, heating and energy limited plant, and the use of electricity and derived fuels for transportation. The framework will allow the appropriate type and sizing of spinning reserve, fuel production and energy storage to be ascertained, and will support the analysis of supplies and demands for an area of any type and geographical location, to allow potential renewable energy provision on the small to medium scale (from an individual building to a medium sized community) to be analysed. This system will aid the making of informed decisions about suitable overall energy provision for smaller areas, and help guide the transition towards higher percentage sustainable energy provision in larger areas.

This work considers the various ways in which the total energy needs of an area may be met in a sustainable manner, the problems and benefits associated with these, and the ways in which they may be used together to form reliable and efficient energy supply systems. Consideration is given to the type of decision support framework that is required, and the proposed system is described in detail. The applicability and relevance of the decision support framework are shown through the use of a case study, which highlights the complex nature of sustainable energy supply system design.

1.6 Outline of Thesis

Demands for electricity, heat, hot water and transportation fuel may be met, in a sustainable manner, using a number of different processes. These may use climate related sources, biomass or waste fuels, or fuels derived from biomass or waste. Chapter 2 discusses currently available supply technologies for these demand types, methods for producing fuel from biomass and waste, storage technologies and possible overall supply scenarios.

Chapter 3 looks at existing methods for aiding the design of renewable energy systems, and discusses what is required from this type of system. Chapter 4 describes the requirements for a demand and supply matching tool that will allow possible sustainable energy system designs to be evaluated, and shows how this can be achieved by enhancing an existing software package.

Chapter 5 details the algorithms used to describe the behaviour of the supply systems that may be used to follow the demand for all energy types. These include the use of electricity and a variety of fuels derived from biomass and waste in vehicles, engines, turbines and fuel cells, with possible CHP generation. An electrolyser model is included to allow the use of excess electricity for the manufacture of hydrogen, which may then be used in any of the plant described. Also considered are different types of heating system, and the use of electrical storage heaters and hot water storage systems that take in excess electricity or heat.

Chapter 6 describes the algorithms used to model the production of fuels from a variety of biomass and waste sources using various processes. These include transesterification to produce biodiesel, anaerobic digestion, landfill gas production and gasification to produce biogas, fermentation to produce ethanol, electrolysis to produce hydrogen from a dedicated intermittent source, biogas processing to produce hydrogen and methanol, pyrolysis to produce oil and charcoal, and other waste and biomass processing technologies. Some of these processes have energy demands associated with them, and this is taken into account.

Chapter 7 gives a user's view of the developed software package, and discusses how the correct behaviour of the added functionality was verified. Chapter 8 tests the applicability of the program using a relevant case study, highlighting the use of biomass, waste, and derived fuels to complement intermittent renewable energy sources.

Finally, Chapter 9 presents the conclusions of this study, and recommendations for future work.

This chapter discussed the need for sustainable energy development, and the planning issues relating to sustainable energy supply system design. A decision support framework is proposed that will aid the technical design of efficient and reliable sustainable energy systems, in order to support planning for, and encourage, future development. The range of currently available system components that require consideration to allow a full investigation of sustainable energy system design, for any given area, are described in Chapter 2

1.7 References

[1] The International Institute for Sustainable Development, iisd1.iisd.ca/ic/

[2] National Biodiesel Board, www.biodiesel.org

[3] California Energy Commission, www.energy.ca.gov

[4] The European Commission global overview of renewable energy sources, www.agores.org

[5] Department of Trade and Industry, 'UK Energy in Brief', July 2001, www.dti.gov.uk

[6] BP Amoco, "BP statistical review of world energy 2001", www.bpamoco.com/centres/energy/world_stat_rev/index.asp

[7] M. J. Grubb, 'The integration of renewable electricity sources', Energy Policy, 1991, Vol. 19, No. 7, pp 670-688

[8] F. R. McLarnon, E. J. Cairns, 'Energy Storage', Review of Energy, Vol. 14, pp 241-271

[9] T. B. Johansson et al, "Renewable energy: sources for fuels and electricity", Island Press, Washington, D.C., 1993

[10] The European Commission, "Energy technology – the next steps. Summary findings from the ATLAS project", December 1997

[11] H. Lund, P. A. Ostergaard, "Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation", Energy 25, 2000, pp 299-312

[12] D. McEvoy, D. C. Gibbs, J. W. S. Longhurst, "City-regions and the development of sustainable energy supply systems", Int. J. Energy Res. 2000, 24, pp 215-237

[13] The International Energy Agency, CADDET, www.caddet.org

[14] Transco, Energy Efficiency Best Practice Programme, "chp-sizer – a tool to conduct a preliminary evaluation of CHP for new hospitals and hotels", Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk, 0800 585794

[15] L. Sharpe, "When downtime is a disaster", IEE Review, November 2001

[16] The National Grid Company, www.nationalgrid.com

[17] S. Hermansen, A. J. Neilsen, "Towards 100 % RES supply on Samsoe, Denmark. Three years of experiences in a planning period over ten years", Proc.

of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2001

[18] A. G. Rassu, "Towards 100 % RES supply in La Maddalena Island – Sardinia" ", Proc. of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2000

[19] T. Moore, "Emerging markets for distributed resources", EPRI Journal, March/April 1998

[20] M. A. Castro, J. Carpio, J. Peire, J. A. Rodriguez, 'Renewable energy integration assessment through a dedicated computer program', Solar Energy, 1996, Vol. 57, No. 6, pp 471-484

[21] S. Rozakis, P. G. Soldatos, G. Papadakis, S. Kyritsis, D. Papantonis, 'Evaluation of an integrated renewable energy system for electricity generation in rural areas', Energy Policy, 1997, Vol. 25, No. 3, pp 337-347

[22] A. Mourelatos, D. Assimacopoulos, L. Papagainnakis, A. Zevros, 'Large scale integration of renewable energy sources an action plan for Crete', Energy Policy, 1998, Vol. 26, No. 10, pp 751-763

[23] G. C. Seeling-Hochmuth, 'A combined optimisation concept for the design and operation strategy of hybrid-PV energy systems', Solar Energy, 1997, Vol. 61, No. 2, pp 77-87

[24] F. Bonanno, A. Consoli, S. Lombardo, A. Raciti, 'A logistical model for performance evaluations of hybrid generation systems', IEEE Transactions on Industry Applications, 1998, Vol. 34, No. 6, pp 1397-1403

[25] R. Chedid, S. Rahman, 'Unit sizing and control of hybrid wind-solar power systems', IEEE Transactions on Energy Conversion, 1997, Vol. 12, No. 1, pp 79-85

2 Options for New and Renewable Energy Systems

This chapter discusses the options for, and the issues involved in, the design of integrated sustainable energy supply systems that are reliable and efficient, and allow consideration of transport, heat, hot water and electricity demands. Technologies currently available to meet these demands, and their potential role in the overall supply system, are described.

There are various technologies currently available that will supply the energy needs for transport, heat, hot water and electricity, in a sustainable manner. Electricity may be generated by harnessing weather related sources of energy (e.g. wind, sunlight, waves, rainfall), however, this gives an intermittent and unpredictable output. In order to provide a reliable electricity supply, reduce energy wastage, and enable the energy requirements for heat and transport to be met, the outputs of these intermittent sources may be supplemented by various means. These may include the use of storage devices and/or the use of biomass and waste materials (in their original form, or converted into other fuels) in engines, turbines and fuel cells for the production of electricity and heat, in vehicles for transportation, or in heating supply or storage systems.

When intermittent electricity generating sources are used in a sustainable energy supply system, it is important to consider how well the profiles of demand and supply of electricity match, and it is advisable to seek the best possible match by using varying amounts of a range of different intermittent sources [1]. As discussed in Chapter 1, it is prudent to use as diverse a mix of generators as possible, however, the types of intermittent supply and amount of each used would depend on the local climate, availability of suitable sites, and how well the outputs of these sources match with the profile of demand. Also, to ensure security of supply and avoid excessive waste, the use of spinning reserve fuelled by biomass, waste or derived fuels, or storage devices should be considered.

Where substantial amounts of intermittent sources are used in a system, it is useful to have an outlet for excess electricity (at times when more electricity is generated than there is demand for), in order to avoid wastage [2,3]. This electricity may be stored, using various means, depending on the scale of storage required. This stored electricity would then be available for use at times when there is not enough being generated to meet demand. This type of storage system is useful when the overall amount of excess electricity is equal to the overall demand that cannot be met by generation over a given length of time. The sizing and type of storage system required depends on the relationship between the supply and demand profiles. This type of system, however, only addresses the demand for electricity, and not those for heat, hot water and transport.

If large amounts of excess electricity are being produced (much more than is needed overall to meet the electricity demand), this could be used to make hydrogen via the electrolysis of water [4]. This hydrogen could then be stored, used in heaters or vehicles, or converted back into electricity via a fuel cell later as required. Using excess electricity, this hydrogen could be produced centrally and piped to users, produced at vehicle filling stations, or at individual homes or business premises [5].

Alternatively, excess electricity could be used directly to fuel electric vehicles, recharging at times of low electricity demand, or to produce heat for space and water heating for immediate use, or to be stored as hot water or in storage heaters. When there is an electricity demand that cannot be met by the intermittent generators, a small amount of storage, or generators fuelled with biomass, waste or derived fuels could be used in the system to meet this. The same derived fuels can also be used to fuel vehicles.

If large amounts of excess electricity are not desired, or if there is a low percentage of intermittent generation available in the system, the bulk of the electricity generated will need to come from engines or turbines fuelled with biomass, waste or derived fuels [2]. If this is the case, the use of combined heat and power (CHP) generation should be considered, as this provides much better fuel utilisation and can also help meet the heat demand [6]. When considering CHP, it is important to bear in mind the heat to electricity ratio. This ratio states the amount of usable heat that is generated in comparison to the electricity output, and can vary between 1 and 5 times the electricity output, depending on the type of plant being considered. In a system using CHP, it is important to get the balance between heat and electricity demand as close to the heat to electricity ratio as possible to avoid wastage. This may be achieved by using intermittent supplies to meet some of the electricity demand, by using heat and electricity storage, and/or by using supplementary electrical heating. This optimum balance can be difficult to find, especially where there is a large seasonal variation in heat demand.

Where technologies that are best run continuously (e.g. nuclear power stations or slow response energy limited plant), or supplies with predictable but intermittent outputs (e.g. tidal barrages) are run, the same problem of excess electricity occurs at times of low demand. If CHP is being considered, there is also the problem of excess heat. Again, suitable use should be made of these excesses, and this may be achieved using the various methods described previously.

These examples highlight the complex nature of sustainable energy supply systems, especially when considering the total energy needs of an area and the use of intermittent sources of electricity. The integration and control strategies for all of these components must be carefully considered and implemented, and this complexity has been seen as a barrier to renewable energy system deployment. There are many possible supply combinations that can be employed, and the optimum combination for a given area depends on many factors. The balances being considered can be complex, and this highlights the need for a decision support framework through which the relative merits of many different scenarios and control strategies for a chosen area can be quickly and easily analysed.

This chapter describes the technologies currently available to enable the realisation of the systems described above. Alternative transportation fuels and vehicles, and alternatively fuelled technologies for CHP generation are discussed. The production and storage of heat, and other uses for excess electricity are also considered, along with various methods for producing fuels from waste and biomass sources.

2.1 Meeting the Transport Demand

Fossil fuel use due to transport has increased dramatically over the past decade, and shows little signs of abating. This has caused concern about related environmental and health effects, especially in cities where there is a large volume of traffic. A great deal of work has therefore been carried out to develop alternatively fuelled vehicles that produce little or no pollution, though currently these mainly enjoy fleet use and niche applications due to the lack of refuelling infrastructure, which may prove a substantial barrier to their wider use.

The main fuels that can be used in a variety of land, sea and air vehicles are biogas in natural gas and fuel cell vehicles, biodiesel in diesel vehicles, ethanol and methanol in adapted petrol and fuel cell vehicles, hydrogen in fuel cell vehicles and electricity in electric vehicles [7]. In fact the Model T Ford was originally designed to run on alcohol (ethanol or methanol), the advantage being that it was a 'home-grown' fuel. It was the abundance and relative cheapness of oil at the time of development of the original fuel powered vehicles that changed the predominant fuels to petrol and diesel, and this has remained to the present day.

Biogas can be used in vehicles designed or converted to run on natural gas and in some fuel cell vehicles [8-13]. It must, however, be cleaned first to create a high heating value gas (around 95% methane, a minimum of heavy gases, and no water or other particles) [14]. The use of biogas in vehicles does still produce carbon dioxide and particulate emissions, although these are greatly reduced compared with conventionally fuelled vehicles. Also, as methane is twenty-one times more powerful than carbon dioxide as a greenhouse gas, it is better, where biogas is being produced naturally (e.g. from animal and vegetable wastes or landfill sites), that it is captured and converted, whilst gaining useful work [15]. Increased fuel storage requirements and weight have been barriers to the conversion of petrol cars; however, specially designed vehicles take these issues into account.

The use of alcohol-fuelled vehicles is well tested, and has achieved great success in countries such as Brazil [16]. A variety of flexible fuelled vehicles (FFVs) are available which can run on 100% alcohol (ethanol or methanol), 100% petrol, or a combination of the two [8-13,17-19]. This type of vehicle uses an internal combustion engine (ICE), which is able to sense the percentage of alcohol in the mixture, and adjust its parameters accordingly. The use of alcohol as a fuel does still produce various emissions, though these are substantially lower than if using petrol or diesel. However, as the carbon dioxide produced by these vehicles is reused when growing the crops used to make the alcohol, this process is classed as carbon neutral [7]. Fuel cell vehicles are also being developed with on-board fuel reformers that convert the alcohol to hydrogen, and it is estimated that these will achieve 2.1 to 2.6 times greater fuel efficiency than using the alcohol in an ICE [20]. The efficiency of an FFV is comparable to a petrol engine.

Fuel cell powered vehicles can run on pure hydrogen, producing clean water as the only emission. They are also being designed to run on alcohol, biogas or even petrol, with onboard reformers converting these fuels into hydrogen. These latter vehicles, therefore, still produce some emissions, though fuel efficiencies are greater than equivalent use in ICEs. The use of fuel cell vehicles is less established than the other types of vehicle being considered here, and, although a number of buses are in operation, commercially available cars are still three to five years away from the market, so little performance data is available from manufacturers [13,19,21].

Biodiesel can be used directly in a diesel engine with little or no modifications, and burns much more cleanly and thoroughly than diesel, giving a substantial reduction in unburned hydrocarbons, carbon monoxide and particulate matter. This does still produce carbon dioxide, but this is balanced by the continued growing of the crops used to produce the biodiesel [7]. It is a well-tested fuel, and experience shows that the fuel consumption of a diesel vehicle in litres increases by 10% when it is being run on biodiesel [11,13], due to its reduced lower heating value (LHV), and slightly higher density. This increase, however, is less than would be expected due to the cleaner and more thorough burning of the fuel. Therefore, fuel consumption figures for diesel vehicles may be used directly for biodiesel-fuelled vehicles if they are increased by 10%, and these figures are widely available [8,22].

There are a wide number and range of different types of electric vehicles on the market [8,9,23], which give no emissions at the vehicle (and none overall if renewable electricity generating methods are used). These may be recharged slowly overnight, or at any time, providing an excellent use for off-peak excess electricity. Vehicles may also be recharged quickly (in under 5 minutes), but this should be kept to a minimum to prevent damage to the battery. The travelling range of these vehicles is less than conventionally fuelled vehicles, but is increasing with further research.

None of these types of alternatively fuelled vehicles have, as yet, emerged as a clear front-runner to replace traditional vehicles, but it is likely that different countries or areas will favour different fuels, depending on their available natural resources. For example, biodiesel is becoming a popular alternative in many states of the United States of America where large areas can be devoted to soybean growth [24], whereas Iceland is looking towards a hydrogen economy and the use of fuel cell vehicles [4]. The main barriers to the implementation of alternative fuels will be the requirement for a choice of fuel at a national level, the necessity to create a suitable refuelling infrastructure, the length of time it will take to replace or convert existing vehicles, and the need for a strong public incentive to change.

2.2 Combined Heat and Power Production Technologies

Various types of engine, turbine and fuel cell may be run on a variety of fuels for combined heat and power (CHP) production, and these technologies are described in this section. Plant types which have slow response times are best suited to base load operation, where they are run at a constant percentage load at set times, producing a constant electricity and heat output. Other types, with faster start-up and response times, are also suitable for load following applications, where they can be used to follow the demand for electricity, heat or both.

2.2.1 Internal Combustion and Diesel Engines

Two common load following generation technologies involve the use of diesel in compression ignition engines (diesel engines), and natural gas in internal combustion engines (ICEs). Both of these engine types may also be run on sustainable fuels derived from biomass and waste, with diesel engines running on biodiesel, pyrolysis oil, or vegetable oil, and ICEs running on biogas, ethanol or methanol [25,26], and this requires little or no modification. Diesel engine generating sets with rated outputs from 50 kWe to 10 MWe, and ICE generating sets with rated outputs of between 100 kWe and 2 MWe are available.

These engine types are both suited to CHP production as the electrical output of a typical engine generating set is around 40% of the fuel input, the rest being lost as heat, around 50% of which is recoverable. This gives heat to electricity ratios ranging from 1:1 to 2:1, depending on the efficiency of the engine. The efficiency of these engine types decreases (substantially below 60% of rated power), and the heat to electricity ratio increases at lower percentage loads, which further complicates system design. These engines are also subject to a minimum recommended load, generally around 20% of the rated power [25], and constant starting and stopping should be avoided as this increases engine wear.

2.2.2 Stirling Engines

A Stirling engine is an external combustion engine, where combustion of the fuel does not take place inside the engine, but in an external boiler. Mechanical work is derived from the pressure changes that result from the cyclic heating and cooling of an enclosed working gas [27]. In fact, heat from any source may be used to run a Stirling engine, including concentrated solar rays, and waste heat, but only fuelled Stirling engines will be considered here. This type of engine has many advantages over other engines and turbines as it allows the use of fuels that are hard to process, and it has a fairly simple design, which makes it suitable for small-scale applications, gives the plant a lower capital cost and reduces maintenance costs. Theoretical efficiency is also greater than steam turbines (discussed later), which can also use the same types of fuel, and Stirling engines are particularly suited to CHP production due to the large amount of heat that is passed through the engine cooler [25]. Interest in Stirling engines is beginning to re-emerge due to increased interest in biofuel use; however, they are not yet commonly used. Currently available Stirling engine generating set outputs vary from 1 kWe to 200kWe, although larger engines are feasible. Electrical efficiencies can vary from 15 to 35%, and heat to electricity ratios can be from 1.5:1 to 5:1, again, varying with partial load [27,6].

Stirling engines are better suited to constant loads at specified times of the day and year or continuous operation, rather than load following, due to their fairly slow response times. They are generally run constantly, and sized to provide for the heat demand, with hot water storage smoothing out the peaks and troughs, and electricity production sent to the grid [28,29]. Engines may be run on any number of combustible fuels, including biodiesel, biogas, straw and wood, with varying efficiencies depending on the plant and fuel used [30,31].

2.2.3 Gas Turbines

Another common type of plant used for electricity and heat generation is the gas turbine. Gas turbines may be run on biogas, and are available with rated outputs of between 3 and 50MWe [32]. Their operation is based on the Brayton Cycle, where incoming air is compressed to a high pressure, fuel added to the air is burned to increase the gas temperature and pressure, and the resulting gases are expanded across the turbine blades, giving rotational movement [25]. Coupled to a generator, this provides electricity generation, and waste heat may also be recovered for use. Heat to electricity ratios are typically in the order of 2:1, and electrical efficiencies at full load are around 25 to 30%, again varying with partial load. Fast response and start-up times make gas turbines suitable for load following applications.

2.2.4 Steam Turbines

For larger applications (between 1 and 1000 MW), steam turbines may be used. These use an external boiler to raise steam, which may be fuelled by any type of solid, liquid or gaseous fuel desired. This steam is then expanded across turbine blades to produce rotary motion, and, when coupled with a generator, electricity [25,30,31]. Again, waste heat may be recovered for use. Electrical efficiencies at full load can range from 15 to 50%, depending on the complexity of design. This means that heat to electricity ratios can vary from 1:1 to 5:1, and it is common practice to use a simple, electrically inefficient and relatively inexpensive turbine when there is a useful outlet for large quantities of waste heat. This generation method is particularly suited to the use of large quantities of solid waste or biomass, provided suitable boilers are used, though start-up times are slow. The efficiency of a steam turbine decreases, and the heat to electricity ratio increases at lower loads.

2.2.5 Fuel Cells

The principle of the fuel cell was discovered over 150 years ago, but was not significantly developed until NASA started to investigate their emission free operation for use in spacecraft. Over the past two decades, further investigation has also been carried out into their use in vehicles, and in stationary and portable applications. As a result of this increased interest, stationary power plants from 200W to 2 MW are now commercially available, with efficiencies ranging from 30 to 50% and heat to electricity ratios from 0.5:1 to 2:1 [33-35]. As the efficiency of a fuel cell typically increases at lower loadings, the opposite situation to all the other plant being considered here, fuel cells are more suited for low load factor applications, and this, coupled with their fast response, make them well suited to load following and transport applications.

Fuel cells are classified by the type of electrolyte they use, and this dictates the type of fuel and operating temperature that are required. The most commonly used fuel cell for small scale and transport applications, due to its low operating temperature, and compact and lightweight form, is the Proton Exchange Membrane fuel cell (PEMFC). Phosphoric Acid and Molten Carbonate fuel cells (PAFC and MCFC) are also available for larger scale applications, and require higher operating temperatures (roughly 200°C and 650°C), which means they must be kept at this temperature if fast start-up is required. All of these fuel cells may be run on pure hydrogen, natural gas or biogas. Certain PAFCs may also use methanol or ethanol as a fuel. If pure hydrogen is used, the only emission from a fuel cell is pure, clean water. If other fuels are used, some emissions are given off, though the amounts are lower due to the better efficiencies achievable with fuel cells, especially at partial load. Figure 2.1 shows the basic components of a fuel cell.

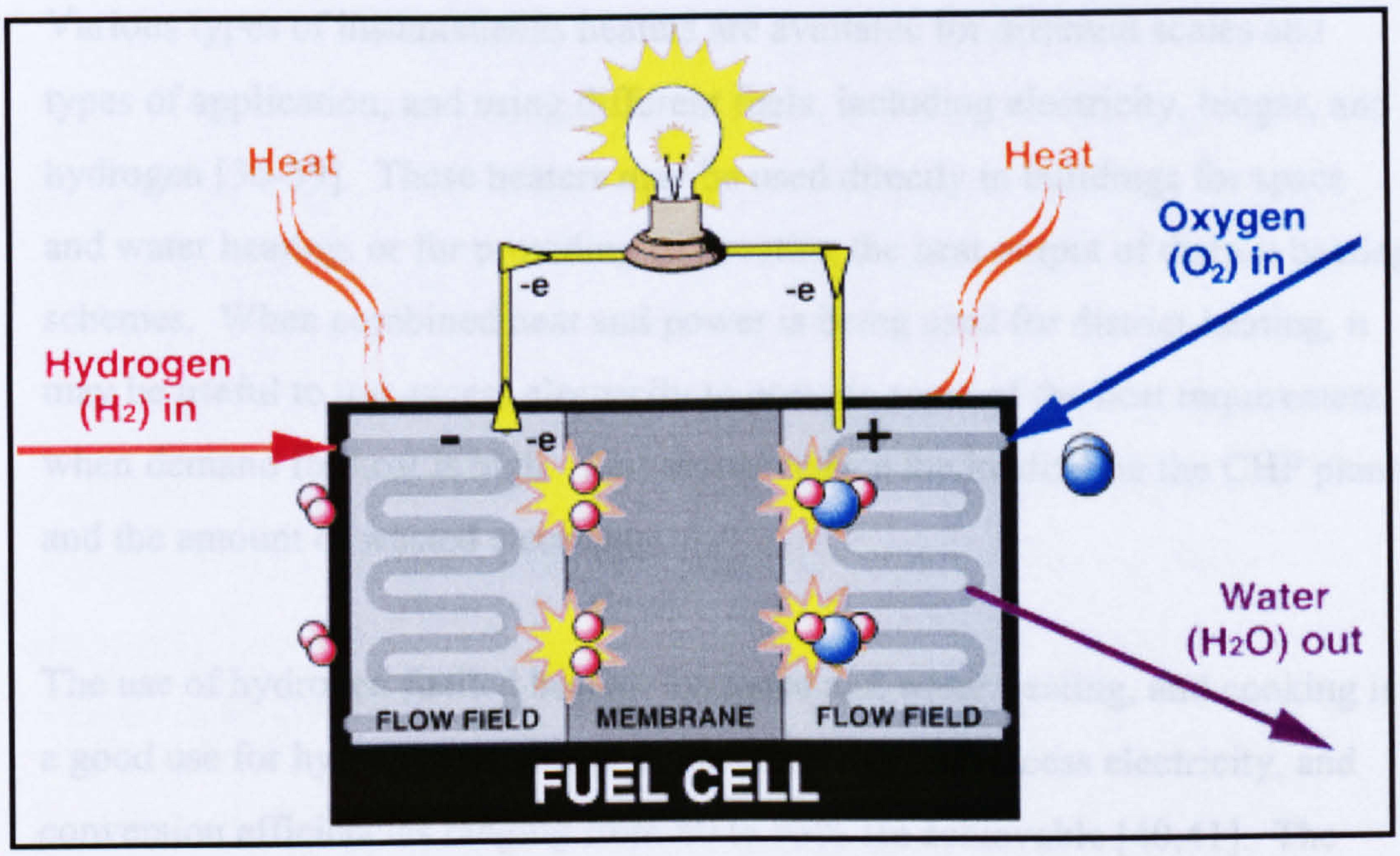


Figure 2.1 Basic Components of a Fuel Cell [41]

2.3 The Production and Storage of Heat

The demand for space and water heating may be met through the use of CHP, or through dedicated heaters using electricity or fuels derived from biomass or waste. This heat may be produced on demand, or produced and stored in electric storage heaters for space heating (using excess electricity when available), or in hot water storage tanks (heated by excess heat from dedicated boilers or CHP systems, or excess electricity). This storage provides a good use for excess electricity in a system, allows dedicated boilers to be run continuously, and/or allows CHP plant to follow the electricity demand or run continuously. Heat stored as hot water may be used later for space heating and the supply of hot water.

2.3.1 Instantaneous Space and Water Heaters

Various types of instantaneous heaters are available for different scales and types of application, and using different fuels, including electricity, biogas, and hydrogen [36-39]. These heaters may be used directly in buildings for space and water heating, or for providing or boosting the heat output of district heating schemes. When combined heat and power is being used for district heating, it may be useful to use excess electricity to provide some of the heat requirement when demand for heat is high. This would reduce the loading on the CHP plant, and the amount of wasted electricity.

The use of hydrogen fuelled heaters for space and water heating, and cooking is a good use for hydrogen produced by electrolysis from excess electricity, and conversion efficiencies ranging from 80 to 95% are achievable [40,41]. The production of heat from electricity is 100% efficient, though not necessarily the best use for this high grade energy source, and biogas heating systems have electricity to heat conversion efficiencies of 60% to 80%, depending on the type of plant used. Biomass and waste, generally in the form of pellets, can also be used for space heating in domestic-sized and larger boilers, though start-up and response to change in demand times are slower. Figure 2.2 shows the similarity in design between a hydrogen fuelled domestic heater and a wood pellet boiler.

Figure 2.2 A Hydrogen Fuelled Heater and a Wood Pellet Fuelled Boiler [37,41]

2.3.2 *Space Heating Storage Heaters*

Many electricity supply networks provide a two-rate tariff structure to encourage the use of electricity throughout the night, when demand is low, in an attempt to level the electricity demand curve and reduce peak loads. A common outlet for this cheaper electricity is the use of night storage heaters, which take in electricity during the night, convert it into heat, and store it in heat storing bricks. This heat is then available for use, when desired, throughout the day. In the context of a renewable energy supply system, this type of heater could provide a form of storage, and a useful outlet for excess electricity, either whenever it is available, or between a set start and end time, providing heat at any time to meet the demand as necessary.

2.3.3 *Hot Water Storage*

Hot water storage systems are commonly used in a variety of different situations, and on a variety of scales. In a domestic system, water may be heated by various methods, and stored in tanks to supply space heating, hot water or both. This system may be scaled up to the level of a farm where electricity, biogas, straw, wood, or other wastes or fuels may be used to fuel a dedicated boiler, which runs continuously, or at set times, storing excess heat in hot water storage tanks [42]. This is particularly useful when using biomass and waste fuels with slow response times.

Hot water heating and storage can also be a good outlet for excess electricity and heat in any size of renewable system, as they can be used, when possible, to heat stored water, which is then available as and when required for space heating or as hot water [43]. District heating schemes also utilise hot water storage, on a much larger scale, to allow their heat producing plant (whether heat only or CHP) to run at a constant load, or to follow electricity demand. This is particularly important where fuels and plant with slow response times are being used (e.g. Stirling engines, steam turbines, wood, straw and waste fuels) as this allows them to run continually or only follow larger demand trends. For example, a typical Danish CHP plant that produces 20 MW of heat via a steam turbine uses a 5 million-litre storage tank to allow continuous operation and supply with minimal waste [6]. However, for any size and type of system, the size of storage tank and rated output necessary depend heavily on the heat demand and supply profiles (and electricity demand profiles if CHP is being considered). Although tank sizes are likely to fall within an appropriate range for different applications [44], it is important to be able to determine appropriate tank sizes and rated outputs for different demand and supply mixes.

2.4 Uses for Excess Electricity

If there is excess electricity being generated in a system, this could be used for the production and storage of heat as described in section 2.3, or for the recharging of electric vehicles as described in section 2.1. Other uses for excess electricity include the generation of hydrogen for use in vehicles, fuel cells, engines or heaters, via the electrolysis of water, or the use of electrical- storage by various means, allowing stored electricity to be available when demand exceeds supply [45-47].

2.4.1 Electrolysis

An electrolyser acts as a reverse fuel cell, producing pure hydrogen and oxygen when electricity and water are input. A range of electrolysers are commercially available, with outputs ranging from 1 to 100 normal cubic metres of hydrogen per hour (3 to 300 kW), subject to a minimum load of 10% to 20%. Electrolysers, like fuel cells, work more efficiently at partial load, and average around 50% conversion efficiency [41,48]. As the resulting fuel may be used in a variety of ways with reasonable efficiency (to meet transport, heat and electricity demands), the production of hydrogen via electrolysis provides a good use for excess electricity in an energy supply system [4]. Figure 2.3 shows the components of a typical hydrogen filling station utilising electrolysers.

2.4.2 Electricity Storage Devices

Pumped hydroelectric schemes are currently the only main form of electricity storage used in large-scale generation. It is a proven technology, with typical electricity-to-electricity efficiencies of around 70%, depending on the size of the plant [25]. When there is a surplus of electricity in the network water is pumped into a high reservoir, storing potential energy. When required, the water runs down through turbines, generating electricity. These types of plant are currently used in the UK to absorb excess nuclear capacity when demand is low and to provide electricity at times of peak demand. The amount of pumped hydro that can be used in a certain area, however, is restricted by the availability of suitable landscape, climate and ecological concerns.

In smaller scale projects banks of rechargeable batteries can be used to help match demand with supply. These have electricity-to-electricity efficiencies of around 75%, and are subject to self-discharge which limits their effectiveness for longer-term storage [45]. Although batteries work well for individual or small groups of buildings, they do not easily scale up for network use. This is because a battery's power rating and storage capacity are directly linked to the size and shape of their electrodes, so the overall size is directly dictated by the

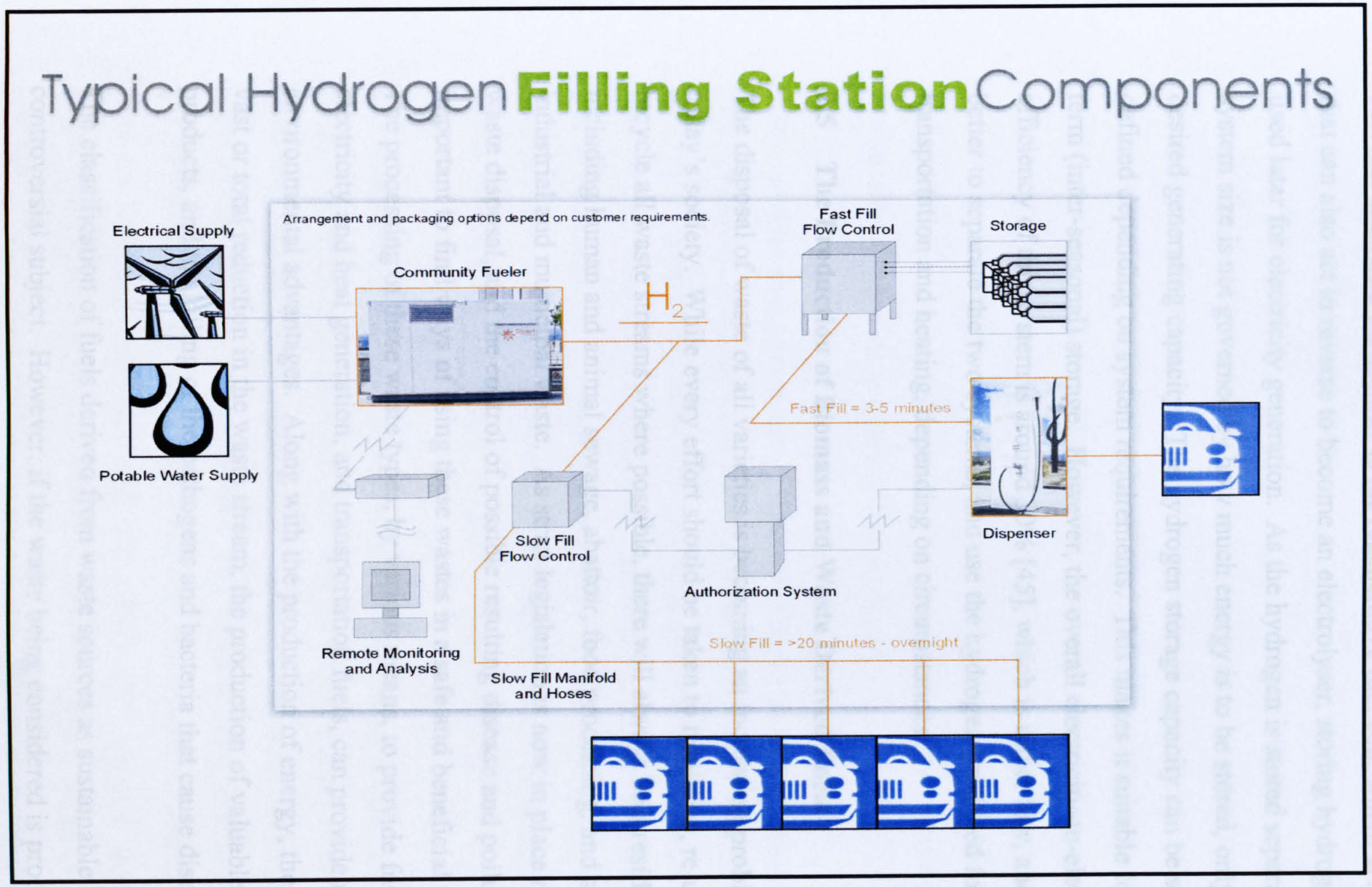


Figure 2.3 A Typical Hydrogen Filling Station [48]

desired storage capacity, even though only a small generating capacity may be required. This makes them relatively bulky and expensive for large-scale use where greater storage capacities are required [46,47]. The use of flywheels is also suitable for small-scale projects that require low amounts of energy to be stored [1].

Another emerging technology is the regenerative fuel cell, which is a fuel cell that can also act in reverse to become an electrolyser, storing hydrogen to be used later for electricity generation. As the hydrogen is stored separately, the system size is not governed by how much energy is to be stored, only by the desired generating capacity. The hydrogen storage capacity can be separately defined depending on system requirements. This makes it suitable for longer-term (inter-seasonal) storage. However, the overall electricity-to-electricity efficiency of this system is around 30% [45], which is rather low, and it may be better to separate the two systems, and use the hydrogen produced for transportation and heating, depending on circumstances.

2.5 The Production of Biomass and Waste Derived Fuels

The disposal of waste of all varieties is becoming an increasing problem in today's society. While every effort should be taken to minimise, re-use and recycle all waste streams where possible, there will always be a residual amount, including human and animal sewage, abattoir, food processing, and some industrial and municipal waste. As strict legislation is now in place regarding waste disposal, and the control of possible resulting disease and pollution, it is important to find ways of using these wastes in a safe and beneficial way [50]. The processing of these waste types, by various means, to provide fuels for electricity and heat generation, and transportation fuels, can provide many environmental advantages. Along with the production of energy, these include a vast or total reduction in the waste stream, the production of valuable by-products, and the killing of the pathogens and bacteria that cause disease.

The classification of fuels derived from waste sources as sustainable is a controversial subject. However, if the waste being considered is produced as part of the natural carbon cycle (agricultural and forestry wastes, animal waste, sewage, paper etc) then this makes the use of these wastes as fuels carbon dioxide neutral as long as the crops used, and feed for the animals and humans, continue to be grown [51]. Other waste types should be kept to a minimum, and alternative biodegradable or natural sources used instead where possible. When such waste is produced, however, it is better that it is processed in a suitable way to allow the removal of heavy metals and other contaminants and pollutants, whilst also gaining some benefit.

The growing of crops specifically for the production of energy is also, increasingly, becoming an important source of fuel throughout the world, and a useful source of revenue for farmers [52]. Again, provided the crops continue to be grown, the production of energy from these sources is carbon dioxide neutral. It is important, however, to take the seasonal nature of both energy crops and agricultural wastes into consideration when deciding how they may be best used in a sustainable energy system, and processing these feedstocks to derived fuels provides many benefits in terms of fuel storage.

There are a number of sustainable fuels that may be used in a variety of ways to meet electricity, heat, hot water and transportation demands as discussed previously. These fuels include biogas, hydrogen, biodiesel, ethanol, methanol, pyrolysis oil, charcoal, refuse derived fuel (RDF), wood, straw and other waste and biomass sources. Some of these fuels may be used as they are, and some may be derived, in various ways, from different biomass and waste feedstocks, giving many advantages over the original energy source.

The production of derived fuels converts possible feedstocks into a more easily usable form of fuel, and generally increases the energy density of the available feedstock, making it more easily transportable and better for use in portable applications. This can also make these fuels easier to store, and can greatly reduce their degradation rates – both of which are important considerations when the feedstock supply or energy demand is highly seasonal. Importantly, thanks to the efficiencies of the processes and technologies being used, the subsequent use of these fuels in various plants to provide heat and/or electricity can often provide a more efficient overall conversion process (original feedstock to energy) than the direct use of the original feedstock for energy production [53].

2.5.1 Gasification and Pyrolysis

Gasification is a thermal decomposition process that converts a solid organic fuel into a liquid or gaseous one via a partial oxidation process. The main output from this process is a mixture of gases typically containing hydrogen, methane, carbon monoxide, carbon dioxide, nitrogen and water vapour. Small amounts of pyrolysis oil and charcoal are also produced, and are often used as fuels to provide heat and/or electricity for the process. The exact proportion of each gas in the mixture, and the amount of oil and charcoal produced, depend on the original feedstock and specific process parameters. If the oxidation is carried out in air, the final biogas mixture will be heavily diluted with nitrogen, giving a low heating value biogas (typically 5 MJ/Nm^3). If the oxidation is carried out using pure oxygen, little nitrogen is present in the final mixture, and a medium heating value biogas is produced (typically 14 MJ/Nm^3) [54]. This process, however, is more expensive, and requires a higher energy input. A typical gasification plant layout is shown in Figure 2.4.

Both of these biogas mixtures may be used in a variety of plant types provided they are amended for use with low or medium heating value gases. Alternatively, the methane and hydrogen contents may be separated and used in suitable plant. The use of biogas mixtures with different heating values in engines and turbines is equivalent to the use of natural gas in terms of efficiency, but specific fuel consumption will increase with the decrease in lower heating value (LHV) [55]. A gas mixture containing 95% methane is equivalent to natural gas. The methane in the mixture may also be converted to hydrogen via steam reforming, or the biogas mixture can be further processed to methanol via catalytic conversion. Both of these processes are discussed later.

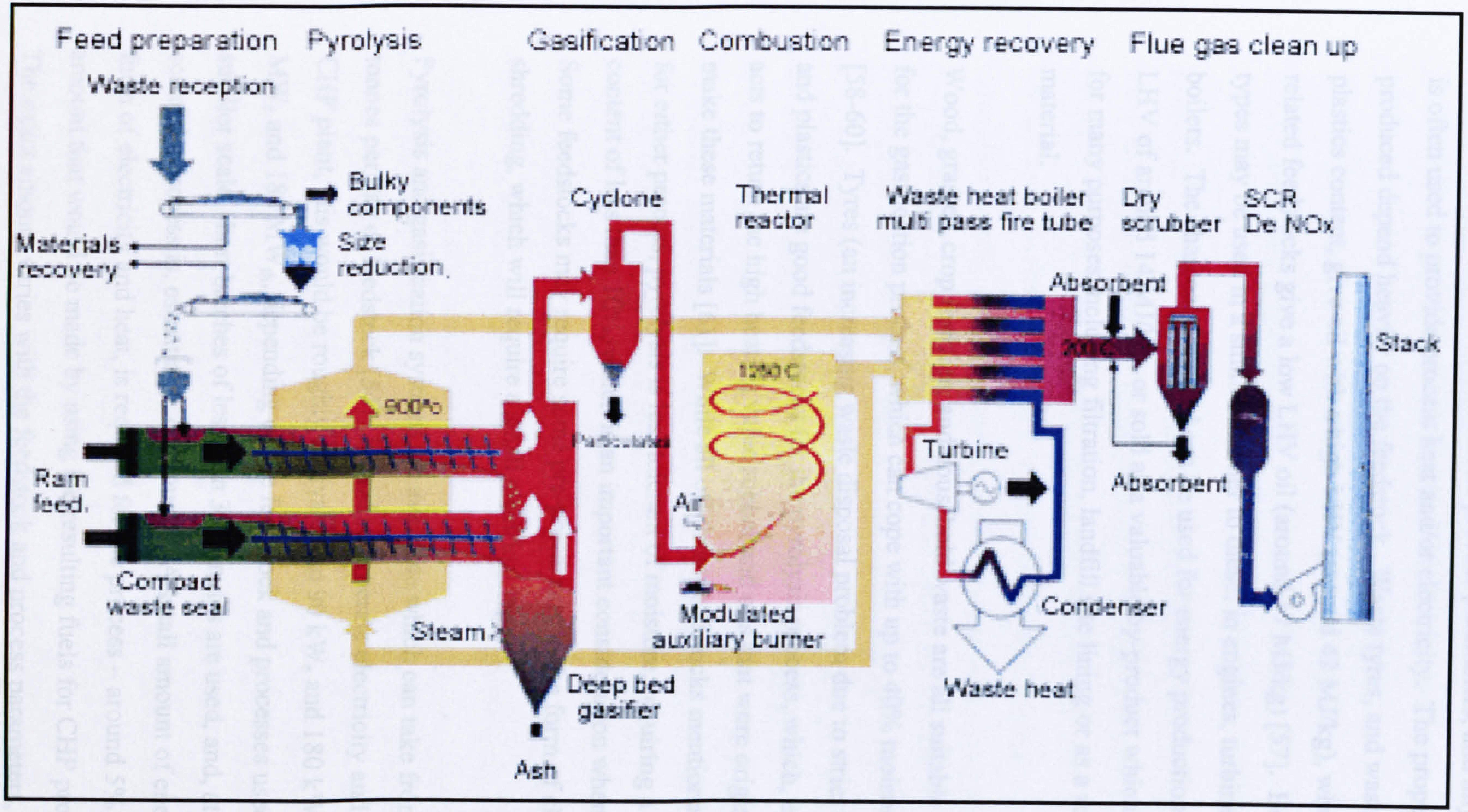


Figure 2.4 Layout of a Gasification Plant [56]

Pyrolysis is a similar process to gasification, but it is carried out at a lower temperature, and with little or no air, encouraging more pyrolysis oil and charcoal to be produced. Again, the exact output of gas, pyrolysis oil and charcoal depend on the feedstock and process parameters, and any gas produced is often used to provide process heat and/or electricity. The properties of the oil produced depend heavily on the feedstock. Waste tyres, and wastes with high plastics content, give oil with a high LHV (around 42 MJ/kg), whereas wood related feedstocks give a low LHV oil (around 17 MJ/kg) [57]. Both of these oil types may be used in a similar manner to diesel in engines, turbines, heaters and boilers. The charcoal produced can be used for energy production (with an LHV of around 14 MJ/kg), or sold as a valuable by-product which can be used for many purposes including filtration, landfill site lining or as a road building material.

Wood, grasses, crop residues, and household waste are all suitable feedstocks for the gasification process, which can cope with up to 40% moisture in the feed [58-60]. Tyres (an increasing waste disposal problem due to strict legislation) and plastics are good feedstocks for the pyrolysis process, which, essentially, acts to return the high heating value rubber and oils that were originally used make these materials [61]. While all off these feedstocks mentioned can be used for either process, pyrolysis is less tolerant of moisture, requiring a moisture content of less than 10%, which is an important consideration when using wood. Some feedstocks may require some pre-processing in the form of chipping or shredding, which will require a small electrical input.

Pyrolysis and gasification systems are available which can take from 3 to 3000 tonnes per day of feedstock [54]. If used to generate electricity and heat in a CHP plant, this would be roughly equivalent to 90 kW_e and 180 kW_{th} to 90 MW_e and 180 MW_{th}, depending on the feedstock and processes used. At the smaller scale, short batches of less than 30 minutes are used, and, at the larger scale, the process is, essentially, continuous. A small amount of energy, in the form of electricity and heat, is required for the process – around 5% of the amount that would be made by using the resulting fuels for CHP production. The exact amount varies with the feedstock and process parameters, and can be met by process integration and the use of some of the fuel produced. Many available systems provide a straight route from feedstock, through pyrolysis or gasification, to CHP generation via gas or steam turbines. With this, a high degree of efficiency through process integration is possible, using the waste heat from the turbines to provide process heat for the pyrolysis or gasification stage [62].

2.5.2 Anaerobic Digestion

Anaerobic digestion is the natural decomposition of organic matter, by bacteria, when no oxygen is present, which produces a mixture of methane and other by-products. Any mixture of organic inputs may be used (e.g. animal and human sewage, crop residues, newspaper, abattoir waste, food processing and agricultural waste), as long as the dry matter content of the feedstock mixture does not exceed 15%, making this a suitable option for wet wastes. The outputs of this process are a medium heating value biogas mixture (typically containing 60% methane and 40% carbon dioxide), and a solid and liquid fertiliser mix. Anaerobic digestion is carbon dioxide neutral as the making of the biogas and its subsequent use in any type of plant does not produce any more carbon dioxide than would be produced through the natural decomposition of the waste [63]. The inputs and outputs of this process are shown in Figure 2.5.

The digestion process may take place in a variety of different designs of digester, all based around the same, main process characteristics. The waste is pumped periodically (usually once per day) into the digester, which consists of an airtight container, with an expandable cover to allow the build up of biogas before siphoning. The waste remains in the digester for between ten to forty days (retention time), and, as new waste is introduced, an equal amount of fertiliser output is displaced. Some designs require the mechanical mixing of the feed in the digester, others circulate biogas through the mixture to achieve this, and others do not require mixing. Other electrical requirements may include pre-processing of the waste, and pumping as necessary [52,64].

To allow digestion to take place, the feedstock in the digester must be between 30°C and 70°C. This may be achieved by heating the feedstock before entering the digester, or directly heating the contents of the digester. As the digester itself is well insulated, there is a negligible heat loss from the feedstock once inside [65]. The most commonly used method is the pre-heating of the feedstock, which is often heated to 70°C for 1 hour before entering the digester. This heat treatment process kills weed seeds, and the pathogens, viruses and bacteria that cause disease, creating a better and safer fertiliser. Different types of feedstock will displace a different amount of biogas per kg of feed introduced into the digester, and this production will be spread over its time inside the digester. If a higher temperature is used, a shorter retention time is required, but the same overall amount of biogas will be produced as would be with a longer retention time and lower temperature [63].

The required size of a digester may be determined by multiplying the retention time by the maximum volume feed rate per day, and digesters with volumes ranging from 200 m^3 to 7000 m^3 are available. These would produce between 250 Nm^3 and 9000 Nm^3 of biogas from 12 tonnes to 425 tonnes of cow manure per day, in turn producing between 65 kW_e and 95 kW_{th}, and 2300 kW_e and 4300 kW_{th}, if used in a typical suitable CHP system. The energy requirements for an anaerobic digester are, typically, 10% of the electricity output and 30% of the heat output of the biogas used in a typical suitable CHP system [66].

The digester should remain active where possible, as starting up and stopping are difficult processes. The feedstock feed rate can vary, however, down to 20% of the maximum feed rate per day without stopping the process [65]. As the feedstock type and amount available may vary with different harvest times, and with the ease of collection (i.e. manure collection if animals are inside in winter and outside in summer), different feedstock mixtures may require to be used at different times of the year in order to keep the digester active.

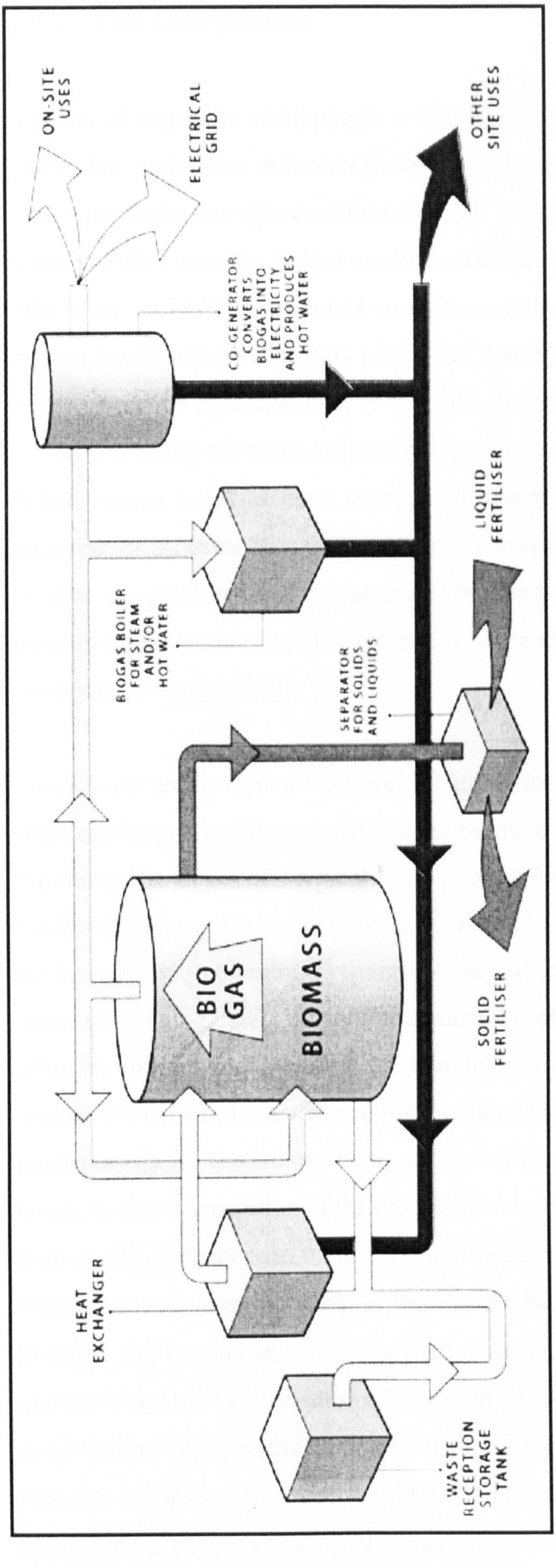


Figure 2.5 The Inputs and Outputs of an Anaerobic Digestion System [67]

2.5.3 Transesterification

The use of vegetable oils (straight or blended) in a diesel engine gives higher particulate emissions, reduced efficiency, and greater maintenance requirements compared to the use of conventional diesel. However, if these oils are transesterified to make methyl or ethyl esters (biodiesel), increased relative efficiency, and lower particulate emissions can be achieved, with little or no engine modifications necessary [68]. The transesterification process can use waste vegetable or animal oils, or specially grown energy crops with high oil yields (including soybeans, oilseed rape, olives, or sunflowers) as a feedstock. Where energy crops are used, energy in the forms of heat and/or electricity is required for oil extraction from the crop. The residue left after oil extraction can be used as cattle feed, put into an anaerobic digester or gasifier, or burned directly to produce heat and/or electricity, depending on the residue type, and energy requirements [69].

Small-scale production of biodiesel is batch-wise, where batches of up to 2000 litres can be processed, each batch taking around 10 hours to complete. Figure 2.6 shows the stages of a typical batch process for producing 'backyard biodiesel'. If necessary, the oil is first filtered to remove particles, and boiled for between 30 to 60 minutes to remove any water, which is often required when waste oil is being used. Ethanol or methanol (between 10 to 15% of the amount of oil by volume) and a catalyst (sodium hydroxide or potassium hydroxide, around 1% by weight) are mixed together and added to the oil. This is mixed mechanically for around one hour, and then allowed to settle for about eight hours, to allow separation of the biodiesel and glycerine. The glycerine is drained off, and any soap in the mixture is removed, if necessary, by adding water and mixing, or bubbling air through the biodiesel. This, again, is allowed to settle, and the biodiesel is drained off, leaving the soapy water. This process yields around the same volume of biodiesel as oil that was input, and around the same volume of glycerine as alcohol that was input [24,70,71]. Glycerine is a valuable by-product that can be sold to the pharmaceuticals or explosives industry or used to make soap or cosmetics.

1. Scale for measuring out lye and chemical supplies used for a titration.
2. Sample of used oil about to be titrated.
3. Colour of titrated liquid sample when at the correct pH.
4. Weighing correct amount of lye.
5. Lighting burner under transesterifyer vessel.
6. View of sodium methoxide mixer (left) and transesterifyer vessel (right).
7. View of sodium methoxide mixer being drained into transesterifyer vessel (note thermometer).
8. Valve on bottom of transesterifyer vessel user to decant out more dense glycerine from less dense esters.
9. Fuel pump and filters -- these are used last, after soapy residues and lye have had time to settle out of biodiesel.
10. Overview of trailer-mounted processor: propane tank is for heating grease, PVC containers on either side are soap settling tanks for biodiesel prior to pumping through filters. Pick-up line for filter pump is inserted into tank only deep enough to siphon esters and not soaps on bottom.
11. The finished product.
12. Mike's original 5-gallon biodiesel mill.

Figure 2.6 Biodiesel Production Process [71]

Larger scale biodiesel production can take place through a continuous process that goes through the same stages as the batch process and is, therefore, not easily stopped and started [72]. The energy required for either process is around 2% of the electricity and 3% of the heat that would be obtained from a typical suitable CHP plant using the fuel produced [73].

A substantial amount of alcohol is required for this process, and methanol is the easier alcohol to use, though it is more difficult to make in a sustainable manner. Suitable processes are beginning to be developed using ethanol, which can be made by fermentation, as described in the next section. The batch transesterification process can be time consuming, and safety precautions must be taken at all stages due to the chemicals being used and the reactions taking place.

2.5.4 Fermentation

Fermentation is the biological conversion of sugar, starch or cellulose, to ethanol and carbon dioxide, through anaerobic respiration by yeast or other organisms. Roughly half of the weight of sugars is converted to ethanol, and half to carbon dioxide, and the ethanol produced has roughly 90% of the energy content of the sugars used, or roughly 96% of the heat of combustion of the cellulose used. The carbon dioxide produced is pure, and can be sold to industry [17].

Possible feedstocks for fermentation include sugar cane, sugar beet, fruit waste, wheat, cereals, potatoes, wood, newspapers, and municipal waste. Of these feedstocks, grains can be stored without degradation, but tubers, fruits and beet crops rot rapidly once harvested, and should be used as soon as possible. Any crop residues remaining after the harvest of energy crops, can be burned directly to produce heat and/or electricity, or put into an anaerobic digester or gasifier, depending on the residue type, and energy needs [74].

Pre-treatment of the feedstock is required to produce simple, fermentable sugars (glucose and fructose), and the type of pre-treatment required depends on the feedstock being used. Sugary feedstocks (such as sugar beet or fruit waste) require crushing and mixing with water in order to release these sugars. Starchy feedstocks may require grinding or milling to free the starchy material, and cooking in water to dissolve and gelatinise the starch. Cellulosic materials may require chipping or similar pre-processing. Hydrolysis of starchy and cellulosic feedstocks is then necessary, where enzymes are added to break down the starch and cellulose to glucose and fructose. The exothermic fermentation process may then take place where the produced sugars are diluted in water, and yeast or other organisms are added to break down the sugars and convert them to ethanol in solution with water (roughly 10% ethanol by volume). Distillation then takes place to remove the water and other wastes, to produce 95% ethanol by volume [68,75]. An overview of the general ethanol production process is given in Figure 2.7.

Various residues are produced by this process. The non-soluble component separated before fermentation, and the solids separated after fermentation, are known as stillage. This can be used as an animal feed or fertiliser, sent to an anaerobic digester, or dried and used directly as a fuel in boilers, engines or turbines. The liquid remaining after distillation is known as vinasse, and this may be sent to an anaerobic digester, or used as an animal feed or fertiliser [17].

Again, small-scale production of ethanol by fermentation is batch-wise, and various larger scale commercial continuous processes also exist [76-78]. The time for one batch can be between two to four days, but a few fermenters can be run simultaneously to allow a daily production. Batch production processes can take up to two tonnes of feedstock per batch, and continuous ethanol production plants can process from 15 kg/hr upwards. The amount of ethanol and carbon dioxide produced, and the amount of electricity and heat required vary with the feedstock and process being used. A substantial use is often made of crop residues and stillage to provide some or all of the process energy requirements [79-81]. A large amount of water is required for this process, which makes it unsuitable for some areas.

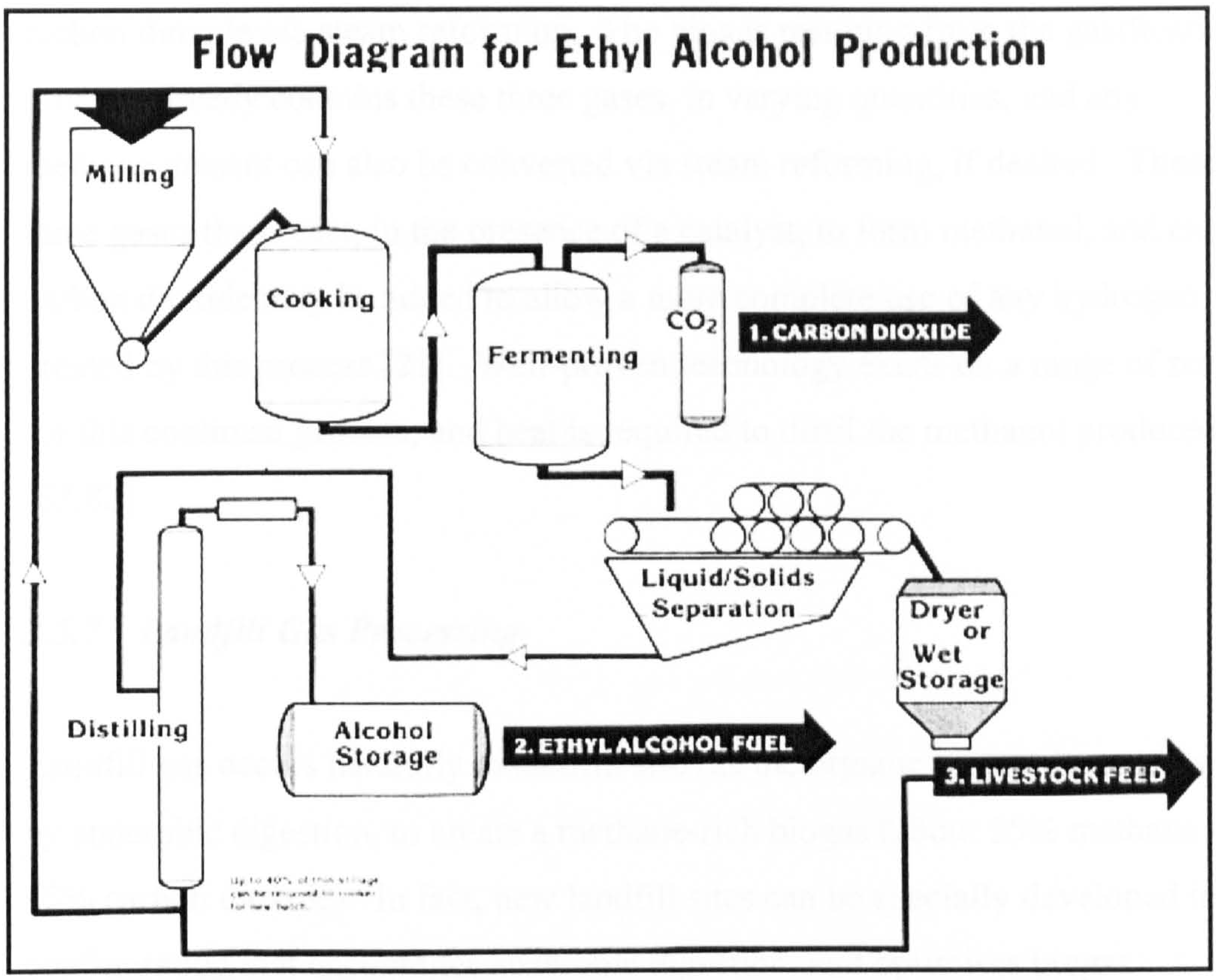


Figure 2.7 The Ethanol Production Process [75]

2.5.5 *Steam Reforming of Methane to Hydrogen*

The steam reforming process produces hydrogen, carbon monoxide and carbon dioxide by the reaction of methane and steam. The usual feedstock for this process is natural gas, but the methane produced from gasification, anaerobic digestion or from landfill sites can also be used. This reaction requires no significant electricity input, but heat is required to produce the steam, and the reaction, in reality, only goes to around 90% completion. Well-proven technology exists on a range of scales for this continual process [82,83]. As this process is often used in conjunction with other plant, significant use can be made of excess heat to reduce the energy requirements.

2.5.6 *Catalytic Synthesis of Methanol*

The biogas produced by gasification, anaerobic digestion or from landfill sites can also be processed to methanol via catalytic conversion. If the biogas has a high methane content, this is first converted to hydrogen, carbon monoxide and carbon dioxide via steam reforming. The biogas resulting from the gasification process already contains these three gases, in varying quantities, and any methane present can also be converted via steam reforming, if desired. These three gases then react, in the presence of a catalyst, to form methanol, and extra carbon dioxide may be added to allow a more complete use of any hydrogen created by this process [21]. Well-proven technology exists on a range of scales for this continual process, and heat is required to distil the methanol produced [82,83].

2.5.7 Landfill Gas Processing

Landfill gas occurs naturally in landfill sites as the organic matter decomposes, by anaerobic digestion, to create a methane-rich biogas (about 55% methane and 45% carbon dioxide). In fact, new landfill sites can be specially developed in a configuration that encourages anaerobic digestion, and optimises biogas recovery. As methane is around 21 times more effective than carbon dioxide as a greenhouse gas, it is better, where it is being produced, to convert it to a less harmful substance, while also gaining useful energy from it. Useful quantities of landfill gas can be available from a site for 10 to 30 years, and a typical site can produce up to 1000 m^3/hr. Around 10% of the electricity made from the biogas will be used for its recovery (for pumping etc) [16,52]. This resource will gradually disappear as less waste is put to landfill, but is still a useful interim source of fuel.

2.5.8 Waste and Biomass Processing Technologies

Many waste and biomass fuel sources require to undergo some type of processing before they can be easily used in boilers, heaters, turbines, engines etc. The purpose of this processing may be to increase the fuel density to allow easier transportation or storage (e.g. briquetting or pelletising), to dry out a wet feedstock (e.g. sewage or wood drying), to reduce the feedstock size (e.g. chipping), or to create a more homogenous fuel (e.g. shredding of waste materials). These processes all require energy in the form of heat and/or electricity [52,84,85].

2.5.9 Electrolysis

The principle behind the production of hydrogen via electrolysis was discussed in Section 2.4.1. As well as providing a use for excess electricity in a system, electrolysers may also be attached to dedicated wind and PV supplies, where all of the electricity output is used for hydrogen production.

2.6 Summary

- There are a number of different processes available that allow the total energy needs of an area to be met in a sustainable manner, and those chosen will depend on a range of area-specific factors.

- The production of fuels from biomass and waste sources is an important source of sustainable fuel for transportation, heat and electricity production, and provides a good waste management solution for unavoidable wastes.

- When designing systems with a large amount of intermittent electricity generation, or systems where generators are run continuously to produce electricity and/or heat, it is important to seek as close a match between the demand and supply profiles as possible.

- This may be done by varying the types and locations of the generators being used, and employing various storage and/or load following generating plant.

- Any excess electricity or heat generated in the system should be put to good use to help meet the demands for different energy types, or stored, in some form, for later use.

- Where CHP is used, the balance between the heat and electricity demand should be maintained as close as possible to the heat to electricity output ratio, to avoid wastage.

- As there are many factors to be considered in the design of sustainable energy supply systems, the interrelationship between the various components can be complicated. This will vary with each different situation considered, which highlights the need for a decision support framework where different supply scenarios may be quickly and easily tried, in order to gain an understanding of these balances, and find the most technically suitable system design for a specific situation.

This chapter discussed the various components that could be used to create a sustainable energy supply system, and how they could be combined to create an efficient and reliable system. As there are many complex operational factors to be taken into consideration when designing integrated systems to supply the electricity, heat, hot water and transportation needs of an area, the creation of a generic framework that would aid informed decisions would be valuable. Chapter 3 describes the various ways in which the design of sustainable energy systems has been approached.

2.7 References

[1] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001, www.esru.strath.ac.uk

[2] M. J. Grubb, 'The integration of renewable electricity sources', Energy Policy, 1991, Vol. 19, No. 7, pp 670-688

[3] A. Mourelatos, D. Assimacopoulos, L. Papagainnakis, A. Zevros, 'Large scale integration of renewable energy sources an action plan for Crete', Energy Policy, 1998, Vol. 26, No. 10, pp 751-763

[4] E. W. Justi, "A solar-hydrogen energy system", New York: Plenum Press, 1987

[5] J. M. Ogden, "Prospects for building a hydrogen energy infrastructure", Annu. Rev. Energy Environ. 1999, 24, pp 227-279

[6] Centre for Biomass Technology "Danish Bioenergy solutions", Energistyrelsen, 2000, www.videncenter.dk

[7] California Energy Commission, www.energy.ca.gov

[8] United States Department of Energy, www.fueleconomy.gov

[9] Alternative Fuels Data Centre, www.afdc.doe.gov

[10] P. Whalen, K. Kelly, R. Motta and J. Broderick, "Alternative Fuel Light Duty Vehicles", NREL, May 1996

[11] Northeast Advanced Vehicle Consortium, "Heavy Duty Vehicles Testing Report – Final Emissions Report" February 15, 2000

[12] R. Motta, P. Norton, K. Kelly, K. Chandler, L. Schumacher and N. Clark, "Alternative Fuel Transit Buses Final Results from the National Renewable Energy Laboratory (NREL) Vehicle Evaluation Program" NREL, October 1996

[13] "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems" General Motors Corporation, Argonne National Laboratory, BP, Exxon Mobil and Shell, April 2001

[14] Personal correspondence, Hank Seiff, Director of Technology, Natural Gas Vehicle Coalition, www.ngvc.org

[15] The UK Biogas Association, www.biogas.org.uk

[16] T. B. Johansson et al, "Renewable energy: sources for fuels and electricity", Island Press, Washington, D.C., 1993

[17] K. J. Kelly, B. K. Bailey, T. C. Coburn, W. Clark, L.Eudy and P. Lissiuk "FTP Emissions Test Results from Flexible-Fuel Methanol Dodge Spirits and Ford Econoline Vans", Society for Automotive Engineers, International Spring Fuels and Lubricants Meeting, Dearborn, MI, May 6-8, 1996

[18] Trucking Research Institute, "Hennepin County's Experience with Heavy-Duty Ethanol Vehicles", NREL, January 1998

[19] DaimlerChrysler Vehicle Manufacturers, www.daimlerchrysler.com

[20] The Methanol Institute, www.methanol.org

[21] International Fuel Cells, www.ifc.com

[22] Vehicle Certification Agency (VCA) "New Car Fuel Consumption and Emission Figures" January 2001, www.vca.gov.uk

[23] European Electric Road Vehicle Association, www.avere.org

[24] National Biodiesel Board, www.biodiesel.org

[25] L. C. Wilbur, "Handbook of Energy Systems Engineering – Production and Utilisation" John Wiley & Sons 1985

[26] Volvo Penta, "Sales Guide – Generating Set Engines – 2001/2002", www.volvopenta.com

[27] Energy Efficiency Best Practice Programme, "A Technical and Economic Assessment of Small Stirling Engines for Combined Heat and Power", Energy Efficiency Office, Department of the Environment, January 1993, www.energy-efficiency.gov.uk, 0800 585794

[28] Personal correspondence, D. Jones, UK Area Manager, Victron Energy, www.whispergen.com

[29] Personal correspondence, S. Kolin, www.sigma-el.com

[30] Centre for Biomass Technology "Straw for Energy Production", Energistyrelsen, 1998, www.videncenter.dk

[31] Centre for Biomass Technology "Wood for Energy Production", Energistyrelsen, 1999, www.videncenter.dk

[32] Alstom Power, Gas Turbines Division, www.power.alstom.com

[33] Fuel Cell Energy, www.fce.com

[34] Energy Partners, www.energypartners.org

[35] International Fuel Cells, www.internationalfuelcells.com

[36] Energy Efficiency Best Practice Programme, "Economic Use of Fired Space Heaters for Industry and Commerce", Energy Efficiency Office, Department of the Environment, 1993, www.energy-efficiency.gov.uk, 0800 585794

[37] Travis Industries, Wood Pellet and Gas Hearth Heating Appliances, www.hearth.com/travis

[38] China Vanward, Water Heating Systems, www.china-vanward.com/products

[39] Energy Efficiency Best Practice Programme, "Good Practice Guide 16 – Guide for Installers of Condensing Boilers in Commercial Buildings", Energy

Efficiency Office, Department of the Environment, 1990, www.energy-efficiency.gov.uk, 0800 585794

[40] O. Ulleberg, S. O. Morner, "TRNSYS Simulation Models for Solar-Hydrogen Systems" Solar Energy, Vol. 59, No 4-6, pp. 271-279, 1997

[41] Thermodynamic Energy Systems, www.hydrogenappliances.com

[42] Teisen Products "FARM 2000, Heat from Wood, Woodchip, Straw and Waste" and other literature, www.farm2000.co.uk

[43] P.Taylor, "Increased renewable energy penetration on island power systems through distributed fuzzy load control", Proc. of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2001

[44] Lochinvar Ltd, www.waterheaters.co.uk

[45] R. G. M. Crockett, M. Newborough, D. J. Highgate, 'Electrolyser-based energy management: a means for optimising the exploitation of variable renewable energy resources in stand-alone applications', Solar Energy, 1997, Vol. 61, No. 5, pp 293 – 302

[46] P. D. Lund, 'The energy storage problem in low energy buildings', Solar Energy, 1994, Vol. 52, No.1, pp 67-74

[47] K. Ro, S. Rahman, ' Battery or fuel cell support for an autonomous photovoltaic power system', Renewable Energy, pp 271-279

[48] Stuart Energy, www.stuartenergy.com

[49] Kunzel, www.kuenzel.de

[50] European Topic Centre on Waste and Material Flows, The European Environment Agency, waste.eionet.eu.int

[51] The National Renewable Energy Laboratory, www.nrel.gov

[52] The International Energy Agency, CADDET, various projects, www.caddet.org

[53] C. P. Mitchell, A. V. Bridgewater, D. J. Stevens, A. J. Toft, M. P. Watters, "Technoeconomic assessment of biomass to energy", Biomass and Bioenergy, 1995, Vol. 9 (1-5), pp 205-226

[54] "Pyrolysis & Gasification of Waste: A Worldwide Technology & Business Review. Volume 2 – Technologies and Processes", Juniper Consulting Services, January 2000

[55] M. A. Paisley, J. M. Irving, R. P. Overend, "A Promising Power Option – The Ferco Silvagaso Biomass Gasification Process – Operating Experience at the Burlington Gasifier", Proceedings of ASME Turbo Expo 2001, June 4-7, 2001 New Orleans, Louisiana, USA

[56] Compact Power, www.compactpower.co.uk

[57] Personal Correspondence, B. Conrad, Conrad Industries Inc.

[58] Personal Correspondence, R. McLellan, Gasification Manager, Wellman Process Engineering Ltd, www.wellman.co.uk

[59] Organic Power, www.organicpower.com

[60] B9 Energy Biomass Ltd, www.b9energy.co.uk

[61] "Alcyon BioThermic Process for MSW Disposal" and "Alcyon TiRec Process for Scrap Tyres Recycling", Alcyon S.A., www.alcyon.ch

[62] K. R. Craig, M. K. Mann "Cost and Performance Analysis of Three Integrated Biomass Gasification Combined Cycle Power Systems", National Renewable Energy Laboratory

[63] "Anaerobic Digestion of Farm and Food Processing Residues – Good Practice Guidelines", British Biogen, www.britishbiogen.co.uk

[64] D. Palmer, "Biogas – Energy from Animal Waste", Solar Energy Research Institute, May 1981

[65] Personal Correspondence, M. Richter, ECB AG

[66] ECB Enviro Berlin AG, "Biogas Accountant", www.ecbag.de

[67] ASC Materials Handling Ltd, www.as-c.co.uk

[68] "Biofuels", Energy and Environment Policy Analysis Series, OECD/IEA, 1994

[69] J. Connemann, J. Fischer, "Biodiesel in Europe 1998", International Liquid Biofuels Congress, July 19-22, 1998, Curitiba - Paraná – Brazil, www.biodiesel.de

[70] WebConX Renewable Energy, www.webconx.com/biodiesel.htm

[71] Handmade Projects, Journey To Forever, journeytoforever.org

[72] BioDiesel International, www.biodiesel-intl.com

[73] Personal Correspondence, Camillo Holecek, DonauWind GmbH&Co KG

[74] S. W. Mathewson, "The Manual for the Home and Farm Production of Alcohol Fuel", Handmade Projects, Journey To Forever, journeytoforever.org

[75] "Mother Earth Alcohol Fuel", Mothers' Alcohol Fuel Seminar, The Mother Earth News, 1980, journeytoforever.org

[76] The Revenoor Co. Inc., www.revenoor.com

[77] Arkenol Inc., www.arkenol.com

[78] "Ethanol Production in Hawaii – Processes, Feedstocks and Current Economic Feasibility of Fuel Grade Ethanol Production in Hawaii", Prepared for State of Hawaii Department of Business, Economic Development and Tourism, July 1994, www.hawaii.gov

[79] F. S. Butterfield, "The Butterfield Still - Preliminary Design and Performance of the FSB Energy Fuel Alcohol Plant", April 1981, journeytoforever.org

[80] H. Shapouri, J. A. Duffield, M. S. Graboski, "Estimating the Net Energy Balance of Corn Ethanol", U.S. Department of Agriculture, Agricultural Economic Report No. 721, July 1995, www.ethanol-gec.org

[81] D. Lorenz, D.Morris, "How Much Energy Does it Take to Make a Gallon of Ethanol", Institute of Local Self Reliance, Aug 1995, www.carbohydrateeconomy.org

[82] ICI, www.synetix.com

[83] Haldor Topsoe, www.haldortopsoe.com

[84] Niro Industries A/S, www.niroindustries.dk

[85] Advanced Recycling Equipment Inc., www.advancedrecyclingequip.com

3 Approaches to Renewable Energy System Design

There are various models that exist to aid the design of sustainable energy supply systems, and, due to the complexity of the tasks required of these systems, they have been produced as computer simulation packages. Several programs have been produced which deal with various aspects of sustainable energy system design and optimisation, but there are none available that deal with all of the issues discussed in Chapter 2. Systems currently available include those based on geographical information systems, the use of demand and supply matching for the temporal analysis of energy supplied from intermittent sources, and the evaluation of energy from biomass and waste sources. This chapter will look at the strengths of these programs, and will highlight areas that require further development in order to enable analysis of the type of multifaceted system required to provide for all the energy needs of any size or type of area in a sustainable manner.

3.1 Geographical Information Systems

A geographical information system (GIS) is a computerised database that allows the integration of different information sources to provide a comprehensive map of an area. Different layers may be built up over this map representing, for example, the three-dimensional relief or wind potential of the area. Muselli et al [1] present an interesting study of the French island of Corsica, which uses a GIS to build up the topology, existing electrical network, land availability, solar potential and other meteorological data, in order to determine the optimal energy supply system for this island. This system considers various supply scenarios, including the use of photovoltaic (PV) systems, battery storage, auxiliary engines and electricity grid extension. Hourly insolation figures are synthesised, and four load profiles are chosen to simulate the hourly consumption of the users under different circumstances. Various system designs are tried by considering the supply potential at each pixel of the satellite map, matching supply with demand, applying average plant efficiencies, and employing storage devices or auxiliary engines depending on the supply scenario being considered.

In this way, the optimum solutions for supply type, siting and sizing are found, and an economic evaluation is then carried out.

This is an excellent system that combines a comprehensive survey of the siting potential of a specific area with a matching of the potentially available supply with local demand. However, this type of survey is site specific, and it would take time to gather the relevant information and build up a model for a specific area. It is also mainly suited to the analysis of larger systems, as this type and depth of analysis would not be necessary for an individual building, farm or small community. Although this system does not consider the use of biomass, waste and derived fuels, and concentrates on electricity supply only, it could be expanded to consider these sources and to look at electricity, heat and transportation fuel supply. This, however, would greatly increase the complexity of the model, and make it increasingly difficult to work with and more time consuming to create.

3.2 Matching Demand and Supply

Temporal, quantitative, and climate analyses are vital when dealing with intermittent renewable energy supplies, and should all be considered in any system that contains these types of supply. For example, many people find the concept of solar powered streetlights strange, however, it is the use of batteries that makes this possible. The key to designing such a system is to correctly size the required photovoltaic array and battery provision, taking into account the energy required during the longest night, with the solar resource available during the shortest day. The effects of cloud cover must also be taken into consideration, and there may be scope for some interseasonal storage in the battery. Clearly, the results for such a system situated near the equator, with its unvarying day lengths, would be very different from one near the north or south pole where there can be six months of darkness followed by six months of light. This system would be even more complicated if it were wind power which was being considered, as the wind resource is much more unpredictable, and varies substantially throughout the day.

Because of the intermittent nature of solar-based and wind-based supply technologies, it is important to consider the daily and seasonal variations in the electricity supplies received from this type of plant, and compare these to the pattern of demand required for a particular area. This allows decisions to be made about how well the demand can be met directly from the supply, and what size and type of intermittent sources, storage devices or reserve would be needed in order to ensure security of supply. There are a number of systems available which allow the evaluation of intermittent PV and wind energy supply systems, on an hourly or more frequent basis, through the temporal matching of required demands with potential supplies [2-11]. The use of storage devices, auxiliary engines or grid connection, are also variously considered, and most models allow the user to see what pattern-of-use would be required of these plant, allowing decisions to be made about suitable plant type and sizing. Unless stated otherwise, all of the programs described in this section use relevant climate data and available manufacturers' information to help predict the output of the intermittent supply sources being considered. The required demand is then subtracted from this output, and auxiliary systems are employed as necessary or as specified at each timestep. This allows supply combinations and plant sizing to be analysed in various ways, depending on the emphasis of the model.

3.2.1 Area Specific Analysis

A program which uses demand and supply matching, F-Cast [2], has been developed to simulate the operation of an integrated system containing wind turbines, micro-hydro plants with pumped storage, biomass combustion, and back-up grid connection, for a particular area on the Greek island of Crete. This model allows the economic and technical assessment of proposed integrated systems, and several chosen system configurations are tested in order to find the best comparative solution. The output of this system is a cost analysis of the various possible schemes. Although this program was developed for a particular area and range of system designs, it could be adapted for use in other areas.

3.2.2 Generic Programs

A more generic approach to energy system design is described by Castro et al. [3]. This easy-to-use program allows the scenario-based assessment of electricity supply systems that contain both renewable and conventional power plants, for any area, provided climate data is available. The renewable technologies considered are PV and wind, with storage being provided in the form of pumped hydro. After the demand and supply have been matched, and the use of storage considered, the output of this program is a series of graphs showing the electrical generation outputs, demand and supply excesses, and the profile of use of the pumped hydro scheme. The suitability and optimum sizing of the required plants may be ascertained by trying different supply scenarios. This is also the case with the system described by Bonanno et al. [4], which can analyse systems containing wind turbines, PV arrays, batteries and diesel generators. Again, different simulations need to be run in order to compare the outputs of different system configurations, and the output of this program is in the form of a graph of supply deficit and an amount of fuel used.

Chedid et al. [5,6] describe a system that analyses the reliability and costs of a renewable energy supply system that may contain wind turbines, PV arrays, batteries, diesel generators and a grid connection. This allows different simulations to be carried out in order to evaluate different control policies and supply mixes. Although complex in terms of its economic analysis, the technical analysis provided by this program is fairly basic.

ARES-II [7] is another economic based model, designed to evaluate autonomous renewable energy systems incorporating PV arrays, wind turbines and batteries. Here, a factor indicating the level of autonomy of a chosen system is calculated using weather data and descriptive component parameters, and the level of autonomy attainable within a given budget may be arrived at through iteration. This economic based model is particularly suited to smaller scale projects, and provides a more in-depth technical analysis.

A renewable energy supply evaluation tool, MERIT [8], has been developed at the University of Strathclyde, which allows the analysis of energy systems over any chosen timescale from a day to a year, or for seasonal representative periods, with a user-specified number of timesteps per hour. Demand profiles for a chosen area (for electricity, heat and hot water) may be designed or built up from a variety of typical available profiles. A range of possible supplies may then be chosen, including wind turbines, PV arrays and PV concentrators for electricity generation, and flat-plate collectors for water heating. Auxiliary supplies may also be defined, including the use of batteries, pumped hydro plants and flywheels for electrical storage, diesel generators for back-up electricity and heat production, and a grid connection. Combinations of these demands and supplies (with one auxiliary supply only) may then be quickly and easily matched, and the outputs of these simulations, in the form of graphs of demand and supply, residual demand and excess supply, and the profile of use of the chosen auxiliary, may be easily compared. This allows many combinations to be tried from the one screen (without the need to go back and redefine the whole system), allowing the optimum system configurations to be determined for a chosen area and set of demand profiles. An auto search facility is also available which allows the optimum matches to be found using a variety of criteria. This program provides a good analysis of electrical demand, supply and auxiliary matching, however, although a start has been made to include demands for heat and hot water, these require further development in order to allow a more full analysis of the available supply possibilities and storage options. MERIT is a flexible and generic simulation tool, which, thanks to its graphical user interface, is easy to use and understand.

Another flexible and generic tool, TRNSYS [9], has been developed at the University of Wisconsin-Madison. This transient systems simulation program allows analysis of any time period, broken down into half-hourly timesteps. Systems may contain a large number of components, which may include, amongst others, solar thermal plant, PV panels, wind turbines, batteries, auxiliary heating and cooling plant, building loads and structures, thermal storage, electrolysers, fuel cells, hydrogen storage and heat exchangers. The modular nature of this program gives it flexibility and makes it easy to expand its range of available components. Unfortunately, a large amount of technical data and specialist system knowledge, much of which may be proprietary or difficult to obtain, is required to let TRNSYS provide its sophisticated and in-depth technical analysis of energy system design. This is, however, an excellent tool for the detailed design of energy systems, especially those incorporated within buildings.

3.2.3 Optimisation Tools

Various tools exist to find the optimum solution to the design of sustainable energy supply systems using demand and supply matching. Ackermann et al. [10] describe an overall system optimisation model and power flow simulation tool that evaluates the effect of embedded wind turbines connected to remote distribution lines, with respect to their influence on power quality. This tool identifies the configurations of embedded generation that give the lowest cost, while also considering the distribution losses over a certain time. This complex technical and economic system provides a thorough examination of actual line design, distances to customers, and power quality issues, which is a more detailed analysis than is necessary for the feasibility study being considered in this work.

The optimisation program described by Seeling-Hochmuth [11] can be used to find the best possible design and operation strategy, for a given area and demand profile set. Systems containing PV arrays, wind turbines, diesel generators and battery storage can be analysed, and the non-linear performance of these components has been taken into consideration in this model. This optimisation is achieved by carrying out a search through the range of system operation possibilities over a given time period, using climate and demand data, and long-term technical and economic system component characteristics. The costing of these various strategies are compared, and the plant sizes altered according to specific search rules, using a genetic algorithm to solve the non-linear optimisation problem. The genetic algorithm imitates the natural selection found in evolution, where factors are randomly changed, and those that improve the system are kept. The output of this program is the sizing and system operation recommendation for the optimum supply system.

The search for an optimum solution is a reasonable pursuit if the system contains only one or two supplies, and one or two auxiliary technologies. However, when consideration is being given to a diverse range of possible supplies and a wide variety of ways of integrating these to form an overall supply system for electricity, heat and transportation, there will often be no optimum answer. Searching for one best answer requires strict selection criteria to be chosen, and rules out all other possibilities, which may, with a slight technical, political, economic or demand change, be much more viable options. It also does not allow the user to see emerging trends that may provide useful information when designing a system that will be put in place gradually, or when designing a system to allow for growth and expansion, especially when the fine balances necessary in an integrated system are being considered. In these cases, it is important to be able to explore the full range of possible solutions in order to judge different scenarios on their relative merits.

3.3 The Use of Biomass and Waste

With the exception of F-Cast [2] that considered a limited use of biomass for electricity production, and MERIT [8] which gives a small consideration to the demand for heat, the systems described Section 3.2 look only at the production and storage of electricity by PV, wind, batteries, pumped hydro plant, back-up diesel generators and grid connection. They do not take into account the valuable sustainable resource available in the form of biomass and waste and their derived fuels, or the demands for heat and transport.

Other models exist which address some of these issues. For example, the OREM (Optimum Renewable Energy Model) system described by Iniyan [12], considers demands for cooking, transportation, pumping, lighting, heating, cooling and electricity. These can be met by the use of wind, solar and PV technologies, direct combustion of biomass and wastes, fermentation to produce ethanol, and gasification to produce biogas. The aim of the model is to develop a system for the sustainable production of energy for India for the year 2020 by minimising the cost/efficiency ratio within the bounds of social acceptance, reliability, demand, and potential supply. This model, however, looks at the energy requirements for the year as a whole, and does not take into account the variable nature of the intermittent supply technologies. It can, therefore, not be used to aid decisions about the suitable type and sizing of storage devices or auxiliary plant that may be required.

Another system, RETScreen [13], has been developed for the Canadian government. This is an Excel spreadsheet based model, which can be used worldwide to evaluate the energy production, life-cycle costs, and greenhouse gas emissions reductions for various single renewable energy technologies. These technologies include wind, PV, biomass heating, solar water and air heating, small-scale hydro, passive solar heating, and the use of ground source heat pumps. These models provide a good in-depth technical and economic assessment of these technologies used on their own, but do not consider the integration of these systems and, again, deal with annual energy requirements only.

Ramakumar et al. [14,15] describe the use of the IRES-KB system to allow the technical analysis of potential renewable energy supply systems for remote areas. Demands for electricity, heat and mechanical power are considered, and these may be met by biogas from digested biomass, solar-thermal energy, hydropower, wind turbines, and PV panels. The year is split up into seasons, each of which is characterised by a set of daily demands and available resources. This information is input as energy needs per day for refrigeration, cooking, lighting etc, and as available wood and crop residues, volume of falling water, and a choice of pre-programmed cloud cover and wind regimes. These demands and supplies are split up throughout the day in hourly intervals, and some variability is added to the intermittent supplies through the cloud cover and wind regimes chosen, in order to analyse the required storage and reserve plant sizes. This system provides a good seasonal evaluation of the energy supplies and demands of an area, however, it lacks the more in-depth temporal analysis that would be necessary when considering more complex systems.

There are various models available which allow the analysis of different aspects of bioenergy system design [16]. For example, BEAM [17] is a spreadsheet-based decision support system that allows the easy technical and economic evaluation of integrated biomass to electricity systems. This is done by splitting the process into three different stages – the production of various feedstocks (biomass and waste), the conversion of these into a suitable energy carrier via gasification, pyrolysis, fermentation or combustion, and the generation of electricity via gas or steam turbines, internal combustion or diesel engines. BEAM allows the user to look at the overall planning issues related to the type, siting, number and sizing of biomass plant by permitting the comparison of the relative cost of different feedstock types, supply strategies, and generating methods. A similar analysis may be carried out with the BIOPOWER program [18], where the cost of power generation from a similar range of fuels and power technologies may be compared. These models, however, are complex, and require data that is not easily available.

Another system, Biomass Toolkit [19] provides a group of programs that make up a diagnostic tool for the assessment of bioenergy projects at a local or regional level. This gives an assessment of biomass resource availability, a technical and economic evaluation allowing selection of the most appropriate conversion technologies, and an assessment of the environmental impact, acceptability and other non-technical factors for proposed projects. Some consideration is also given here to the time dependant output of crops and their by-products. These programs all look at the use of biomass and waste technologies on their own, and are useful when considering the comparative merits of different biomass and waste related energy systems, and the overall planning issues involved, when this is the only technology being considered.

A similar program, MODEST [20] allows the optimisation of dynamic energy systems that have time dependant components and boundary conditions, in order to minimize life cycle costs. This program is capable of considering demands for electricity and heat, and divides the year into seasons, and each season into chosen time periods, in order to find the best operation profile to meet the heat and power requirement. Sensitivity analysis may then be undertaken, using factorial design to highlight any interaction effects which may occur between the different parameters that affect the cost analysis. Although this program provides a good economic analysis of proposed biomass or waste powered generating plant, it does not have the capability to consider the use of heat or electricity storage. Although the in-depth temporal analysis required of a system which includes intermittent supplies is not required when considering biomass and waste systems on their own, it is important to consider harvesting times and production schedules to allow the appropriate sizing of storage facilities and gasification, pyrolysis or fermentation plant.

Although not designed for the evaluation of biofuel use, another package exists which allows the preliminary evaluation of combined heat and power (CHP) schemes, running on natural gas, for hospitals and hotels [21]. This program uses building type, floor area, and degree-day information to generate typical half-hourly demand profiles for heat and electricity for a year. Basic technical and tariff information is then used to give the recommended size of plant and the payback period. This program provides the temporal analysis necessary for the consideration of both electricity and heat demands, but does not allow for the possibility of electricity or heat storage or for an analysis of the relationship between the two demand types. Both of these factors are important in the design of larger scale integrated energy systems.

3.4 Conclusions

There are many different packages available that allow the evaluation of various aspects of sustainable energy system design, however, none deal with all the aspects required to make up an integrated energy supply system, capable of supplying all the needs of a given area, for electricity, heat, hot water and transport. There are, however, many important issues that arise from the evaluation of these different models that must be taken into account when considering the design of a decision support framework capable of dealing with all the technologies discussed in Chapter 2.

When the use of climate dependant intermittent supplies is being considered, it is vital to be able to consider the relationship between the supply and demand as it varies throughout the day, and with the different seasons. This may be done by matching supply with demand at different timesteps throughout the day to ascertain times of energy deficit or excess. This then allows the use of storage devices and/or load-following reserve to be considered in order to provide security of supply, permitting decisions to be made about appropriate plant sizing.

Many of the programs discussed here are suitable for the evaluation of small-scale or specific projects. It would, however, be useful to have a flexible and generic program that is capable of analysing the needs and potential supplies of areas of any size, type and location, where many different combinations of demand and supply may be quickly and easily tried and compared with each other. However, as the analysis of large and small scale projects require a range of different issues to be considered, this work will concentrate on the study of small to medium scale projects (i.e. individual building to small community size). The full range of demand types and possible supply and storage methods should be available (as discussed in Chapter 2), although the overall systems chosen for simulation may be as simple or complex as desired. It would also be useful to be able to simulate power supply from conventional sources in order to evaluate mixed or transitional systems. The system must provide a sound technical analysis, however, the information required should be limited, where possible, to easily available manufacturers' data. This would allow the system to be kept easily up to date, and permit consideration of specific plant for specific simulations. The non-linear efficiencies of most plant types should also be taken into consideration.

When considering the use of biomass, waste and derived fuels, it is important to bear in mind the timing of these supplies, as fuels may be harvested only at particular times of the year (e.g. energy crops and crop residues), or available constantly (e.g. animal wastes and landfill gas). This has a significant effect on the availability of fuel, on the sizing of storage, and on suitable plant type. This becomes even more important if these fuels are to be used in plants that are compensating for the variable nature of intermittent sources and, therefore, the same type of temporal analysis will need to be carried out for the production, availability and use of these fuels as for the intermittent supplies.

Many of the programs discussed in this chapter are based on economic models. Economics and politics, however, will not be considered in this work as they are subject to constant and unexpected change (e.g. reduced capital or running costs, future subsidies, grants or tax credits being introduced or removed), and may vary substantially around the world. Instead this framework will concentrate on evaluating the technical feasibility of a system. The range of best solutions may then be found using the program, and subsequently evaluated by the user, with due consideration given to equipment and running costs, available space and social acceptability, both for current and future predicted situations.

The use of optimisation may be considered in this work, but this will not be the main or sole focus. This is because, when designing systems with so many different possible plant types and configurations, it is important to be able to see the full range of options available, so as not to rule out any viable systems. This then allows these systems to be evaluated, taking economic factors, political incentives, possible future technical advancements, and the potential need for expansion, into consideration.

There are many programs available that allow the evaluation of mainly electricity supply systems containing intermittent supplies, reserve plant and storage. This work will, therefore, concentrate on the modelling of the main components available to complement the use of these intermittent sources in sustainable energy supply systems, as discussed in Chapter 2, and will look at how these may be integrated to form reliable systems for the supply of electricity, heat, hot water and transportation fuel. Chapter 4 gives an outline of a flexible and generic decision support framework that will aid the design of reliable and efficient sustainable systems that can supply the total energy needs of any given area. This will be achieved by extending the MERIT software described in this chapter.

3.5 References

[1] M. Muselli, G. Notton, P. Poggi, A Louche, "Computer-aided analysis of the integration of renewable-energy systems in remote areas using a geographical-information system", Applied Energy, 63, 1999, pp141-160

[2] S. Rozakis, P. G. Soldatos, G. Papadakis, S. Kyritsis, D. Papantonis, 'Evaluation of an integrated renewable energy system for electricity generation in rural areas', Energy Policy, 1997, Vol. 25, No. 3, pp 337-347

[3] M. A. Castro, J. Carpio, J. Peire, J. A. Rodriguez, 'Renewable energy integration assessment through a dedicated computer program', Solar Energy, 1996, Vol. 57, No. 6, pp 471-484

[4] F. Bonanno, A. Consoli, S. Lombardo, A. Raciti, 'A logistical model for performance evaluations of hybrid generation systems', IEEE Transactions on Industry Applications, 1998, Vol. 34, No. 6, pp 1397-1403

[5] R. Chedid, S. Rahman, 'Unit sizing and control of hybrid wind-solar power systems', IEEE Transactions on Energy Conversion, 1997, Vol. 12, No. 1, pp 79-85

[6] R. Chedid, H. Akiki, S. Rahman, 'A decision support technique for the design of hybrid solar-wind power systems', IEEE Transactions on Energy Conversion, 1998, Vol. 13, No. 1, pp 76-83

[7] T. R. Morgan, R. H. Marshall, B. J. Brinksworth, " 'ARES' – a refined simulation program for the sizing and optimisation of autonomous hybrid energy systems", Solar Energy, 1997, Vol. 59, Nos.4-6, pp 205-215

[8] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001, www.esru.strath.ac.uk

[9] The University of Wisconsin-Madison, Solar Energy Laboratory, sel.me.wisc.edu/trnsys

[10] T. Ackermann, K. Garner, A. Gardiner, "Embedded wind generation in weak grids – economic optimisation and power quality simulation", Renewable Energy, 1999, 18, pp 205-221

[11] G. C. Seeling-Hochmuth, 'A combined optimisation concept for the design and operation strategy of hybrid-PV energy systems', Solar Energy, 1997, Vol. 61, No. 2, pp 77-87

[12] S. Iniyan, L. Suganthi, T. R. Jagadeesan, "Renewable energy planning for India in 21st Century", Renewable Energy, May-Aug 1998, Vol. 14 (1-4), pp 453-457

[13] Ministry of Natural Resources Canada, CANMET Energy Diversification Research Laboratories (CEDRL), retscreen.gc.ca

[14] R. Ramakumar, I. Abouzahr, K. Krishnan, K. Ashenayi, "Design scenarios for integrated renewable energy systems", IEEE Transactions on Energy Conversion, December 1995, Vol. 10, No. 4

[15] R. Ramakumar, I. Abouzahr, K. Ashenayi, "A knowledge-based approach to the design of integrated renewable energy systems", IEEE Transactions on Energy Conversion, December 1992, Vol. 7, No. 4

[16] C. P. Mitchell, "Development of decision support systems for bioenergy applications", Biomass and Bioenergy, 2000, Vol. 18, pp 265-278

[17] C. P. Mitchell, A. V. Bridgewater, D. J. Stevens, A. J. Toft, M. P. Watters, "Technoeconomic assessment of biomass to energy", Biomass and Bioenergy, 1995, Vol. 9 (1-5), pp 205-226

[18] C. R. McGowin, G. A. Wiltsee, "Strategic analysis of biomass and waste fuels for electric power generation", Biomass and Bioenergy, 1996, Vol. 10 (2-3), pp 167-175

[19] E. G. Koukios, N. J. Kyriazis, K. Blatsoukas, "Biomass Toolkit: Modelling for a new age", Renewable Energy, Sep-Dec 1996, Vol. 9 (1-4), pp 1001-1006

[20] G. Sundberg, B. G. Karlsson, "Interaction effects in optimising a municipal energy system", Energy, Sep 2000, Vol. 25 (9), pp 877-891

[21] Transco, Energy Efficiency Best Practice Programme, "chp-sizer – a tool to conduct a preliminary evaluation of CHP for new hospitals and hotels", Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk, 0800 585794

4 A Procedure for Demand and Supply Matching

A flexible and generic decision support framework is required through which the design of sustainable energy systems for the supply of electricity, heat, hot water and transportation fuel may be evaluated. This will be a valuable decision making tool for the design of integrated energy systems that include intermittent renewable energy supplies. This chapter discusses the requirements of such a system, and the developments that have been made to an existing software package, MERIT, in order to achieve this.

The previous chapters have shown that the following issues must be considered in order to create an effective demand and supply matching procedure that can analyse the total energy requirements of a given area: -

- The procedure must be flexible and generic, allowing small and medium sized areas in any location and climate, with different demand needs and supply possibilities to be analysed.

- The temporal matching of supply and demand is required in order to analyse variations throughout the day and between seasons.

- Demands for electricity, heat, hot water and transport must be able to be considered.

- Intermittent supplies, and the range of alternative transportation fuels and vehicles, alternatively fuelled technologies for CHP generation, heat storage and production technologies, other uses for excess electricity, and methods for producing fuels from waste and biomass sources must be available for consideration (as discussed in Chapter 2).

- The procedure must aid decisions about the best mix, type and sizing of all technologies and processes being considered, and about the amount of fuel or other storage required as appropriate. Informed decisions can then be made about the suitability of potential supply systems based on subsequent cost analyses.

- It must be possible to analyse and compare a number of potential combinations quickly and easily.

Along with the temporal pattern of demands and supplies, the timing of the production of derived fuels must also be taken into account in the design of sustainable energy systems. If seasonal energy crops are used, the fuel may be harvested for two months of the year only, and requires to be stored if it is to be used for the remainder of the year. Other sources, such as biogas from anaerobic digestion or landfill gas, are produced by a steady, continual process, and biodiesel and ethanol are often made by batch production processes that can take from eight hours to five days to complete. These different production rate profiles must be compared with demand variation in order to determine daily and seasonal storage requirements, and to ensure that there is enough fuel at any given time to meet peak demands. Also, if excess electricity, or electricity from intermittent renewable sources, is used to generate hydrogen, this production will be intermittent and unreliable, and again must be compared with demand for the same reasons. This is further complicated if the fuel is to be used for two different purposes, for example, the supply of heat and as a transportation fuel. It is, therefore, important to be able to analyse this daily and seasonal production and use, along with the daily and seasonal demand and supply matching, in order to assess the suitability and storage requirements of different types or mixes of fuel, with different availabilities, for each particular demand and supply mix.

A program (MERIT) has been developed, which contains some of the desired features described above [1]. This program allows electricity, heat and hot water demands to be matched with supplies from intermittent sources (wind turbines, PV cells, PV concentrators and flat plate collectors) and a basic base load small high-speed diesel generator that can supply electricity and heat. Auxiliary plant (load following supplies) such as storage devices (batteries, pumped storage and flywheels), a back-up diesel generator, and tariff structures are also available for use.

MERIT is written in Visual C++, and is easy to use thanks to its graphic user interface. The program allows the user to select an appropriate climate file and time period for the study, and the desired number of timesteps per hour can be chosen. The time period is chosen by date, and can be anything from one day to the whole year. To save time when matching, the program can also select seasonal representative days, weeks or months based on the climate information.

As MERIT already contains many of the important basic elements of the procedure outlined above, it is used as the basis for this work. This chapter describes the existing MERIT system and the changes made to provide the required functionality.

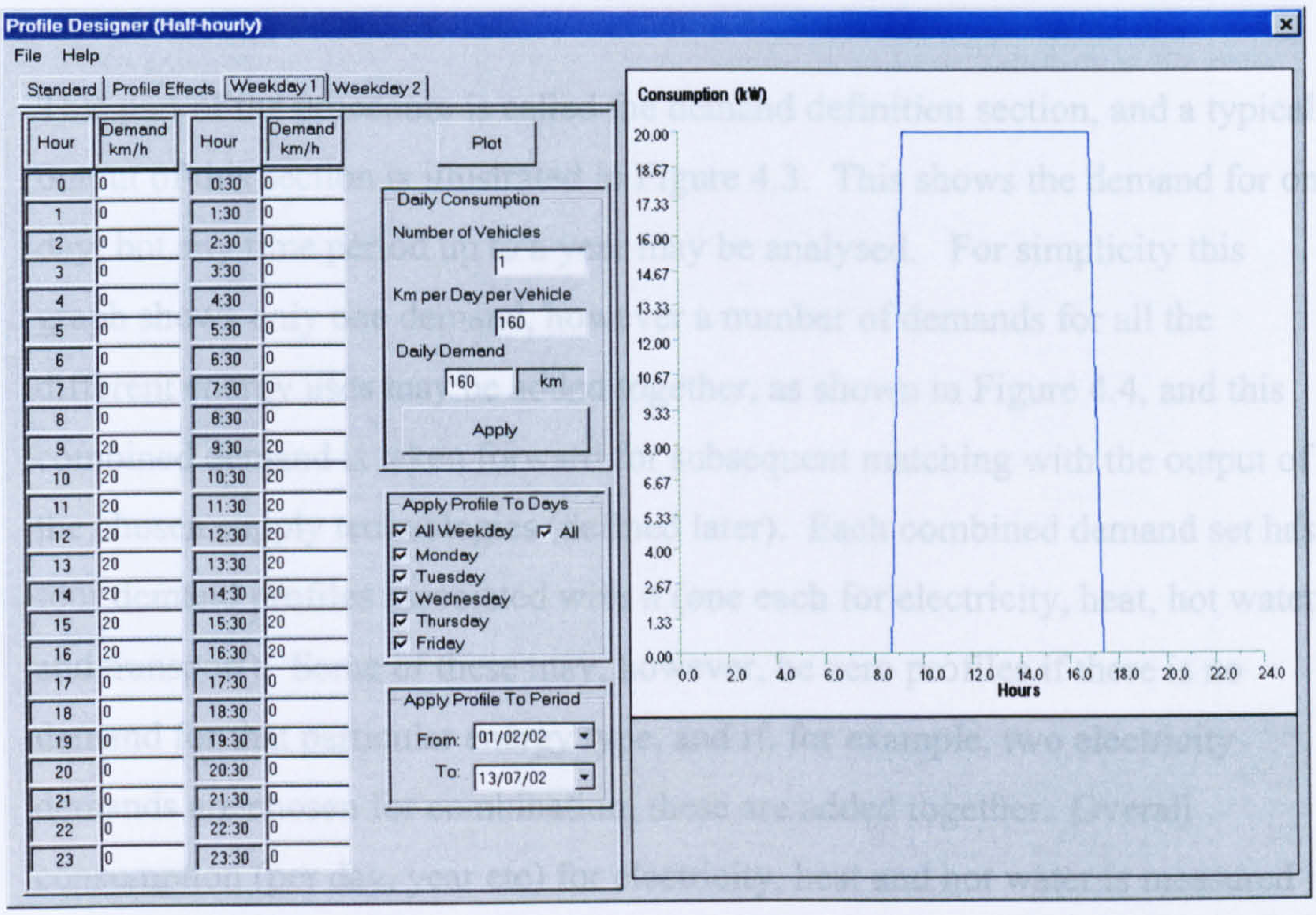
4.1 Demand Definition

To gain a complete view of energy use in an area, the demands for electricity, heat, hot water, and transport must be considered. Profiles of use for these different types of energy demand and supply are considered at half-hourly intervals, as electricity and heat demand profile information available in the form of metered and load research data is typically defined in this manner [1]. Half-hourly intervals are sufficiently detailed for an initial analysis of various supply options, and further, more in-depth analysis can be carried out once suitable supply mixes have been found.

A procedure already exists in MERIT to select demand profiles for electricity, heat and hot water from a database of existing profiles, or to create new half-hourly profiles. To create new profiles, these may be designed, based on existing templates held in a database, or by manually inputting the half-hourly consumption figures, in a part of the demand definition section called the Profile Designer. To increase or decrease the magnitude of the profile, whilst maintaining its shape, an alternative overall daily demand can be applied to the profile. Different profiles can be defined for different time periods throughout the year, and for different days of the week. An annual profile is then created, and the magnitude of this profile can also be scaled up or down by applying a different overall annual consumption figure. This profile may then be added to the database of profiles for selection for matching. When a profile is chosen from the database, only the demands for the time period being considered are extracted. Profiles from the database can be selected in multiples, which multiplies the magnitude of the profile by a chosen figure. When selecting multiples, the user can specify a diversity factor, which introduces a degree of variability between the profiles.

A number of methods for incorporating transport demand have been considered for this procedure, and it has been decided to define the demand for transport as a profile of distance that a vehicle or group of vehicles require to travel in a certain period of time (km/h), against time. Therefore, the profile shows the number of km that require to be travelled by a vehicle or group of vehicles per hour throughout each day, just as the electricity demand is the amount of electricity that is required per hour, and is given in kWh per hour (kW) and, later, the demand for a liquid fuel is given in litres per hour. This keeps all demand types equivalent.

Transport demand profiles can be created using the Profile Designer, where the half-hourly demands may be input, and, if desired, the overall daily transport demand can be calculated from the number of vehicles and the number of kilometres per day per vehicle, and applied to the profile. Otherwise, as km/h is also the measure of speed, by knowing the average speed of a single vehicle, the distance it requires to travel per hour is known, and multiplying this figure by the number of vehicles gives the necessary distance per hour. For example, if two tractors run at an average speed of 10 km/h between set times of the day, the transport demand is 20 km/h between these set times. This information is then be used to create a profile of vehicle use throughout the day, varying with time of year, weekdays and weekends if necessary, to create an annual transport demand profile. This is illustrated in Figures 4.1 and 4.2, which show the definition of a daily transport demand profile, and the derived yearly demand, for the agricultural vehicle use required to cultivate and harvest oilseed rape for transesterification.


Profile Designer (Half-hourly)

Weekday 1

Hour	Demand km/h	Hour	Demand km/h
0	0	0:30	0
1	0	1:30	0
2	0	2:30	0
3	0	3:30	0
4	0	4:30	0
5	0	5:30	0
6	0	6:30	0
7	0	7:30	0
8	0	8:30	0
9	20	9:30	20
10	20	10:30	20
11	20	11:30	20
12	20	12:30	20
13	20	13:30	20
14	20	14:30	20
15	20	15:30	20
16	20	16:30	20
17	0	17:30	0
18	0	18:30	0
19	0	19:30	0
20	0	20:30	0
21	0	21:30	0
22	0	22:30	0
23	0	23:30	0

Daily Consumption

Number of Vehicles: 1

Km per Day per Vehicle: 160

Daily Demand: 160 km

Apply Profile To Days

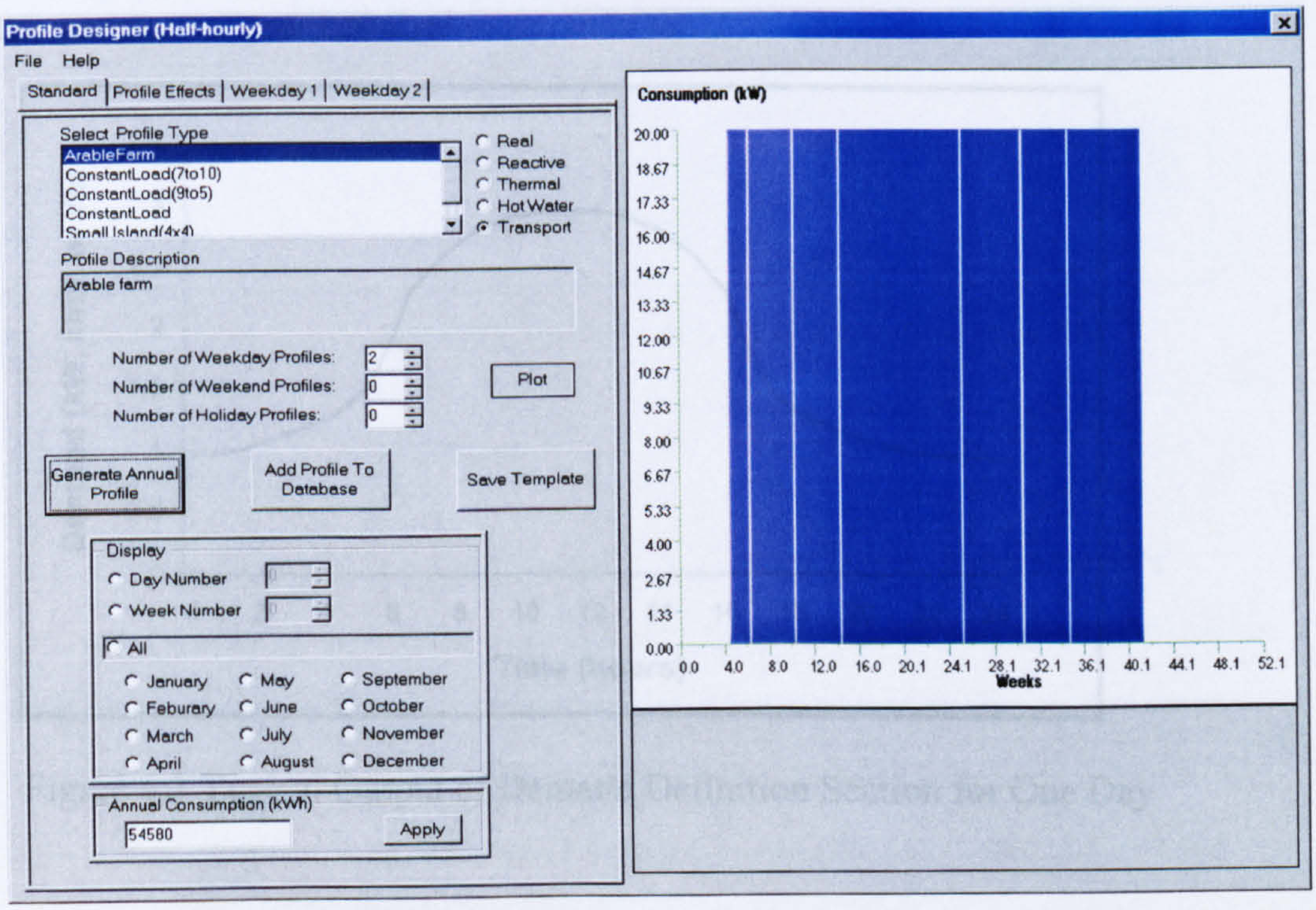
☑ All Weekday ☑ All
☑ Monday
☑ Tuesday
☑ Wednesday
☑ Thursday
☑ Friday

Apply Profile To Period

From: 01/02/02

To: 13/07/02

Figure 4.1 Daily Transport Demand Profile Definition


Profile Designer (Half-hourly)

Standard

Select Profile Type

ArableFarm
ConstantLoad(7to10)
ConstantLoad(9to5)
ConstantLoad
Small Island(4x4)

○ Real
○ Reactive
○ Thermal
○ Hot Water
● Transport

Profile Description: Arable farm

Number of Weekday Profiles: 2

Number of Weekend Profiles: 0

Number of Holiday Profiles: 0

Display

○ Day Number
○ Week Number
○ All

○ January	○ May	○ September
○ Feburary	○ June	○ October
○ March	○ July	○ November
○ April	○ August	○ December

Annual Consumption (kWh): 54580

Figure 4.2 Derived Yearly Transport Demand

Separate databases have been created for each demand type in Profile Designer, and the demand type is saved along with the profile information, allowing the correct profile type to be created in the demand definition section.

This part of the procedure is called the demand definition section, and a typical output of this section is illustrated in Figure 4.3. This shows the demand for one day, but any time period up to a year may be analysed. For simplicity this graph shows only one demand, however a number of demands for all the different energy uses may be added together, as shown in Figure 4.4, and this combined demand is taken forward for subsequent matching with the output of the chosen supply technologies (defined later). Each combined demand set has four demand profiles associated with it (one each for electricity, heat, hot water, and transport). Some of these may, however, be zero profiles if there is no demand for that particular energy type, and if, for example, two electricity demands are chosen for combination, these are added together. Overall consumption (per day, year etc) for electricity, heat and hot water is measured in kWh, and transport in kilometres. The rate of consumption is measured in kW and km/hour.

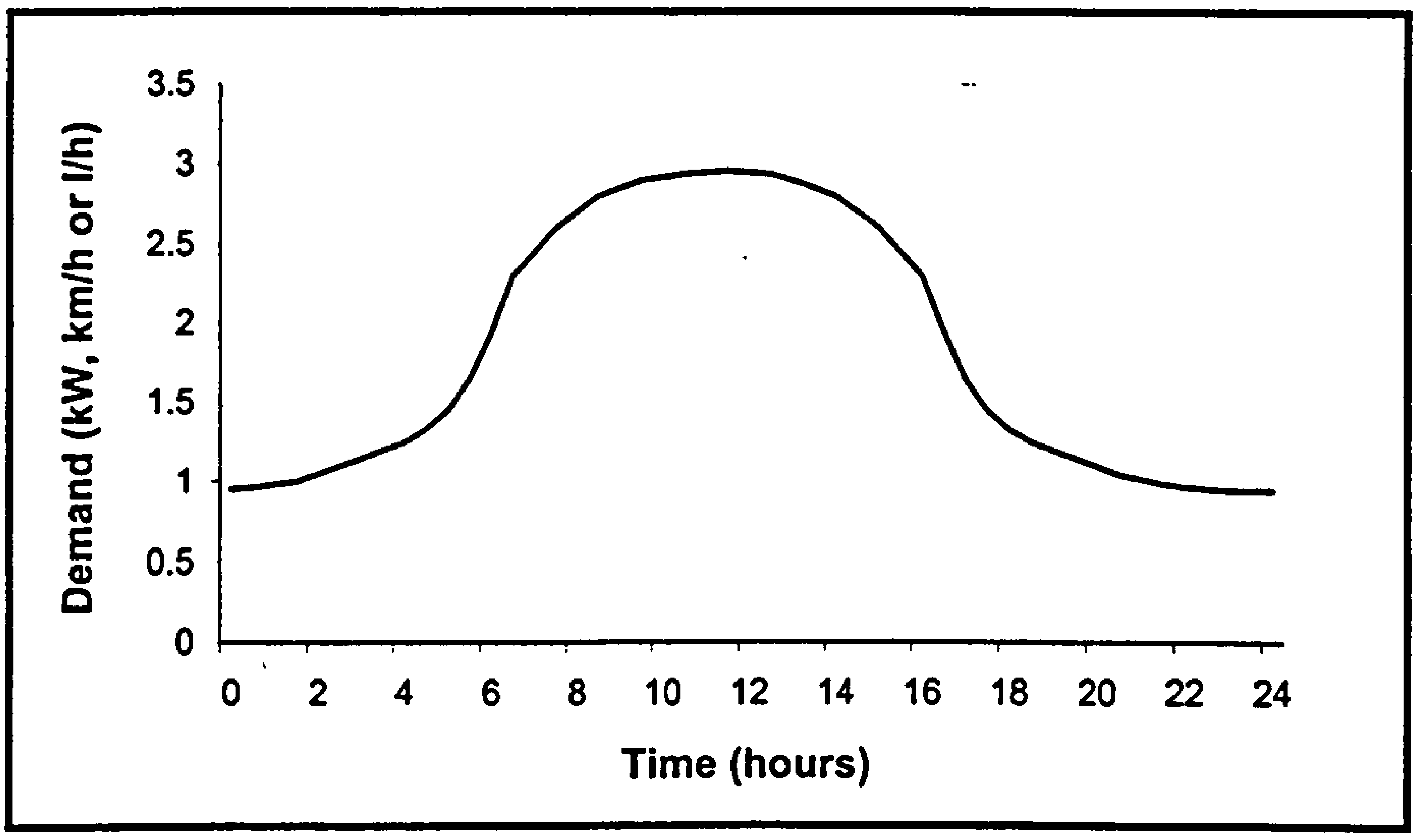


Figure 4.3 Typical Output of Demand Definition Section for One Day

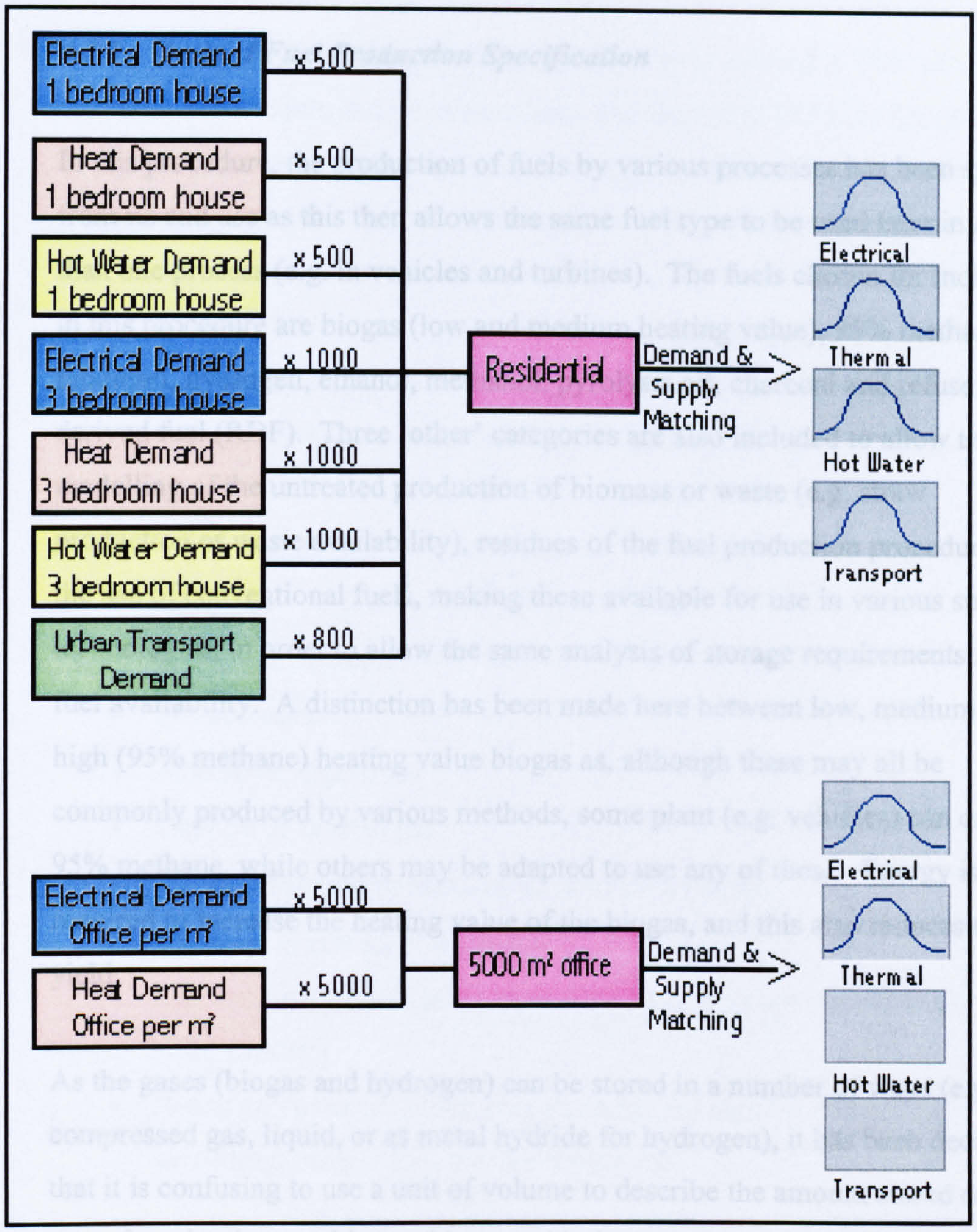


Figure 4.4 Combining Demands to Take Forward For Matching

4.2 Supply Definition

Three layers of supply choice now exist within the program where there previously were two. The new layer is the first, which allows the specification and creation of half-hourly profiles for the production of fuels derived from waste or biomass. The second layer allows the specification and creation of half-hourly profiles from intermittent sources, and the final layer allows the definition of supplies that follow demand and/or use fuel.

4.2.1 Derived Fuel Production Specification

In this procedure, the production of fuels by various processes has been split from its end use as this then allows the same fuel type to be used later in more than one process (e.g. in vehicles and turbines). The fuels chosen for inclusion in this procedure are biogas (low and medium heating value), 95% methane, biodiesel, hydrogen, ethanol, methanol, pyrolysis oil, charcoal and refuse derived fuel (RDF). Three 'other' categories are also included to allow the modelling of the untreated production of biomass or waste (e.g. straw production or waste availability), residues of the fuel production procedures, or the use of conventional fuels, making these available for use in various supply technologies, in order to allow the same analysis of storage requirements and fuel availability. A distinction has been made here between low, medium and high (95% methane) heating value biogas as, although these may all be commonly produced by various methods, some plant (e.g. vehicles) can only use 95% methane, while others may be adapted to use any of these. Energy is required to increase the heating value of the biogas, and this also reduces the yield.

As the gases (biogas and hydrogen) can be stored in a number of ways (e.g. compressed gas, liquid, or as metal hydride for hydrogen), it has been decided that it is confusing to use a unit of volume to describe the amount stored or the rate of production, as this would vary with the storage medium. These parameters will, instead, be described by their energy content – kWh for storage, and kW for rate of production. As the lower heating value of the biogas produced by various processes can vary significantly within the broad bands of low and medium heating value, this also means that the lower heating value of the gas need only be considered once during the procedure, and that gases, made by different methods, with slightly different lower heating values, may be combined under the headings of low or medium heating value biogas.

To make results more meaningful for the user, however, the liquid fuels (ethanol, methanol, biodiesel and pyrolysis oil) are described in litres for storage and litres/hour for production rate of the liquid fuel. As liquid fuel consumption rates for vehicles, engines and other plant tend to be quoted in this way, this also saves an unnecessary double conversion. For the solids (RDF and charcoal), the weight measurement of kg for storage and kg/hour for production rate are used for the same reasons. The 'other' categories will be defined by the user as solid, liquid or gas, and use the appropriate units.

Fuels can be made from waste and biomass by a number of processes. The most common methods, and those included in this procedure, are: -

- Gasification
- Pyrolysis
- Transesterification
- Fermentation
- Anaerobic digestion
- Capture of landfill gas
- Steam reforming of methane to produce hydrogen
- Catalytic synthesis of methanol
- Electrolysis of water using electricity from intermittent sources (e.g. wind and PV)
- Waste and biomass processing technologies such as pelletising, shredding, briquetting, sewage drying etc.

The method for defining the process characteristics, and creating half-hourly production rate graphs for the derived fuels, is based on the process already used in MERIT for defining the intermittent supply technology characteristics and creating their output profiles. The same methods for selecting and combining profiles have also been used to provide continuity. The algorithms used to model the production of fuels and other residues from these processes are described in more detail in Chapter 6. Consideration is also given, in these models, to the energy required to carry out these processes and, where appropriate, to put the produced fuel into storage.

To define a fuel production system, the desired system type is selected from the top list shown in Figure 4.5. This opens a system definition window for the selected system type, in which easily available manufacturers' data, and system and feedstock characteristics, may be input, or existing systems may be chosen from a database. The half-hourly fuel production rate and energy use profiles are then calculated as described in Chapter 6, and these graphs are drawn (see Figure 4.5). An information box is also given along with each profile set as it is calculated (see Figure 4.6), giving information about the overall inputs and outputs required for the process.

Each process is defined, in its system definition window, as either seasonal or continuous, and this information is taken through to the matching stage. If a seasonal supply is defined, and the simulation period is less then a year, the user is warned that this will give misleading results. The procedure for dealing with seasonal fuel supplies at the matching stage is described later in Section 4.3.

A Derived Fuel Profile Designer has also been created, based on the Demand Profile Designer, which allows the definition of any known fuel supply profile or related energy demand profile, in the same manner as described in Section 4.1. This allows a profile for any fuel or demand type to be created, and is particularly useful for assigning a profile of supply of wood, waste or other fuels which can be used directly in auxiliary supplies without prior processing, to one of the 'other' categories. The pattern of storage requirements, and the suitability of the fuel supply pattern for these fuels can then be analysed in the same manner as for the other defined supplies, as described later.

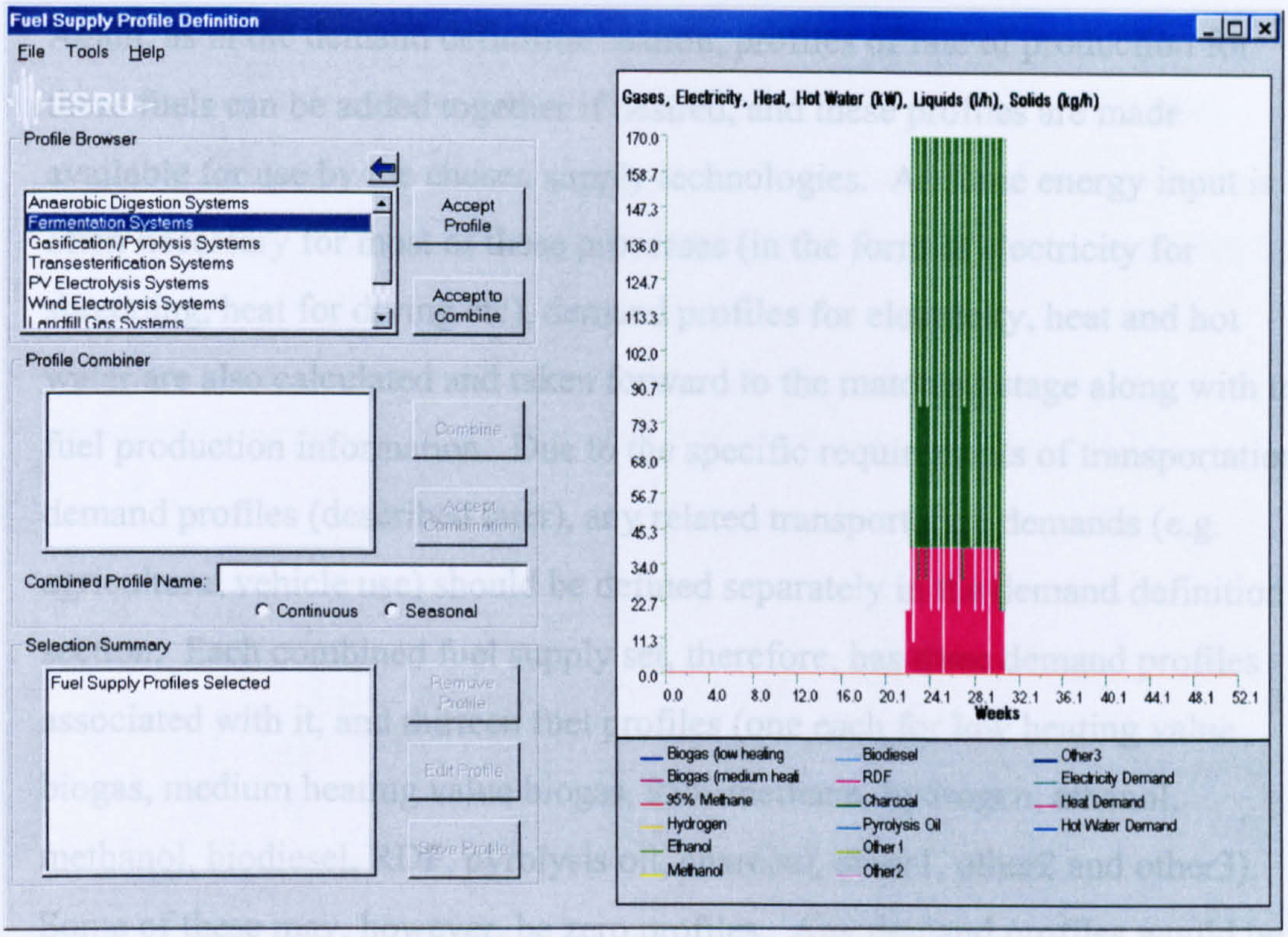
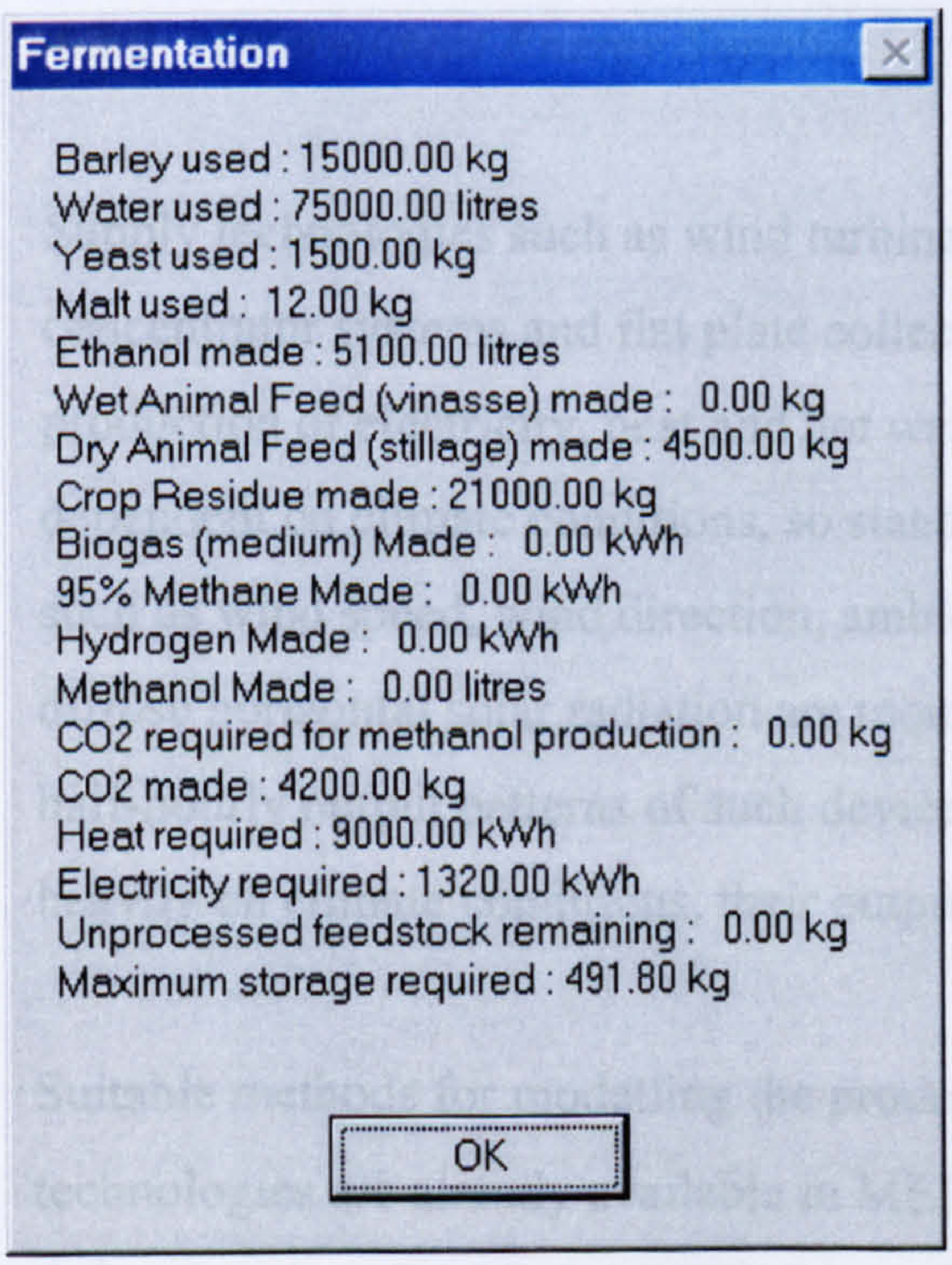


Figure 4.5 Derived Fuel Production Specification



Barley used : 15000.00 kg
Water used : 75000.00 litres
Yeast used : 1500.00 kg
Malt used : 12.00 kg
Ethanol made : 5100.00 litres
Wet Animal Feed (vinasse) made : 0.00 kg
Dry Animal Feed (stillage) made : 4500.00 kg
Crop Residue made : 21000.00 kg
Biogas (medium) Made : 0.00 kWh
95% Methane Made : 0.00 kWh
Hydrogen Made : 0.00 kWh
Methanol Made : 0.00 litres
CO2 required for methanol production : 0.00 kg
CO2 made : 4200.00 kg
Heat required : 9000.00 kWh
Electricity required : 1320.00 kWh
Unprocessed feedstock remaining : 0.00 kg
Maximum storage required : 491.80 kg

Figure 4.6 Information Box

Again, as in the demand definition section, profiles of rate of production for these fuels can be added together if desired, and these profiles are made available for use by the chosen supply technologies. As some energy input is often necessary for most of these processes (in the form of electricity for shredding, heat for drying etc), demand profiles for electricity, heat and hot water are also calculated and taken forward to the matching stage along with the fuel production information. Due to the specific requirements of transportation demand profiles (described later), any related transportation demands (e.g. agricultural vehicle use) should be defined separately in the demand definition section. Each combined fuel supply set, therefore, has three demand profiles associated with it, and thirteen fuel profiles (one each for low heating value biogas, medium heating value biogas, 95% methane, hydrogen, ethanol, methanol, biodiesel, RDF, pyrolysis oil, charcoal, other1, other2 and other3). Some of these may, however, be zero profiles. Any demand profiles would be added to the chosen demands on matching so, when it comes to demand and supply matching, there is a facility to allow the chosen fuel production processes to be turned on or off to avoid unnecessary demands being considered.

4.2.2 Intermittent Energy Supplies

Supply technologies such as wind turbines, photovoltaic (PV) panels, PV concentrator systems and flat plate collectors are commonly used for the production of electricity, heat and hot water. These supplies are highly dependent on climate conditions, so standard half-hourly climate information such as wind speed, wind direction, ambient temperature, direct normal and diffuse horizontal solar radiation are required in order to be able to predict the half-hourly output patterns of such devices. As these supply technologies rely heavily on climate conditions, their output is intermittent and unreliable.

Suitable methods for modelling the production of energy from these intermittent technologies are already available in MERIT. Technologies are chosen or defined as described in Section 4.2.1, and rate of supply profiles for electricity, heat and/or hot water are created, similar to those for demand, and using the same units. Again, as with the demand definition section, profiles can be added together if desired, and taken forward for matching with the demand profiles. Each combined supply set has three supply profiles associated with it (for electricity, heat and hot water). It is not possible to use any of these supplies to meet the transport demand. A typical output graph for this section is shown in Figure 4.7.

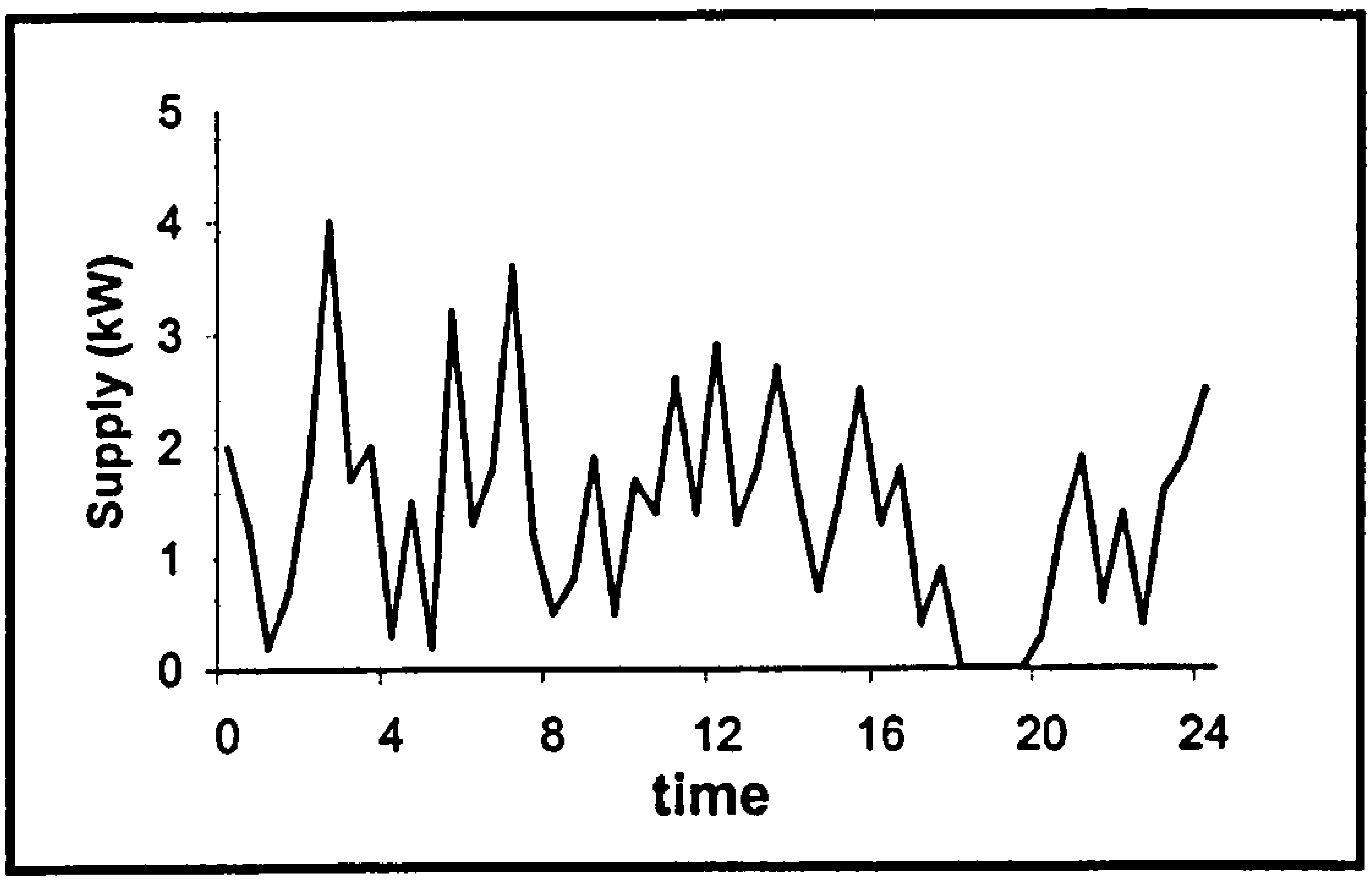


Figure 4.7 Typical Output Graph for the Intermittent Supply Definition Section

A Supply Profile Designer has also been added in the intermittent supply section to allow known supplies, constant supplies such as geothermal, base load nuclear, or other conventional supplies etc, to be added to simulations. This functions in the same way as the other Profile Designers, but only supplies of electricity, heat and hot water can be defined.

If fuel using supplies are chosen later in the procedure, intermittent sources will be considered first when matching supply with demand, as they provide a source of energy that is, effectively, free after initial manufacturing and installation costs (i.e. no fuel is required). The matching procedure is discussed later.

4.2.3 Supplies Which Follow Demand and/or Require Fuel

Supplies that are used to meet the excess demands not met by the intermittent supplies are classed as load following supplies. Their output depends on the required demand and there are various different types that need to be considered here, including: -

- Storage devices (e.g. batteries, flywheels, pumped storage, hot water storage systems) take in energy at times when there is excess, and supply the same type of energy when there is an unmet demand. These are, generally, less than 100% efficient, so the output will be less than the input, and their use is often subject to a minimum load, where they can only take in or supply energy above a certain percentage of their rated power.

- Gas, steam and combined cycle turbines, internal combustion, diesel and stirling engines, fuel cells, space and water heaters, can use fuels derived from waste and biomass, other directly used waste and biomass fuels, and excess electricity for the production of electricity, heat and hot water. These supplies can be used to follow the unmet demand, run constantly as a base load at a specified percentage load, or used at different load levels at specified times of the day and year. Where CHP is being considered, the supply is also able to follow the electricity demand, the heat demand or both. The use of this type of plant will also allow the simulation of conventional power sources.

- Vehicles running on various secondary fuels are considered at this stage as their output depends on the transport demand, and fuel availability. Onboard storage and refuelling methods are taken into consideration here as they affect the pattern of use of the fuel.

- Electrolysers to produce hydrogen also provide a good use for excess electricity. The hydrogen produced is added to the hydrogen already available, and the total is then available for use in other load following devices using hydrogen as a fuel.

MERIT already contains the procedures to allow various auxiliary plants to be defined and selected for use in the matching procedure, and this is done in a similar manner to that for the derived fuel supply definition. However, no profiles are output from this part of the procedure, as these cannot be calculated until the residual demand, supply, and fuel availability are known. This is done at the matching stage by applying the demand, supply and fuel availability information to the defined model parameters and specified plant algorithm. Existing available technologies in MERIT include batteries, pumped storage, flywheels, basic diesel generators, and tariff structures [1]. The specific algorithms developed to model the other technologies mentioned in this section are described in more detail in Chapter 5.

As the demand and supply profiles change after each load following supply has been used, the order in which they are applied is important, and each process is applied in the order in which it is chosen at the matching stage. This allows different control strategies to be tried. For example, if hydrogen is to be produced for immediate use, the electrolyser should be selected first. However, if the electrolyser is there to produce hydrogen for storage after all other electricity using supplies have had their share, then it should be selected last.

Although some of these devices have quite different uses, they are all either load following devices and/or devices that require fuel. They have been put together here as they may then be employed in any order, to create any desired control strategy. Engines, turbines and fuel cells are also considered in this section as base loads as this allows fuel availability to be checked. If there is not enough fuel available, the possible output with the available fuel is calculated.

4.3 The Matching Process

The matching procedure available in MERIT allows different mixtures of demands, supplies and one auxiliary (load following supply) to be chosen from those already selected and brought through to the matching stage. This can be achieved by pressing the desired demand, supply and auxiliary buttons on the matching screen, and, when selected, these buttons are highlighted in colour. Graphs showing the combined supplies and demands for each energy type are shown, and can be 'toggled' between using a button above the graph. A new analysis is performed each time a new demand, supply or auxiliary is chosen, or the energy type is changed.

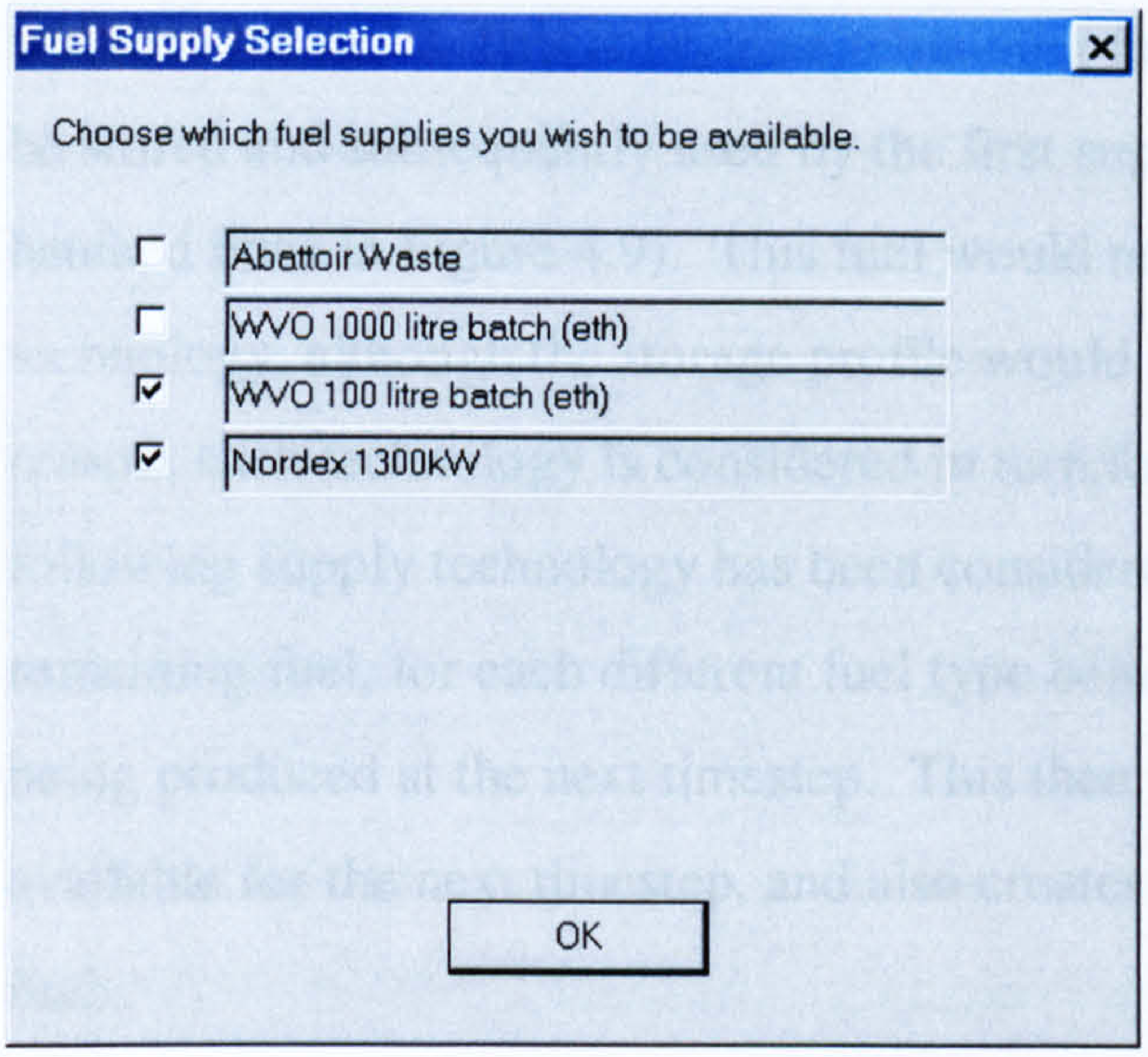
All of the chosen demands are added, and the chosen supplies are subtracted from these, giving a second graph of residual supply and demand for electricity, heat or hot water. If an auxiliary is chosen, the residual demand or supply for each timestep, and the defined plant parameters are applied to the appropriate plant algorithm. This produces a third graph showing the profile of use of the auxiliary supply, and the residual demands and supplies are reduced accordingly. A statistical analysis is carried out, and the match is given a rating out of ten for electricity, heat or hot water, based on the inequality and correlation of the profiles [1]. Many different combinations of supplies, demands and auxiliaries may be analysed in this way, and MERIT also has an automatic searching facility that can find the best supply and demand match combinations, using various user-selected criteria, based either on the electricity, heat or hot water demand only.

Various changes to this matching procedure have been necessary to provide the desired functionality, and these are described below. An overview of the amended matching procedure is also given.

4.3.1 Derived Fuel Availability

When the matching procedure window is first opened, the window shown in Figure 4.8 is also opened. This allows the choice of which derived fuels are to be used for a particular simulation. This choice may be changed at any time by pressing the 'Fuel Supply Choice' button on the matching procedure window, which opens the same fuel choice window. It is important to select only the fuels being used, as there may be energy demands associated with these fuel supplies, which should not be considered if the fuel is not being used.

Before matching, the production rate graph for each fuel being considered is changed to a graph of the amount of the fuel available at each timestep, by dividing the production rate at each timestep by the number of timesteps per hour.


Fuel Supply Selection

Choose which fuel supplies you wish to be available.

☐ Abattoir Waste
☐ WVO 1000 litre batch (eth)
☑ WVO 100 litre batch (eth)
☑ Nordex 1300kW

Figure 4.8 Derived Fuel Supply Selection

When considering the use of energy crops or fuel production from energy crops, the possible production times are often highly seasonal. If an analysis were to be carried out for a year, there may be a number of months being analysed before the production can start, which would be without fuel. This, however, is not likely to be the case in reality, as excess fuel would probably have been stored from the previous year. In order to obtain realistic results when considering such seasonally stored supplies, the simulation is run for two consecutive years with the same demands, allowing any fuel remaining in storage to be used at the beginning of the next year. Using the second of these years gives the required results, and will also allow the user to see if there was any substantial over or under-production. When looking at this type of supply, the simulation period should not be less than a year.

4.3.2 Multiple Load Following Supplies

The matching procedure has been changed to allow the use of multiple load following supplies, and where more than one supply is chosen, these are applied in the order in which they are selected. This is important, as the residual supplies, demands, and available fuel will change after each supply type has been considered. Also, each supply must be considered in turn for each timestep being evaluated, rather than looking at one supply over the whole time period, and then the next. This is because remaining fuel is being stored, and this may be stored and subsequently used by the first supply technology (as shown by the hatched lines in Figure 4.9). This fuel would not then be available for another technology, although the storage profile would suggest otherwise. For this reason, each technology is considered in turn for each timestep. When each load following supply technology has been considered for a given timestep, any remaining fuel, for each different fuel type being used, is added to the amount being produced at the next timestep. This then stores the fuel and makes it available for the next timestep, and also creates a storage profile of remaining fuel.

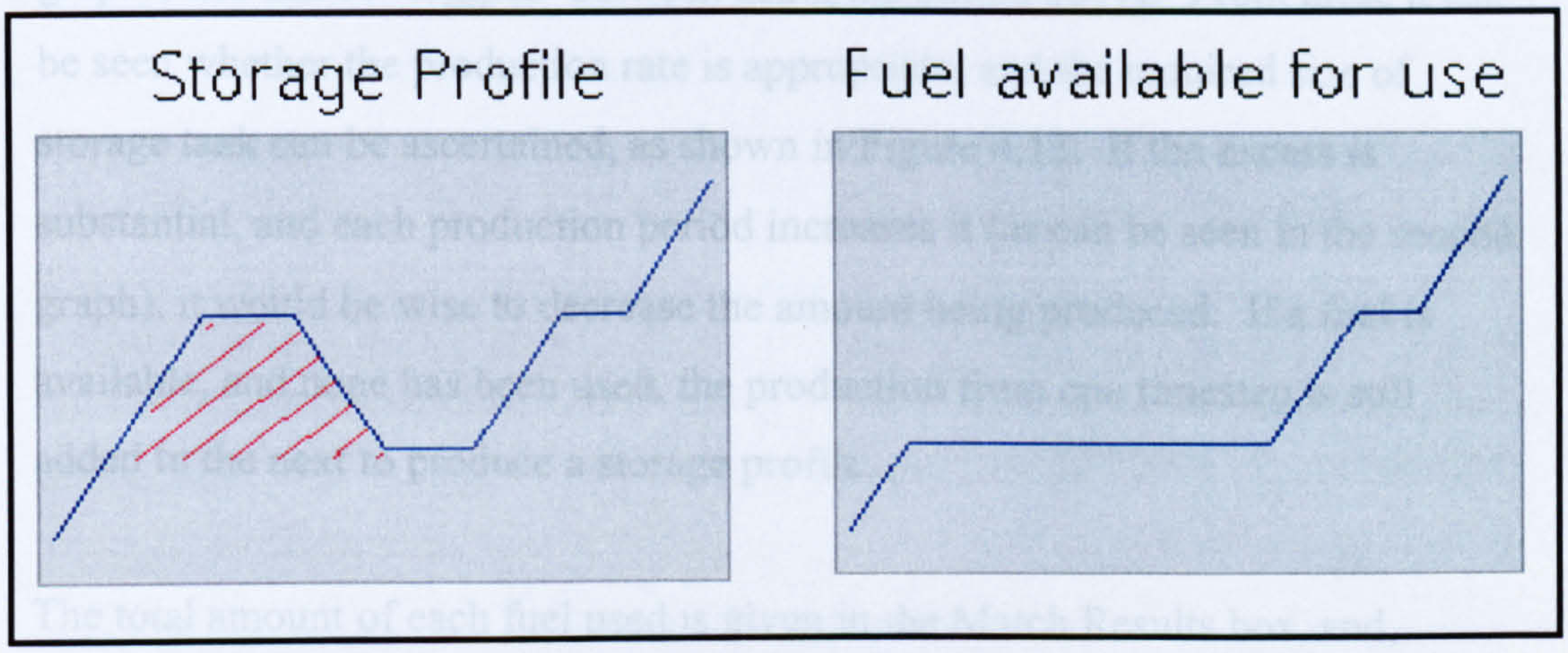


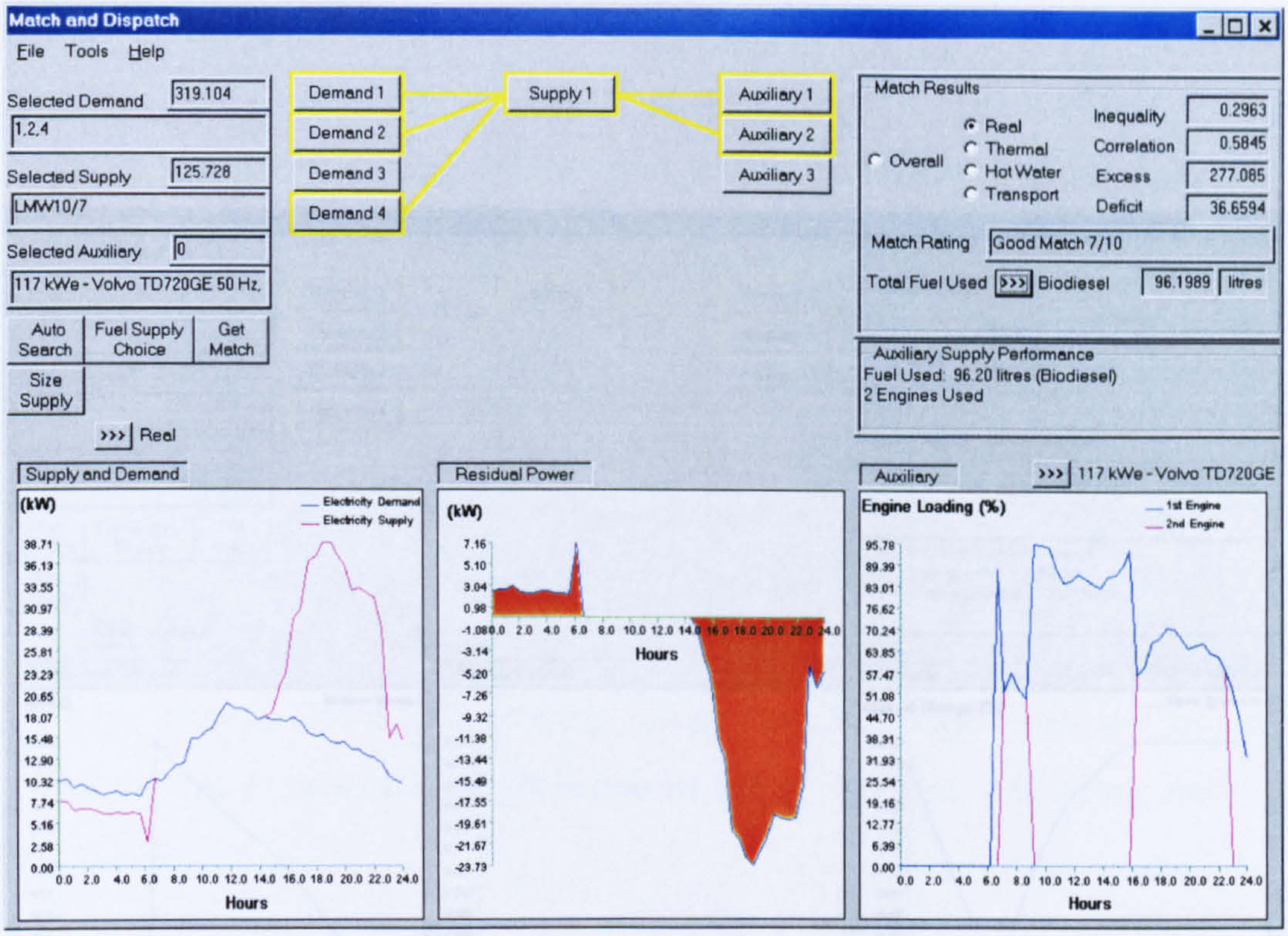
Figure 4.9 Fuel Availability

When load following supplies which require fuel are being used, the amount of the relevant fuel type available is checked by the algorithm to ensure there is enough to run the supply at the required rate. If electricity is the required fuel, the amount of excess electricity for that timestep is used as the available fuel. When there is insufficient fuel to run the plant at the required rate, the possible rate is determined by the algorithm, as described for each plant type in Chapter 5, and a warning message is displayed on the matching procedure window.

As it would be too confusing to show the profile of use graphs, for each load following supply being considered, all in the one graph, a button has been placed above this graph area to allow the different graphs to be 'toggled' between. The name of each load following supply appears above the relevant graph, as shown in Figures 4.10 and 4.11, and the type of graphical information given depends on the type of plant used (see Chapter 5). Other relevant process information, including the number of engines used where multiple sets have been defined, is given in the Auxiliary Supply Performance box above the graphs. The engine being used in this example has been set to follow both the electricity and heat demand.

The fuel storage graphs may be seen in the first graph area on the matching procedure window (see Figure 4.12), along with the energy demand and supply graphs, and can be 'toggled' between using the button above. From these it can be seen whether the production rate is appropriate, and the required size of storage tank can be ascertained, as shown in Figure 4.13. If the excess is substantial, and each production period increases it (as can be seen in the second graph), it would be wise to decrease the amount being produced. If a fuel is available, and none has been used, the production from one timestep is still added to the next to produce a storage profile.

The total amount of each fuel used is given in the Match Results box, and, again, the different fuel types can be 'toggled' between. This is useful when the same fuel is being used in different plants, and can be an important consideration when comparing different scenarios. If seasonal representative time periods are being used, an estimated annual overall consumption for each fuel is also given below this.



Selected Demand 319.104
1,2,4

Selected Supply 125.728
LMW10/7

Selected Auxiliary 0
117 kWe - Volvo TD720GE 50 Hz,

>>> Real

Match Results
○ Overall
● Real
○ Thermal
○ Hot Water
○ Transport

Inequality 0.2963
Correlation 0.5845
Excess 277.085
Deficit 36.6594

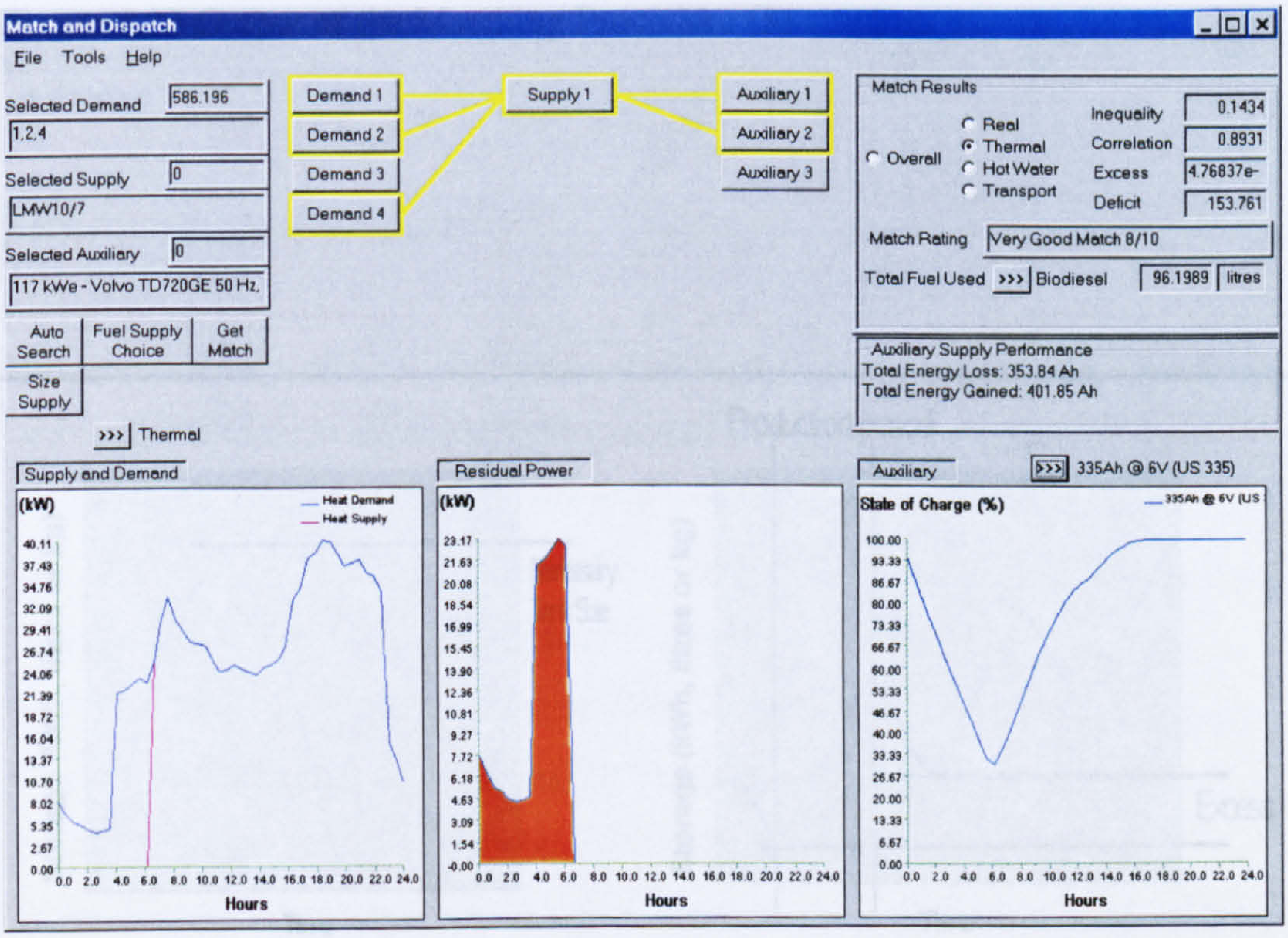
Match Rating Good Match 7/10

Total Fuel Used >>> Biodiesel 96.1989 litres

Auxiliary Supply Performance
Fuel Used: 96.20 litres (Biodiesel)
2 Engines Used

Auxiliary >>> 117 kWe - Volvo TD720GE

Figure 4.10 Output of the Matching Procedure (1)



Selected Demand 586.196
1,2,4

Selected Supply 0
LMW10/7

Selected Auxiliary 0
117 kWe - Volvo TD720GE 50 Hz,

>>> Thermal

Match Results
○ Overall
○ Real
● Thermal
○ Hot Water
○ Transport

Inequality 0.1434
Correlation 0.8931
Excess 4.76837e-
Deficit 153.761

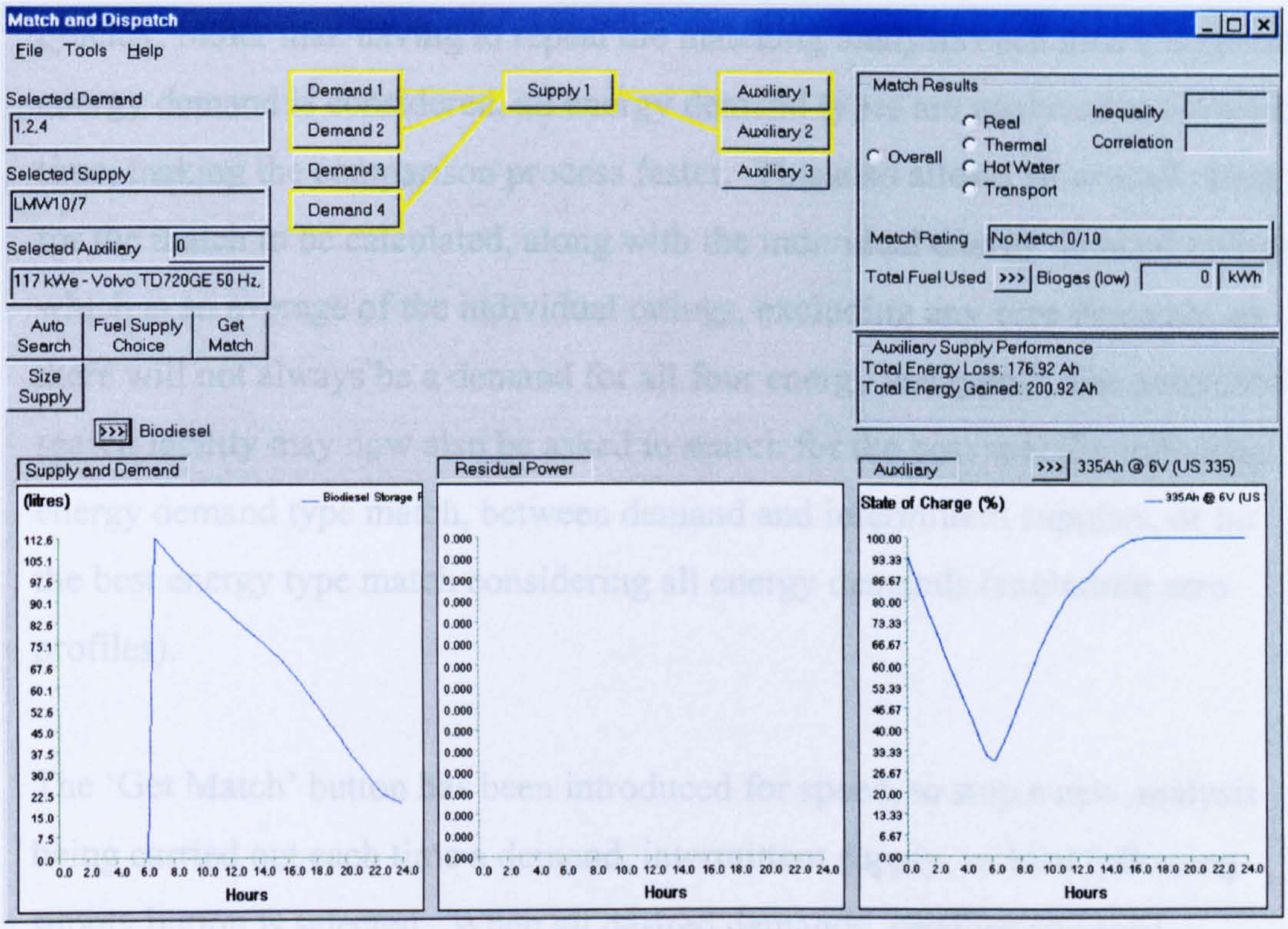
Match Rating Very Good Match 8/10

Total Fuel Used >>> Biodiesel 96.1989 litres

Auxiliary Supply Performance
Total Energy Loss: 353.84 Ah
Total Energy Gained: 401.85 Ah

Auxiliary >>> 335Ah @ 6V (US 335)

Figure 4.11 Output of the Matching Procedure (2)



Match and Dispatch

Selected Demand: 1,2,4

Selected Supply: LMW10/7

Selected Auxiliary: 0

117 kWe - Volvo TD720GE 50 Hz,

>>> Biodiesel

Match Results

○ Overall

○ Real

○ Thermal

○ Hot Water

○ Transport

Match Rating: No Match 0/10

Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance

Total Energy Loss: 176.92 Ah

Total Energy Gained: 200.92 Ah

Auxiliary >>> 335Ah @ 6V (US 335)

Figure 4.12 Output of the Matching Procedure (3)

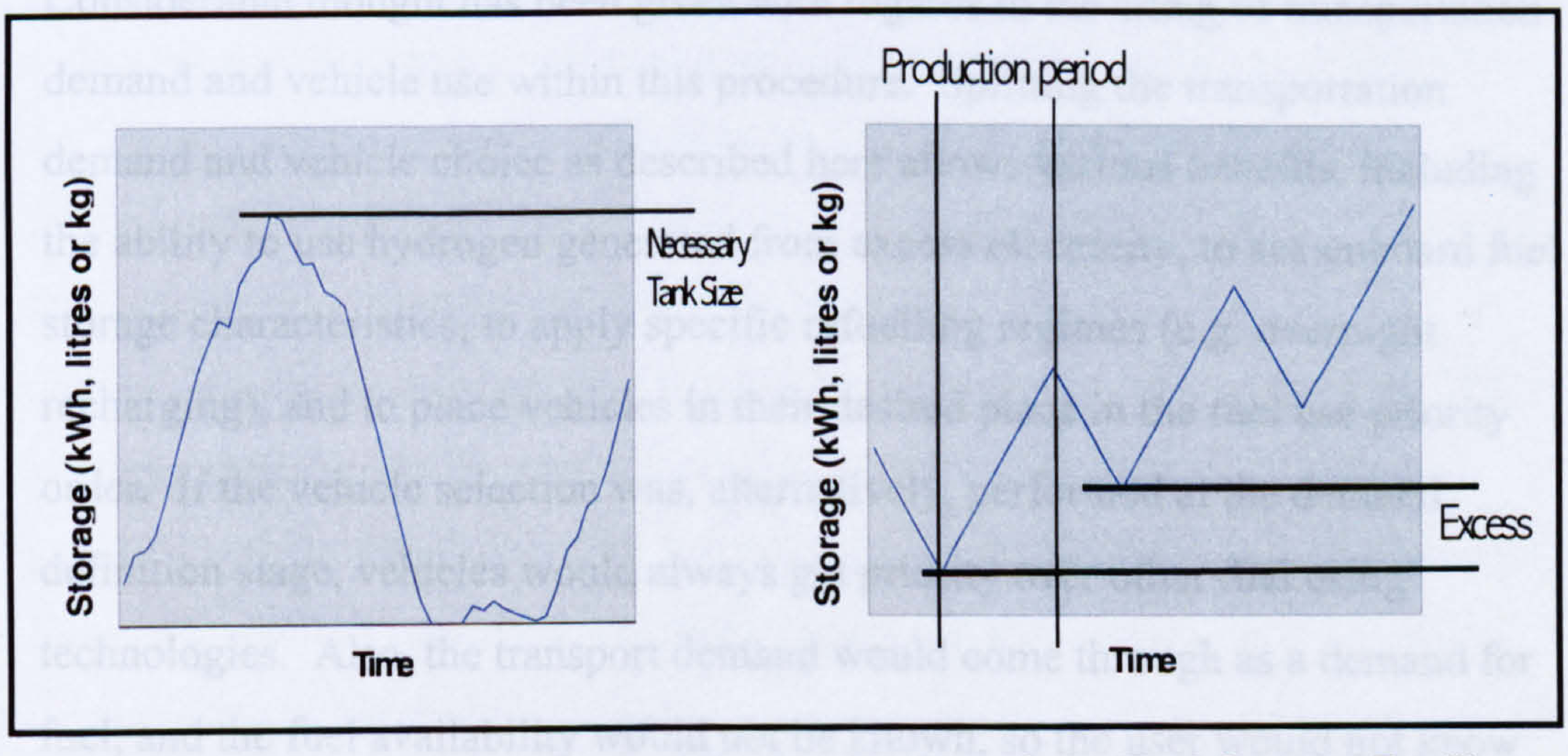


Figure 4.13 Estimating Storage and Production Rate from Fuel Storage Profiles

4.3.3 Four Different Energy Demand Types

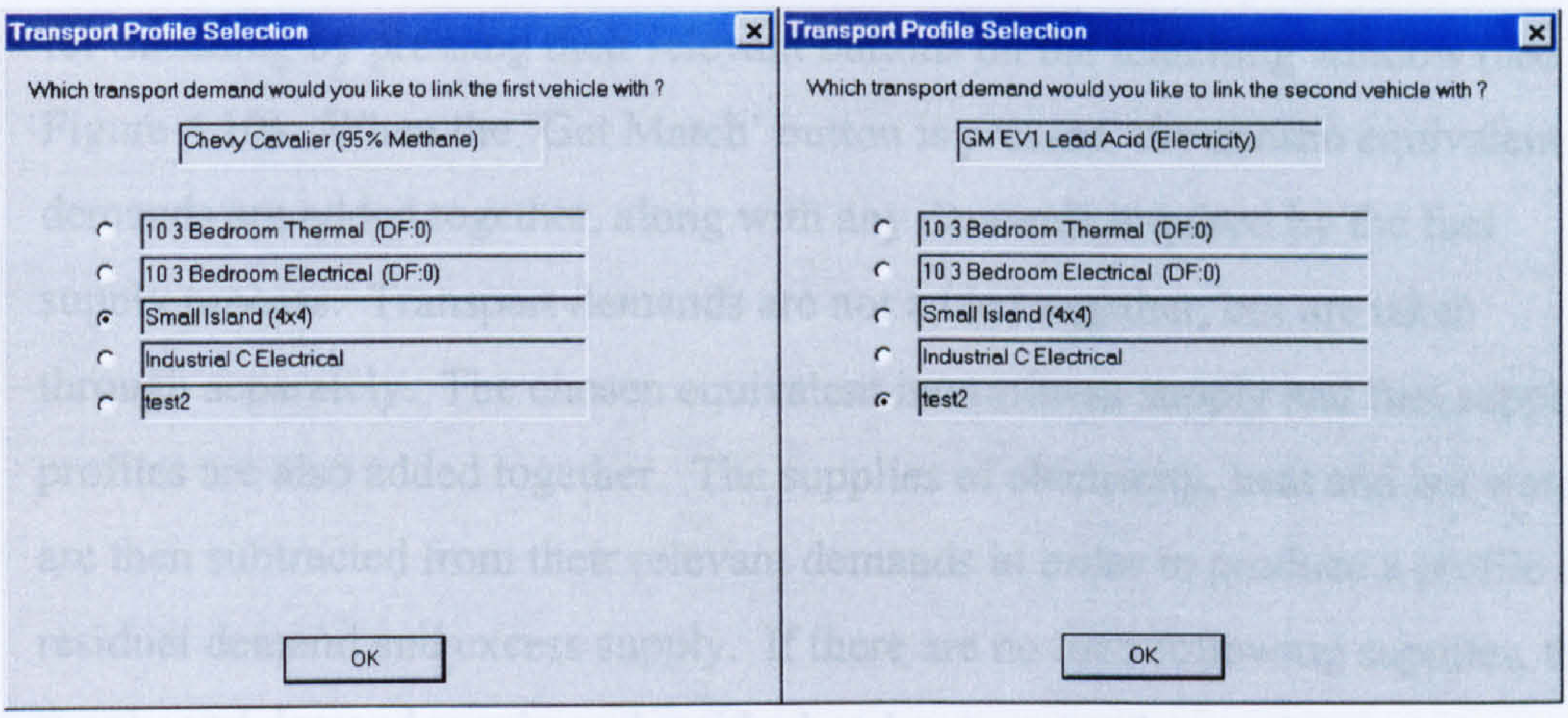
So that the supply, demand and residual graphs can be 'toggled' between quickly, rather than having to repeat the matching analysis each time a different energy demand is considered, all energy demand types are analysed at the same time, making the comparison process faster. This also allows an overall rating for the match to be calculated, along with the individual energy demand ratings, which is an average of the individual ratings, excluding any zero demands, as there will not always be a demand for all four energy use types. The automatic search facility may now also be asked to search for the best specific individual energy demand type match, between demand and intermittent supplies, or for the best energy type match considering all energy demands (excluding zero profiles).

The 'Get Match' button has been introduced for speed, to stop a new analysis being carried out each time a demand, intermittent supply, or load following supply button is selected. When all desired demands, supplies and load following supplies have been chosen, this button is pressed to start the matching process.

4.3.4 Transport Demands

Considerable thought has been given with regards to the siting of transportation demand and vehicle use within this procedure. Splitting the transportation demand and vehicle choice as described here allows various benefits, including the ability to use hydrogen generated from excess electricity, to see onboard fuel storage characteristics, to apply specific refuelling regimes (e.g. overnight recharging), and to place vehicles in their desired place in the fuel use priority order. If the vehicle selection was, alternatively, performed at the demand definition stage, vehicles would always get priority over other fuel using technologies. Also, the transport demand would come through as a demand for fuel, and the fuel availability would not be known, so the user would not know when the transport demand could not be met without adding unnecessary complexity to the procedure and outputs.

However, when more than one transport demand has been defined, as specific vehicle types may be required for specific transport demands (e.g. agricultural vehicles, buses), it is necessary to link these demands with their specific vehicle type during the matching procedure. Windows are, therefore, opened during matching to allow the user to link each vehicle with its specific demand, as shown in Figure 4.14. If this were not done, the first vehicle chosen would try to satisfy all of the chosen transport demands.



Transport Profile Selection

Which transport demand would you like to link the first vehicle with ?

Chevy Cavalier (95% Methane)

- ○ 10 3 Bedroom Thermal (DF:0)
- ○ 10 3 Bedroom Electrical (DF:0)
- ● Small Island (4x4)
- ○ Industrial C Electrical
- ○ test2

Transport Profile Selection

Which transport demand would you like to link the second vehicle with ?

GM EV1 Lead Acid (Electricity)

- ○ 10 3 Bedroom Thermal (DF:0)
- ○ 10 3 Bedroom Electrical (DF:0)
- ○ Small Island (4x4)
- ○ Industrial C Electrical
- ● test2

Figure 4.14 Linking Transport Demands

4.3.5 *The Overall Matching Procedure*

Once all desired demands, fuel supplies, intermittent supplies, and load following supplies have been chosen using the procedures outlined in Sections 4.1 and 4.2, various combinations of these may be tried via the matching window shown in Figure 4.10. There are two streams that need to be considered here – the energy supplies and demands, and the fuel availability. For each chosen demand set there are four demand profiles, for the fuel supply sets there are three demand profiles and thirteen fuel profiles, and for the intermittent supply sets there are three supply profiles. As the output and fuel use of the load following supplies depend on the residual demand and supply, these are not calculated until matching.

Before going forward for use in the matching procedure, the fuel availability profiles are chosen using the window shown in Figure 4.8, and are changed from being an amount of fuel available in kW, litres/h or kg/h, to an amount available for each timestep interval (kWh, litres or kg, per timestep interval). This is done by dividing the fuel produced per hour figure by the number of timesteps per hour (equal to 2 when looking at half-hourly intervals).

The flow chart in Figure 4.15 represents the matching procedure. A number of different demands, intermittent supplies and load following supplies are chosen for matching by pressing their relevant buttons on the matching window (see Figure 4.10). When the 'Get Match' button is pressed, the chosen equivalent demands are added together, along with any demands required by the fuel supply process. Transport demands are not added together, but are taken through separately. The chosen equivalent intermittent supply and fuel supply profiles are also added together. The supplies of electricity, heat and hot water are then subtracted from their relevant demands in order to produce a profile of residual demand and excess supply. If there are no load following supplies, the supply and demand graphs and residual and excess graphs are drawn.

If load following supplies have been chosen, if more than one transport demand has been chosen, the windows shown in Figure 4.14 appear to allow the user to link each demand with the relevant vehicle. Each chosen load following supply is then considered in the order in which it was chosen, and the output of each of these technologies is predicted by applying the residual demands, excess supplies, fuel availabilities, and defined plant parameters to the appropriate algorithm (as described in Chapter 5). Only the appropriate transport demand is considered for each vehicle as necessary. Each algorithm returns amended residual demand, excess supply, and fuel availability information for use in the next supply, and this process is repeated for each chosen load following supply in order. Each time fuel is used, it is subtracted from the amount of fuel available at that particular timestep. If there is not enough fuel available, the demand that can be satisfied with the available fuel is calculated by the supply algorithm and the user is alerted that there is not enough fuel to run the plant at the desired capacity. If there is some fuel remaining after all supplies have been considered, this amount is added to the production value for the next half-hourly time step. This is now stored and available for use at this next timestep. In this manner, a required storage profile is built up for each fuel being considered. Once all supplies have been considered, this procedure is repeated for each subsequent timestep.

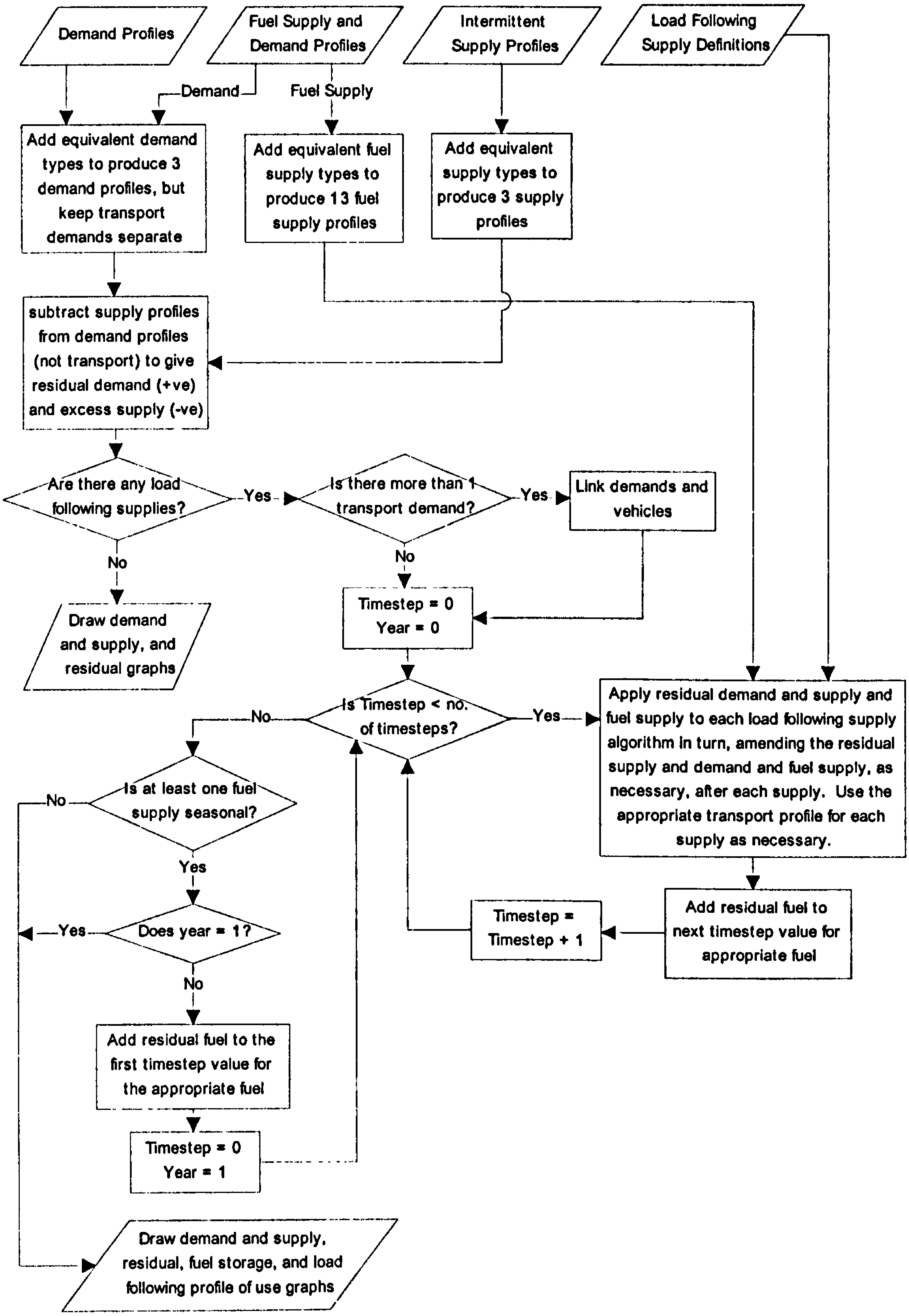


Figure 4.15 The Matching Procedure

When all timesteps have been considered, if one or more of the fuel supplies is seasonal, any remaining fuel is added to the fuel availability for the first timestep, the process is repeated, and the second year's results are used for the graphs. The supply and demand graphs, residual and excess graphs, fuel storage graphs, and load following supply profile of use graphs are then drawn.

4.3.6 Outputs of the Matching Process

Through the matching process the user is able to assess a number of important criteria, in order to allow the comparison of different supply scenarios.

- Graphs are available to show the residual demand and supply, so that decisions can be taken about any demand and supply changes that may be made, and what type of load following or storage technologies might be appropriate.

- A statistical analysis is made to show how well profiles match [1], and the user is able to analyse each energy carrier individually, or get an overall rating. This overall rating only considers energy carriers for which there is either a demand or supply, as there will not always be a need for all four of the demand types.

- A graph showing the profile of use of the load following supplies (e.g. percentage load of the engine over time, state of charge of the battery, vehicle tank contents) is given in order to ensure that the equipment is not being used in a way which would be damaging to it, and that the rated capacity or other parameters chosen are appropriate for this particular application. Other useful information is also given about the performance of these supplies in the box above the graph.

- The overall fuel use for each fuel type (and estimated annual fuel use if seasonal representative periods are being analysed) is calculated, and users are alerted if there is not enough fuel to run any of the fuel using supplies at the desired capacity at any time.

- A graph of the final storage profile for each fuel is displayed in order to allow decisions to be made about the required size of fuel tanks, and the suitability of the fuel type and production rate.

As there are a large number of different graphs, to save confusion, there is a means of 'toggling' between the appropriate graphs for the four different energy carriers, the thirteen different fuel storage graphs, and the profile of use graphs for supplies that follow demand and/or require fuel.

This chapter has described the requirements for and the general layout of a demand and supply matching program which allows the total energy needs for an area to be analysed. The specific algorithms employed to determine the outputs, with the available inputs, for the various load following supplies mentioned in this chapter are described in detail in Chapter 5. The algorithms used to determine the derived fuel supply and related energy use profiles are described in detail in Chapter 6.

4.4 References

[1] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001, www.esru.strath.ac.uk

5 Load Following Supply Algorithms

This chapter presents the algorithms used to describe the behaviour of a variety of load following supplies. In each case, the residual demands, supplies and fuel availabilities are sent to each model at the matching stage, in the order in which they were chosen, for each consecutive half-hourly timestep, and this information is amended appropriately and returned. Each technology also gives a relevant output graph, showing plant use or storage characteristics, and information about overall fuel consumption or energy taken in and given out, as appropriate.

These models have been designed to be generic to a particular plant type group (e.g. gas turbines or fuel cells), and require only readily available manufacturers' data in order to predict performance. The main issues that affect the performance of a particular type group are considered, and the performance analysis is based on these. This allows a wide variety of sizes and types of plant to be considered without having to run extensive tests to find specific data for each single engine, turbine or fuel cell, which would be time-consuming, much of the required information may be proprietary, and would quickly be out of date. This level of performance modelling is appropriate for the initial suitability assessment through demand and supply matching that is being considered here.

5.1 Vehicle Performance Algorithm

The input to this part of the procedure, at the demand and supply matching stage, is a transport demand profile (km/h versus time) and the appropriate fuel availability profile. From these, the ability to meet the transport demand, and half hourly fuel use, must be derived. To do this, the specific fuel consumption of the chosen vehicle, the amount of fuel that can be stored on board, and the refuelling requirements are defined when choosing the load following supplies, and examples of the vehicle definition windows for the different fuel types can be seen in Appendix 1 (Figures A1.40 to A1.44). This information is then used at the matching stage, along with the fuel availability, to determine what demand may be met, to determine the necessary refuelling times and amounts, and to reduce the available fuel accordingly. The procedure for this is described in this section.

5.1.1 Fuel consumption

A number of factors affect the fuel consumption of a vehicle, including personal driving style, driving speeds, and the number of stops and starts. To allow comparison, international standard test conditions have been set to determine fuel consumption figures for different vehicles for three typical types of driving condition - urban, extra-urban and combined driving [1], and these typical figures are used in this program in order to calculate vehicle fuel use. The fuel consumption units used by the program depend on the fuel type, as discussed below, but all are quoted as an amount of fuel per 100km. As the transport demand is in km/h, all consumption figures are converted to the amount of fuel required per km by dividing by 100, to allow the actual fuel requirement to be calculated in the correct units (kWh for gases and electricity, and litres for liquid fuels). This calculated specific fuel consumption (kWh/km or litres/km) is then input into the algorithm defined later.

Biogas vehicle fuel consumption is quoted in petrol equivalent litres per 100km, with one petrol equivalent litre being the quantity of biogas that has the same energy content as one litre of petrol. This is because there are various different storage mediums being used in vehicles, so the use of a measure of the energy content saves confusion and provides a standard. By quoting in petrol equivalent litres rather than kWh, it allows comparisons to be made with petrol driven engines, as this is generally better understood. As the transport demand is in km/h and the biogas fuel use is in kWh, this consumption figure is converted to kWh/km using Equation 5.1.

$$FU = \frac{8.827 \times FC}{100} \tag{5.1}$$

Where FU = Fuel Use (kWh/km)
FC = Fuel Consumption (petrol litres equivalent/100km)
1 petrol equivalent litre = 8.827 kWh

The fuel consumption for alcohol (ethanol and methanol) fuelled vehicles (both flexible fuelled internal combustion engine and fuel cell vehicles) is quoted in litres/100km for 100% petrol, and for a blend called E85 (or M85), which is 85% ethanol (or methanol) and 15% petrol. However, figures for E100 or M100 (100% ethanol or methanol) and E50 or M50 (50% ethanol or methanol and 50% petrol) are also sometimes quoted. As the fuel consumption varies with the percentage of alcohol in the mixture, the percentage blend at which the fuel consumption is being quoted is required along with the fuel consumption figure. If this is less than 100% alcohol, the program allows the fuel to be employed at that blend, or the fuel consumption may be approximated for 100% alcohol. If approximating for 100% alcohol, the fuel consumption at 100% petrol must also be given, and this is generally quoted with the blended fuel consumption. As the fuel consumption figure varies linearly between 100% petrol and 100% alcohol, the fuel consumption at 100% alcohol is calculated by direct proportion using Equation 5.2.

$$A100 = \frac{(AFC - PFC) \times 100}{\text{Percentage}} + PFC \qquad (5.2)$$

Where Percentage = Quoted percentage of blended alcohol
AFC = Fuel consumption at quoted percentage of blended alcohol (litres/100km)
PFC = Fuel consumption at 100% petrol (litres/100km)
A100 = Fuel consumption at 100% alcohol (litres/100km)

To give the fuel consumption figure in litres/km, this figure, or the chosen fuel consumption figure if not approximating for 100% alcohol, is divided by 100.

Biodiesel consumption is quoted in litres/100km, and the fuel consumption figures for vehicles running on diesel can be used directly for biodiesel-fuelled vehicles if they are increased by 10% [2]. To give the fuel consumption figure in litres/km, this figure is divided by 100.

The use of fuel cell vehicles is less established than the other types of vehicle being considered here, so there is a limited amount of information available from manufacturers. The fuel consumption for these vehicles is input in kWh/100km, using a measure of the energy content to eliminate the problems associated with the different storage mediums. This fuel consumption unit has been chosen, as this is easy to convert to from the various ways in which fuel consumption is being quoted for this type of vehicle. To give the fuel consumption figure in kWh/km, this figure is divided by 100.

Fuel consumption figures for electric vehicles are quoted in kWh/100km, which is divided by 100 to give the fuel consumption in kWh/km. The overall amount of energy available from a battery depends on its rate of discharge [3], however, when considering vehicles, no information is given about the effects of rate of discharge on the delivered energy. As the vehicle 'fuel consumption', or more correctly for a battery, discharge rate, is quoted for typical use, and there are a limited range of discharge rates at which the vehicle would require to draw energy, the quoted discharge rate (kWh/100km) is used, and not varied with the energy drawn. This is the same simplification as using average fuel consumption rates for the other types of vehicle, as the fuel consumption of these vehicles would vary with the speed and type of driving. Also, as general transport demands are being modelled over half hourly time periods, and the use of onboard storage is being taken into consideration, these are reasonable assumptions.

Batteries also suffer from self-discharge if left unused for months. As these vehicles would generally be in almost constant use, and as information about self-discharge rates for vehicles are not easily available, this has not been taken into consideration here. Therefore, the energy use (discharging) of electric vehicles is treated in a similar way to the other types of vehicle being considered here. Recharging, however, must be treated slightly differently, and this is discussed later.

5.1.2 Storage and Refuelling Options

As vehicles have onboard storage, it is unrealistic to model them as continuous users of fuel. Instead they require refuelling when their tank is running low, or at certain times each day, depending on the users requirements. Therefore, the initial fuel level as a percentage of the tank capacity must be known, and a refuelling method must be defined. Options for refuelling given in the program are, refilling to maximum when the level falls below a given minimum percentage, or choosing to refuel at the same time or times each day. If continuous use is to be analysed, the options to always keep at maximum or an input minimum, where possible, are also available. These options are available for all types of vehicle, except electric vehicles, whose recharging is a separate case with specific considerations, which is described later.

The amount of storage available on the vehicle is also an important factor when considering fuel use and refuelling profiles. This is not often quoted as a storage amount, and where these figures are available, they are again subject to confusion due to the different storage methods for gases. However, a parameter that is widely available, which is directly related to the storage capacity of the vehicle, is the driving range between refuelling. If the range and fuel consumption of a vehicle, and the number of vehicles, are known, the total available onboard storage capacity can easily be calculated using Equation 5.3. This parameter is required for the vehicle use algorithm described later. Where more than one vehicle is being used, an even distribution of use across these vehicles is assumed.

$$\text{Total Storage} = \frac{(\text{Number} \times \text{Range} \times \text{FC})}{100} \qquad (5.3)$$

Where Total Storage = Total storage (litres, litres(eq), or kWh)

FC = Fuel consumption (litres/100km, litres(eq)/100km or kWh/100km)

Range = Range (km)

Number = Number of vehicles

If biogas is being considered, the total storage in petrol equivalent litres must be changed to kWh by multiplying it by 8.827 as in Equation 5.1.

If ethanol or methanol is being used, and it is wished to approximate for 100% of the fuel, the range for 100% petrol must be given, and the range to be used in Equation 5.3 must be calculated using Equation 5.4

$$\text{Range (A100)} = \frac{(\text{AR} - \text{PR}) \times 100}{\text{Percentage}} + \text{PR} \qquad (5.4)$$

Where Percentage = Quoted percentage of blended alcohol
AR = Range at quoted percentage of blended alcohol (km)
PR = Range at 100% petrol (km)
Range (A100) = Range at 100% alcohol (km)

A filling station can also be modelled rather than a fleet of individual cars. If this is the case, the storage capacity for the filling station tanks is given in the storage units for that particular fuel (litres, litres(eq) or kWh). Again, if biogas is being used as the fuel, the input value must be multiplied by 8.827 to convert from litres(eq) to kWh. The average fuel consumption of the vehicles using the filling station is given, and the options for refuelling the tanks of the filling station are the same as for the individual vehicles, as this covers the main range of possible refuelling schedules. As electric vehicles would be recharged directly from the grid or local electricity supply, the filling station option is not appropriate.

5.1.3 Vehicle Use Algorithm

At the matching stage it is necessary, for each timestep, to calculate the required fuel use, subtract this from the onboard storage tank, and refill the tank when necessary and possible from the available fuel. In order to do this, the specific fuel consumption for the vehicle is calculated as described in Section 5.1.1, the available storage is calculated as described in Section 5.1.2, and the instantaneous transport demand for each half hourly time step is read in to the algorithm outlined in Figure 5.1. This then determines how much of that demand can be met, and the new onboard tank level, and subtracts any fuel necessary to refill the onboard tanks from the fuel available. If the transport demand cannot be met due to a lack of fuel, the user is warned, and the amount of demand that can be met with the available fuel is calculated. The total fuel used is also calculated for information.

Before starting this algorithm, various parameters are calculated, depending on which refuelling option has been chosen. These can be seen in Equations 5.5 to 5.10.

$$\textbf{refill} \text{ (to max if goes below)} = \frac{\text{Total Storage x Refill Percentage}}{100} \quad (5.5)$$

$$\textbf{min} \text{ (always keep at if possible)} = \frac{\text{Total Storage x Min Percentage}}{100} \quad (5.6)$$

$$\textbf{tank} \text{ (initial fuel level)} = \frac{\text{Total Storage x Initial Percentage}}{100} \quad (5.7)$$

$$\textbf{timesteps per day} = \text{24 x timesteps per hour} \quad (5.8)$$

$$\textbf{start time 1} = \text{Time 1 selected x timesteps per hour} \quad (5.9)$$

$$\textbf{start time 2} = \text{Time 2 selected x timesteps per hour} \quad (5.10)$$

Total Fuel Used = 0

Then, for each timestep value, the following are defined,

fuel supply = available secondary fuel from matching stage at timestep value

i = this timestep value

The number of timesteps per hour will be 2 when considering half-hourly profiles.

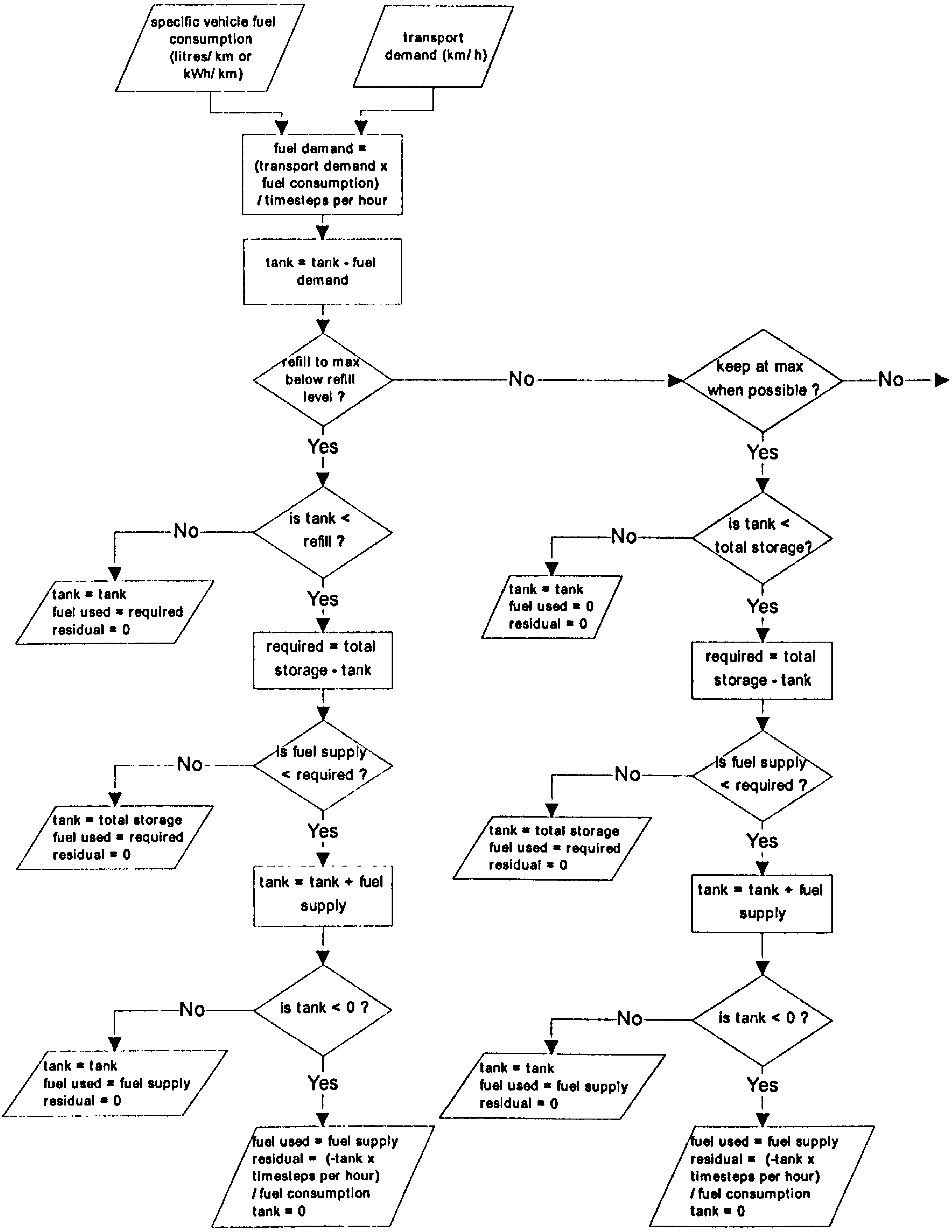


Figure 5.1 Vehicle Use Algorithm

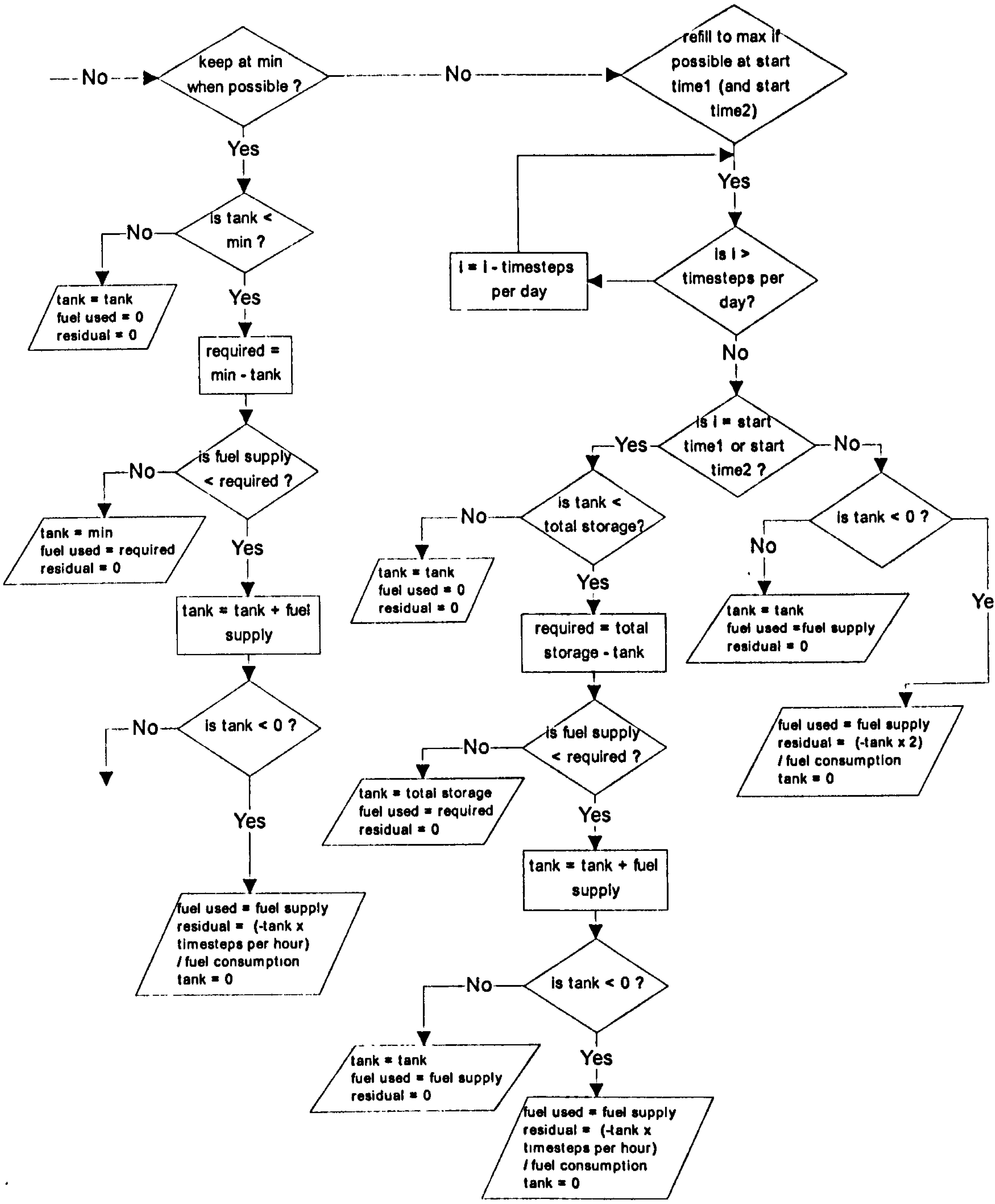


Figure 5.1(cont) Vehicle Use Algorithm

After the algorithm has been followed, the outputs for each time step value that are sent back to the matching stage are,

Residual Demand (km/h) = **residual**

Percentage Tank Contents = **(tank x 100) / Total Storage**

Fuel Used (litres or kWh) = **fuel used**

Total Fuel Used (litres or kWh) = **Total Fuel Used + fuel used**

At the matching stage, it is not useful to display a graph of the vehicle profile of use, as this would be exactly as defined by the user at the demand definition stage. A more useful output of this section to the matching process is a graph of the percentage tank contents, which shows if the chosen number and type of vehicles, and the refuelling policy chosen are appropriate. Overall fuel consumption information is also given.

5.1.4 Electric Vehicle Charge Algorithm

Due to the limitations of the amount and types of information that are readily available for electric vehicle batteries, existing battery models [4] cannot be used for the recharging of electric vehicles. A different model has, therefore, been devised which allows the recharging power requirements of the vehicles to be calculated using available data.

There are two ways to determine the storage capacity of an electric vehicle. Firstly, the total capacity can be found using,

$$TS = SC \times RV \times NV \qquad (5.11)$$

Where TS = Total Storage (Wh)
SC = Storage Capacity (Ah)
RV = Rated Voltage (V)

NV = Number of Vehicles

However, information about minimum discharge levels is not generally quoted for electric vehicles, so it is not easy to tell how much of this is actually available to the driver. The second method is the same as that described earlier for the other types of fuel, where,

$$AS = \frac{FC \times R \times NV}{100} \tag{5.12}$$

Where AS = Available Storage (kWh)
FC = Fuel Consumption (kWh/100km)
R = Range (km)
NV = Number of Vehicles

This is a more useful method of calculating the storage capacity of an electric vehicle as it eliminates the problems of minimum discharge level, which can be misleading, and calculates the total capacity actually available. In this case, the output graph at the matching stage shows the percentage of available battery capacity.

The recharging of a battery generally takes place in three stages, two of which can be seen in Figure 5.2 [3]: -

- **Bulk Charge** - the battery is charged using a constant current until it reaches around 70 or 80% charge. This is the maximum safe charging current that does not cause overheating in the cables.

- **Absorption Charge** - as the battery gets close to full charge, the internal resistance increases. To avoid damage and overheating, the charging voltage remains constant, while the current decreases exponentially.

- **Float Charge** – once the battery reaches full charge, the charging voltage is reduced to prevent damage to the battery from overcharging when the recharger has not been switched off.

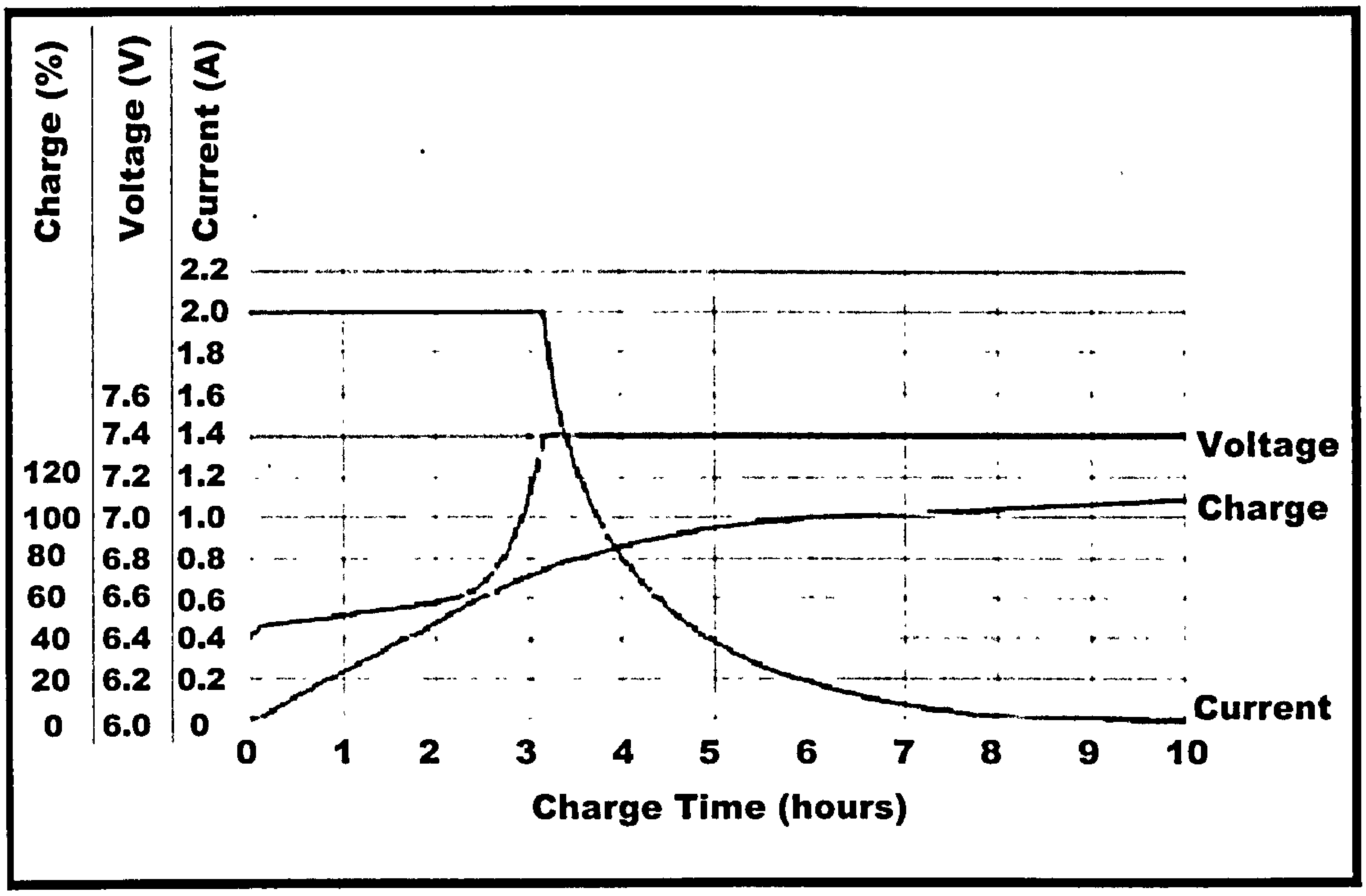


Figure 5.2 Battery Charging Characteristics [3]

In the first stage, bulk charging, the battery charge increases linearly with time, due to the constant charging current, to a specified bulk percentage charge (C_B). In the second stage the charging current tapers exponentially with time, which means that the percentage charge at a time (t) can be defined by Equation 5.13.

$$\text{current\%} = \text{bulk\%} + (\text{max\%} - \text{bulk\%})(1 - e^{-t/\tau}) \qquad (5.13)$$

Where current% = percentage charge at time t

max% = maximum percentage bulk charge

bulk% = maximum percentage charge

t = current time – bulk charge time

τ = 1/5 time for absorption charge (maximum safe rate to avoid overheating)

In general, the bulk charge phase for an electric vehicle takes half of the recharging time, recharging the battery to around 70%, and the absorption charge phase uses the second half of the recharge time [5]. The float charge phase is not considered here as this is designed mainly to limit battery damage due to overcharging, which this model will not allow.

The initial state of charge of the vehicle battery is defined with the vehicle characteristics, along with the time to start the slow recharge, and whether or not to allow fast recharges (although the number of fast recharges a vehicle undergoes should be limited as this affects the battery life). The time taken for a full slow recharge, the maximum bulk charge percentage, and the percentage of the charge time this takes, also need to be input in order to define the recharge curve. This allows the algorithm shown in Figure 5.3, for charging and discharging the electric vehicles, to be used at the matching stage. Discharging is similar to the other vehicles, except that no recharging takes place if the level falls below 0, unless fast recharging has been allowed. The efficiency of the battery must also be taken into consideration, as more energy is required to recharge the battery than will be available from the battery after recharging. This efficiency is generally around 85%, and is taken into account when recharging the battery, by increasing the amount necessary for recharging.

This procedure is slightly different than for the other vehicles as, although the demand is still in storage units (kWh), the supply profile is a supply rate (kW) rather than an available amount. This must, therefore, be taken into consideration throughout the procedure. Firstly, the maximum storage capacity (maxkWh) must be calculated using Equation 5.12, and this should then be used in Equation 5.7 to calculate the initial fuel level (tank). Timesteps per day, start time1, and start time2, should be calculated as before. Then, for each timestep, the residual electricity supply should be read in as the fuel supply, and i is equal to the current timestep value.

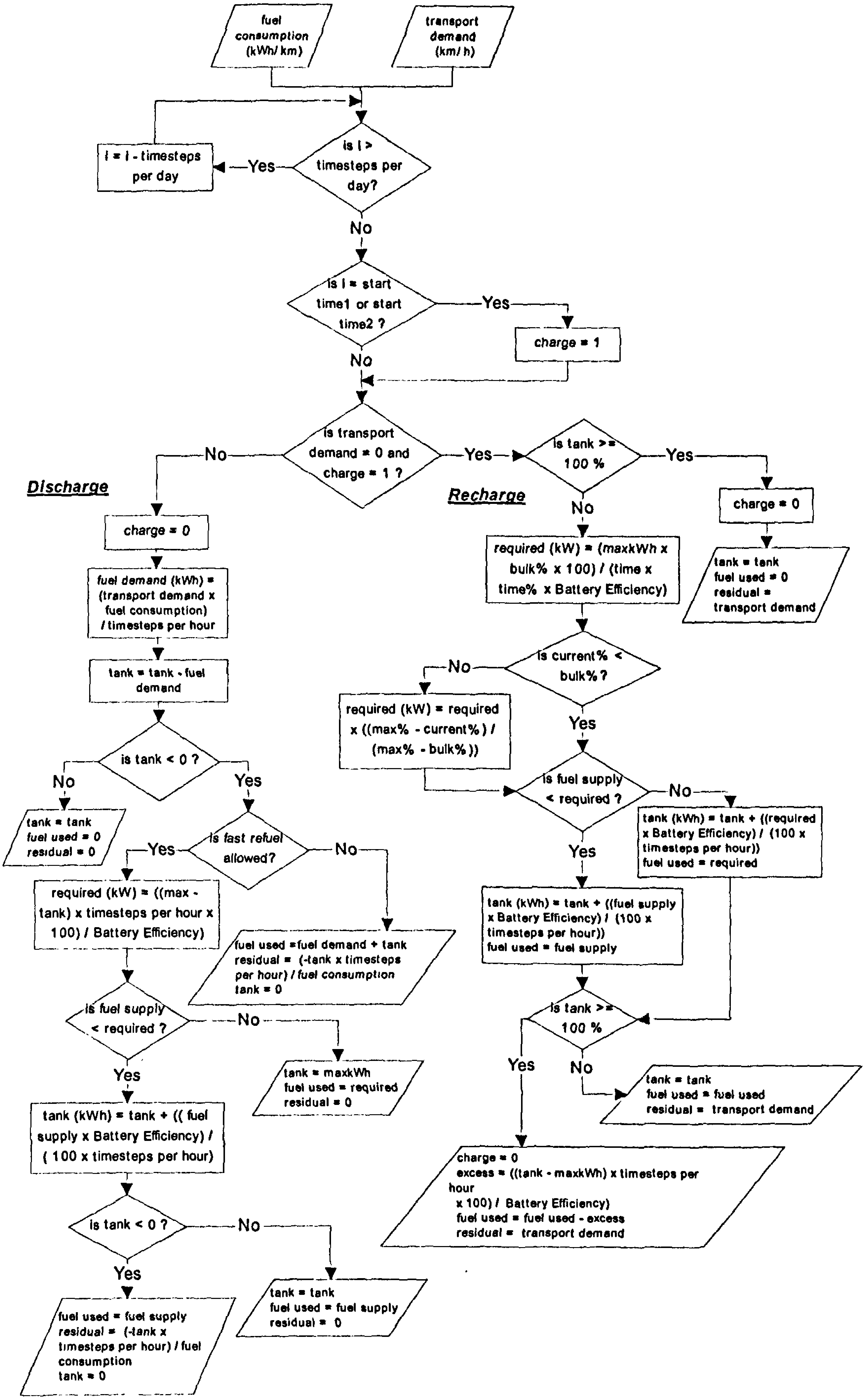


Figure 5.3 Electric Vehicle Fuel Use Algorithm

The i value is checked to see if it corresponds with either of the recharge start times. If not, the vehicle battery is discharged in a similar manner to the other vehicles. If the battery charge goes below zero, and fast recharging is not allowed, the transport demand that can be met with the available charge is calculated and the available battery charge is set to zero. If fast refueling is allowed, the electricity required to fully recharge the battery is calculated in kW rather than kWh, using Equation 5.14. This gives the electricity supply rate required to fully recharge the battery over the available timestep interval in kW, which can be directly compared to the available supply.

$$\text{required (kW)} = (\text{maxkWh} - \text{tank}) \times \text{timesteps per hour} \tag{5.14}$$

Likewise, when this electricity supply is used to add charge to the battery, the electricity supply in kW must be divided by the timesteps per hour to find the storage value (kWh) that can be added to the tank in that timestep interval, as shown in Equation 5.15.

$$\text{tank (kWh)} = \text{tank} + (\text{fuel supply} / \text{timesteps per hour}) \tag{5.15}$$

In reality, the recharge would probably take less time than the full timestep interval, but in dealing with, mainly, half-hourly timesteps, there is a necessary averaging out of all supply data [4]. To avoid this, a greater number of timesteps per hour may be chosen, but this only makes sense if other electricity supply profiles and climate data are also available at that frequency.

If the slow recharge is to start, or continue as the level has not reached 100% and there is no demand, the percentage charge of the battery must be checked. If this is below the bulk percentage level, the percentage charge increases at a constant rate, and this does not vary with the percentage charge in the battery. Therefore, the required energy supply rate is constant, and calculated using Equation 5.16.

$$\text{required (kW)} = \frac{\text{maxkWh x bulk\%}}{\text{time x time\%}} \tag{5.16}$$

Where maxkWh = maximum storage capacity (kWh)

bulk% = maximum percentage from bulk phase

time = recharge time

time% = percentage of recharge time for bulk phase

If the percentage charge of the battery is above the bulk percentage level, the percentage charge being added to the battery decreases exponentially with time, as defined by Equation 5.17.

$$\text{Percentage Charge Added} = (1 - e^{-t/\tau}) \tag{5.17}$$

In order for this to happen, the power drawn by the recharge unit (the recharge rate (kW required)) will decrease exponentially with time, as defined by Equation 5.18.

$$\text{Power Drawn by Recharge Unit} = (e^{-t/\tau}) \tag{5.18}$$

As the vehicle may come to be recharged with varying percentage charges, and there may not always be enough excess electricity to fully supply the recharging demand, the time in these equations will not be known to ascertain the power required. Therefore, the shape of the recharge rate profile (kW required) with percentage charge must be found. From Equations 5.17 and 5.18, it can be seen that this profile can be defined by,

$$x = 1-y \tag{5.19}$$

This is shown graphically in Figure 5.4.

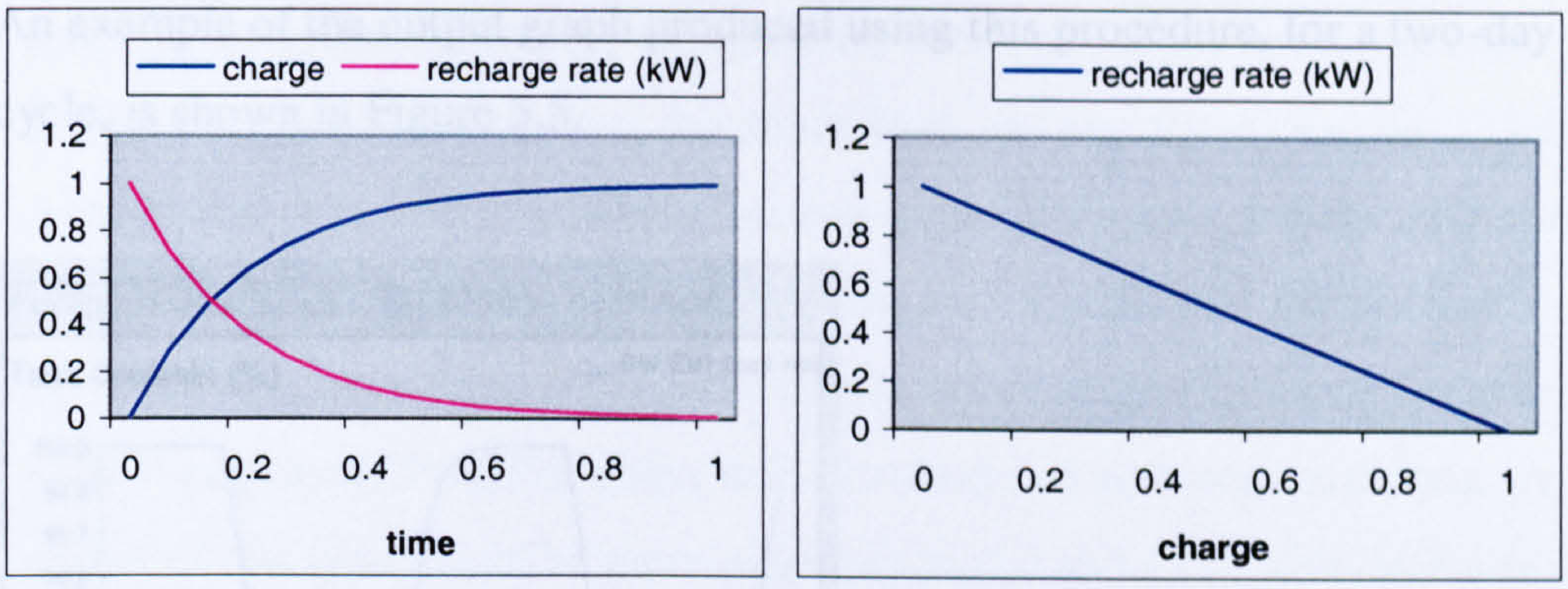


Figure 5.4 Relationship Between Percentage Charge and Recharge Rate

Therefore, if the charge percentage in the battery is greater than the bulk percentage charge, the required power needed for recharging at that percentage charge is given by Equation 5.20.

$$\text{required power (kW)} = \text{required} \times \frac{(\text{max\%} - \text{current\%})}{(\text{max\%} - \text{bulk\%})} \qquad (5.20)$$

Where required = maximum required power (Equation 5.16)
current% = percentage charge at this timestep
max% = maximum overall percentage
bulk% = maximum percentage from bulk phase

If available, this is then added to the battery, compensating for the storage and production rate profiles as before.

After the procedure has been followed, the outputs for each time step value that are sent back to the matching stage are, again,

Residual Demand (km/h) = residual

Percentage Tank Contents = (tank x 100) /maxkWh

Electricity Used (kW) = fuel used

An example of the output graph produced using this procedure, for a two-day cycle, is shown in Figure 5.5.

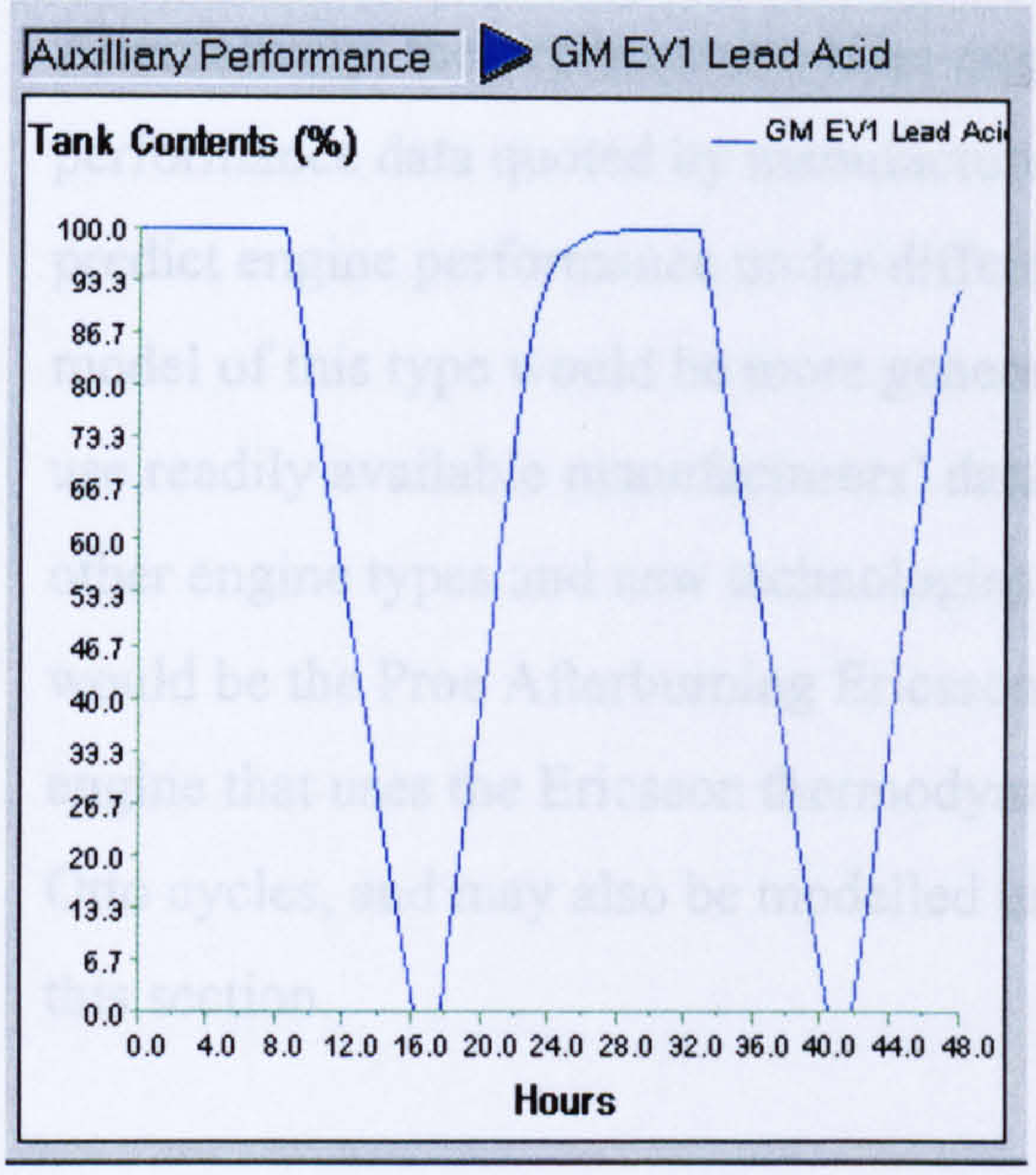


Figure 5.5 Recharge Curve Calculated by the Described Algorithm

5.1.5 Other Vehicle Types

The discussions so far have focussed on land vehicles, but the same processes can be equally applied to aeroplanes and boats providing that fuel consumption and range data are available [6,7]. Diesel trains could also be run on biodiesel, and the processes, again, would be the same. However, electricity demand from electric trains would be more easily modelled at the demand profile selection stage as a direct electricity demand, due to the way in which consumption data is available.

5.2 Internal Combustion and Diesel Engine Modelling

There are two possible ways to approach the performance modelling of internal combustion or diesel engines. Firstly, the combustion process and thermodynamic cycle could be explicitly modelled, in order to predict the performance of different engine designs. This approach, however, would require a large volume of data that would not be easily available (much of which might be proprietary), or may require tests to be carried out on the specific engine being considered. Also, the complexity and variety of designs available would make it difficult to create a generic model for a wide variety of engines. Alternatively, the performance of an engine can be predicted from actual performance data quoted by manufacturers, which is already widely used to predict engine performance under different load and ambient conditions. A model of this type would be more generally useful and applicable, as it would use readily available manufacturers' data, and it could also be easily applied to other engine types and new technologies as they arise. An example of this would be the Proe Afterburning Ericsson Engine [8], which is a multi-fuelled engine that uses the Ericsson thermodynamic cycle rather than the Diesel or Otto cycles, and may also be modelled using the generic approach outlined in this section.

The existing diesel generator model in MERIT has been enhanced to allow consideration of different engine and turbine types, part load performance (of efficiency and heat to electricity ratio), minimum load, the possible use of multiple engine sets to allow more efficient performance (i.e. only one operating at low load times), derating for altitude and ambient temperature, and the possibility of using different types of fuel. The ability to follow heat and/or electricity demand, run at a constant load, or run at specified varying loads at different times of the day and year, has also been added. To allow derating, the altitude of the site is input with the climate data selection.

This section describes the algorithms used to model the behaviour of diesel and internal combustion engines, and the relevant system definition windows are shown in Appendix 1, Figures A1.30 and A1.31. Figure A1.32 shows the window in which different percentage loads can be defined for different times of the day and year. The input to this section from the matching stage, for each timestep, is the appropriate fuel availability, and the residual electricity and heat demands. The output of this section to the matching stage is a graph of percentage engine loading with time. Overall fuel consumption information is also given.

5.2.1 Required Power

Specifically designed engine generator sets are commonly used for electricity generation, where the engine and generator come already coupled, and performance information is given for the overall system (fuel to electricity). If a separate engine and generator are to be used, the engine is run at a fixed rotational speed, which is dictated by the generator coupling. Therefore, the performance information that is quoted for the speed required by the generator should be used, and this rotational speed may be calculated using

$$\text{Engine Speed (rpm)} = \frac{\text{Supply Frequency} \times 60}{\text{Number of Generator Pole Pairs}} \qquad (5.21)$$

where the supply frequency is given in Hz.

As this performance information will only describe the fuel to mechanical work conversion, the percentage generator efficiency must also be known in order to calculate the power output required from the engine to meet the electrical demand.

$$\text{Engine power required} = \frac{\text{Generator Power Required} \times 100}{\text{Generator Efficiency}} \qquad (5.22)$$

If an engine generator set is being modelled, the generator efficiency is set to 100%.

5.2.2 Engine Derating

The maximum rated power that may be drawn from either a diesel engine or ICE is affected by both ambient temperature and altitude [9,10]. The process of calculating this reduced power availability is called derating, and derating factors are given in manufacturers' data. Although figures vary with different engines, typically, the maximum rated power available must be reduced by around 1.5 % for every 5 degrees that ambient temperature is above 40 °C. Also, above 1000 metres above sea level the maximum rated power must be reduced by 4% per 500 metres, and by 6% above 3000 metres. Therefore, if the altitude is above the threshold level, and if the engine is situated in an area where it is affected by ambient temperature, the maximum available power (rated power) must be reduced accordingly. If the engine is situated in an area that is not affected by ambient temperature, the constant average room temperature is used for derating. The algorithm used to determine the rated power used for the rest of the procedure is shown in Figure 5.6.

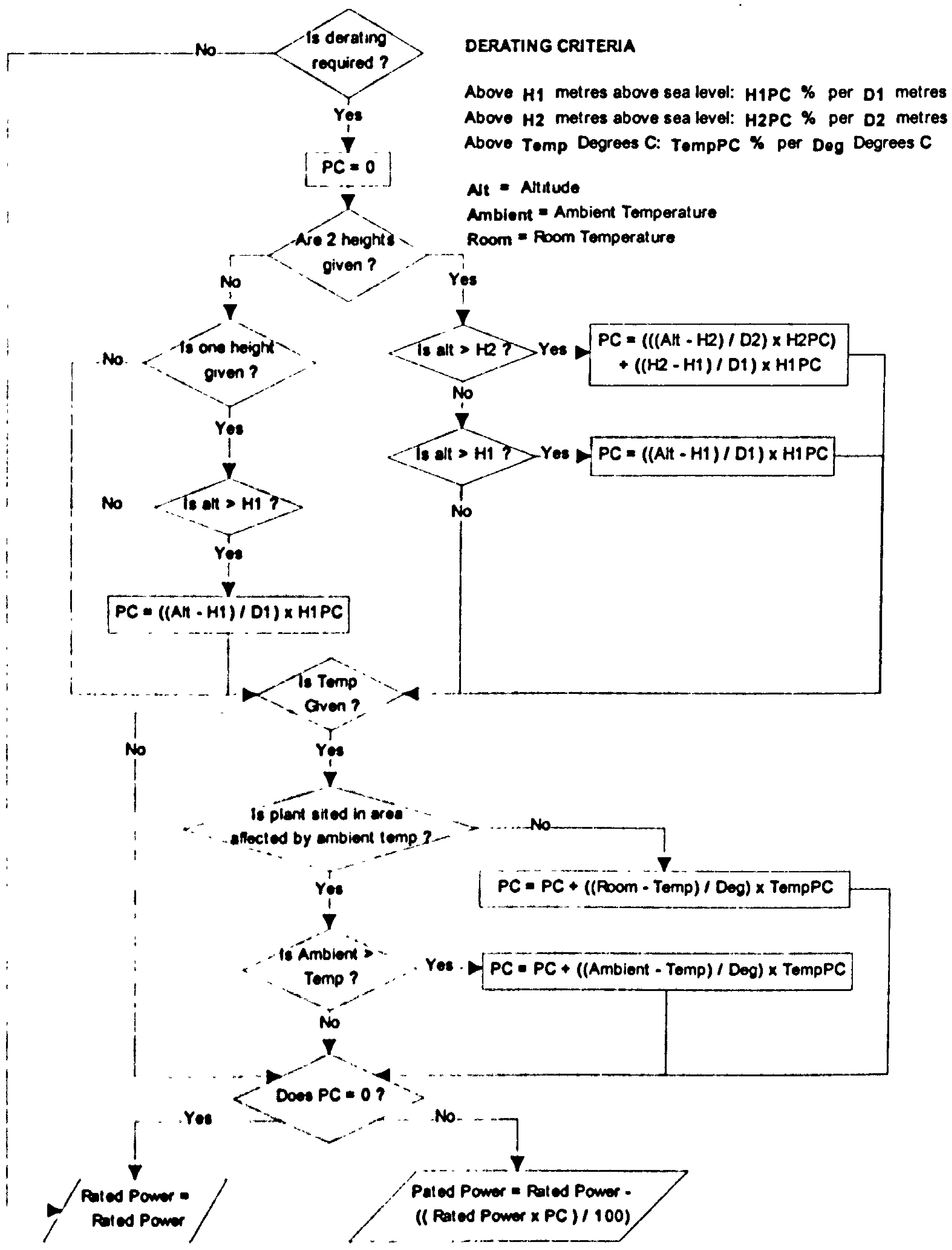


Figure 5.6 Derating Algorithm

5.2.3 Engine Performance in the Context of Varying Load

In order to define the performance of an engine, it is necessary to know the required percentage loading, and its efficiency or fuel consumption at that load. If CHP is to be considered, the ratio of heat to electricity output must also be known. 5.7 shows a representative heat balance curve for a diesel engine, though exact characteristics vary with engine size and configuration. It can be seen that the percentage of fuel energy input which contributes to net work (mechanical work, and hence electricity production) remains fairly constant down to around 70% of full load, but then starts to decrease rapidly, showing that the efficiency of electricity production decreases with percentage load (i.e. more fuel is required per kWh of electricity produced at lower percentage loadings). At the same time, the amount of heat lost to the jacket coolant water and exhaust gases, from which heat recovery is possible for CHP generation, increases due to this decreased efficiency.

It can also be seen from Figure 5.7 that, if the percentage fuel energy input values for net work, exhaust and jacket water are summed at different percentage loadings, the overall percentage of fuel energy input which contributes to these three outputs remains fairly constant. Values below 20% loading have not been taken into consideration here as this is typically recommended by manufacturers to be the minimum load value to avoid damage to the engine. This means that the overall efficiency (for electricity and heat) of a typical engine CHP generation system remains fairly constant, while the fuel to electrical efficiency decreases with decreased load. Therefore, more heat is produced at lower loads, keeping the overall percentage of recoverable energy (electricity and heat) fairly constant. Using this assumption, it is possible to estimate the ratio of heat to electricity production at any percentage loading, provided the ratio is known for 100% loading. These figures are typical for both diesel engines and ICEs, with the overall efficiency (heat and electricity) generally being around 90% of the fuel input.

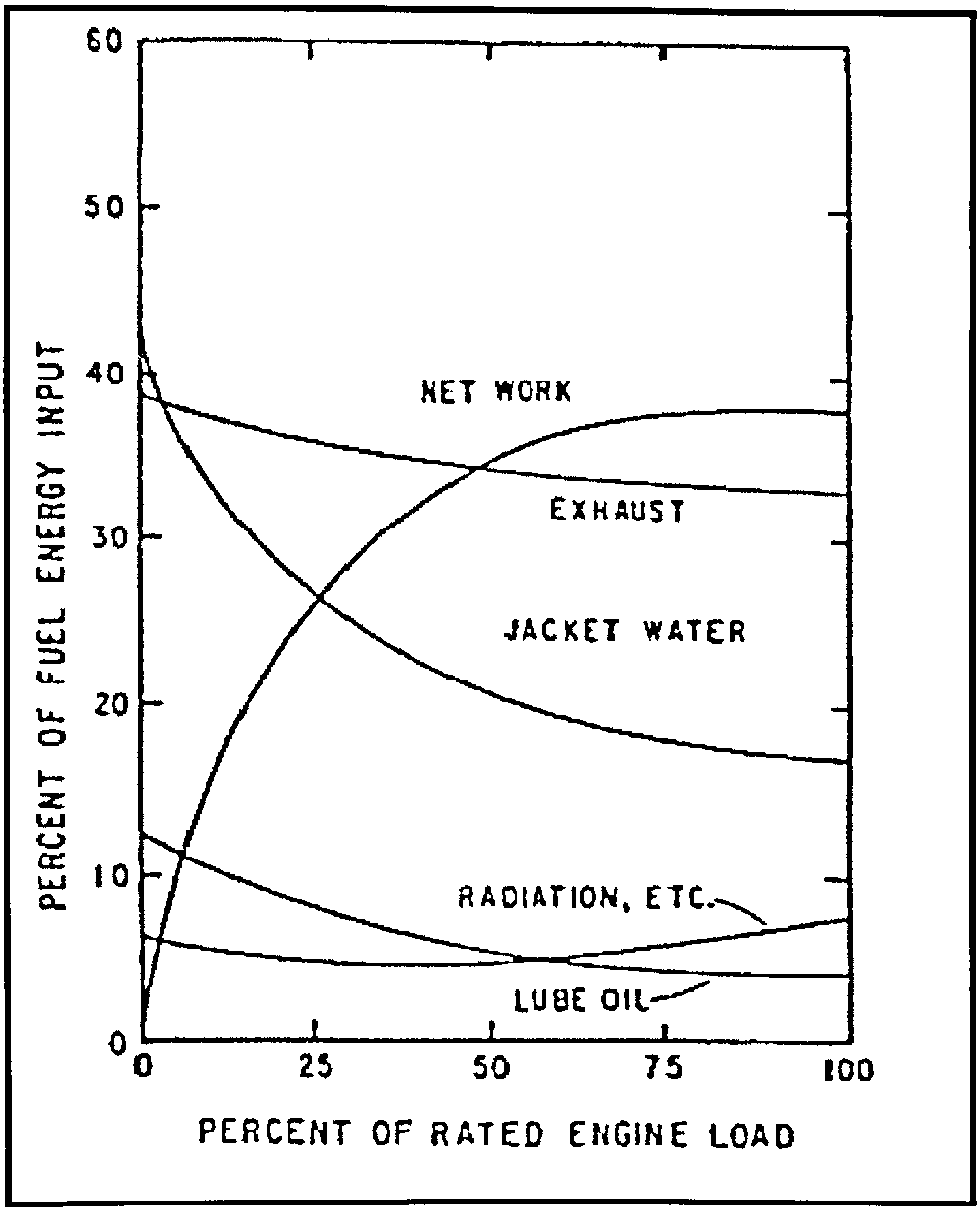


Figure 5.7 Representative Heat Balance Curve for a Diesel Engine [9]

5.2.4 Determination of Required Percentage Load

As the efficiency of electricity production decreases with percentage load, this rate of decrease must be defined. As the shape of this curve varies with different engines, different mathematical descriptions would be required for each different engine, which is not practical. Efficiency information for diesel engines is occasionally quoted in graphical form, showing the fuel consumption versus percentage load. However, for diesel engines and ICEs running on liquid fuel, the specific fuel consumption (g/kWh) is much more commonly quoted as a measure of efficiency, and this is given at specific percentage loadings (generally 25%, 50%, 75% and 100%) [10]. These percentage loadings are also used for gas powered ICEs, but the parameter quoted is usually the efficiency of either electrical or mechanical production, rather than the specific fuel consumption [11]. Therefore, the specific fuel consumption for diesel engines and ICEs running on liquid fuels, and the mechanical efficiency of gas powered ICEs must be given at different percentage loads (which may be specified by the user), and from these figures, the specific fuel consumption or efficiency for any specific load may be interpolated, assuming a linear variation between points.

To determine the percentage load required at any particular timestep, the generation priority must be defined. The user may choose to set the engine to follow the electricity demand, follow the heat demand, follow demands for both electricity and heat, run at a constant percentage load, or run at specific percentage loads at different times of the day or year. With the last two options, it is simply a case of determining the percentage load that should be running at that time of day and year.

If following the electricity demand, the generator power required is equal to the electricity demand, and the power required from the engine is calculated using Equation 5.22. If following the heat demand, the generator power required is equal to the heat demand divided by the heat to electricity ratio at 100% load, and the power required from the engine is, again, calculated using Equation 5.22. If following both the heat and electricity demands, the required generator powers to meet either demand are determined, and whichever value is highest is used in Equation 5.22 to find the required engine power. As the heat to electricity ratio will change at lower percentage loadings, this ratio, the specific fuel consumption or efficiency, and the percentage loading will be recalculated later if the engine is following the heat load. If the engine is following both demands, the choice of which demand to follow will also be reassessed using this recalculated data. If the required engine power is greater than the rated engine power, then the required engine power equals the rated power. If the required engine power is less than the minimum recommended load, the engine is not run. This process is shown in context in Figure 5.8, which uses a flow chart to describe the algorithm used to determine the required percentage load.

The percentage load is then calculated using Equation 5.23,

$$\text{Percentage Load} = \frac{100 \times \text{Required Engine Power (kW)}}{\text{Derated Maximum Power}} \qquad (5.23)$$

The specific fuel consumption or efficiency is calculated by interpolating between the known values for 100%, 75%, 50%, and 25%, as shown in Figure 5.9. If values are known for other percentages, these may also be input and used for interpolation, however, the value for 100% load must be given.

5.2.5 Multiple Engine Generator Sets

In order to work more efficiently, provide a better range of loads that may be supplied, and reduce engine damage, it is common practice to use a number of lower rated engine generating sets rather than one higher rated one. This also means that, if one fails, essential power may still be provided. This possibility has been incorporated into this model, by allowing a maximum of five generating sets, of equal rated power, in the one engine definition. These engine sets share the load between them in a manner that ensures they are working as efficiently as possible. As the engine efficiency has a low rate of decrease at higher loadings and a greater rate of decrease at much lower loadings (see Figure 5.7), the best performance is obtained from the plant by running the lowest possible number of individual engines at equal percentage loadings.

The number of available engine sets is defined, and if the required engine power is less than the maximum derated power, one engine only is required, and its operating parameters are calculated as described previously. All other engines are not used. If the required engine power is between one and two times the maximum derated power, the load is divided equally between the two engines, to allow them to work as efficiently as possible. If this calculated load is below the minimum load, one engine will work at full load, while the other is not used, and there will be some unmet demand. This will only happen, however, if the minimum load is above 50%. This is repeated for between two and three times the maximum derated power, between three and four times, and between four and five times, depending on the number of engine sets specified. If the demand is greater than the possible supply, this excess demand will not be met. As all engines being used will be supplying the same percentage load, the calculation of operating parameters need only be done once. This process is shown in context in Figure 5.8, which uses a flow chart to describe the algorithm used to determine the number of engines that require to be run and the required percentage load for each engine.

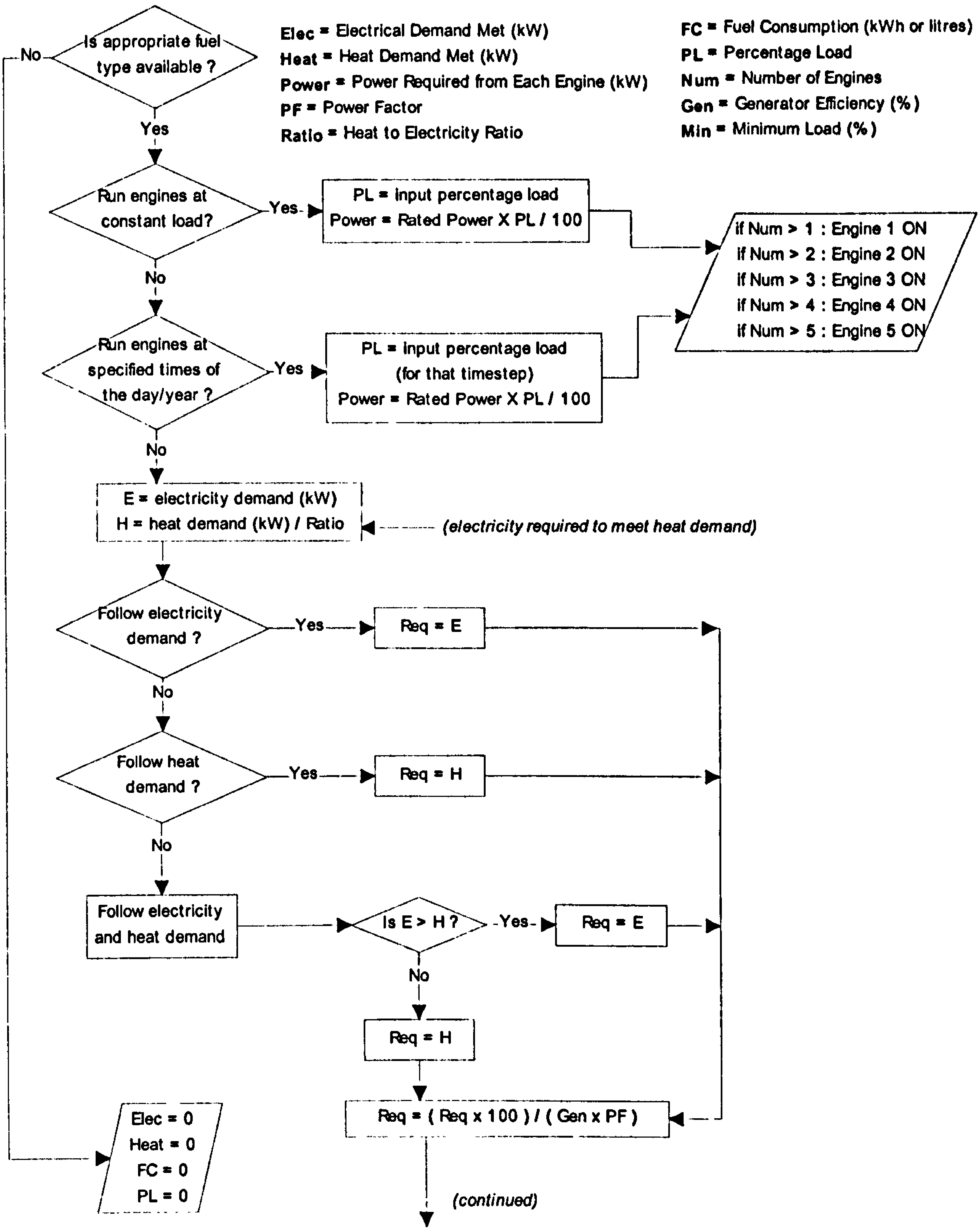


Figure 5.8 Required Percentage Load Determination Algorithm

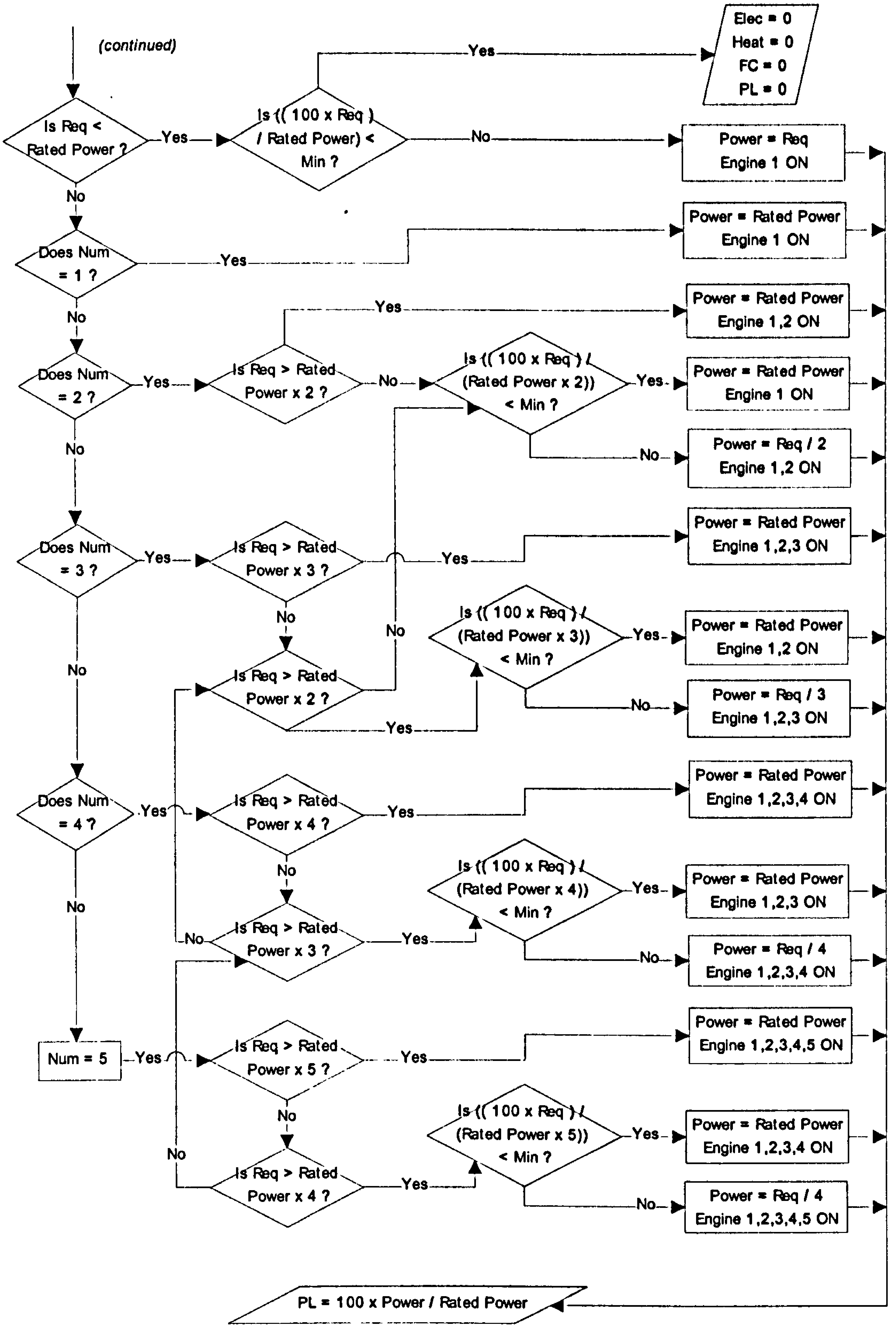


Figure 5.8 (cont) Required Percentage Load Determination Algorithm

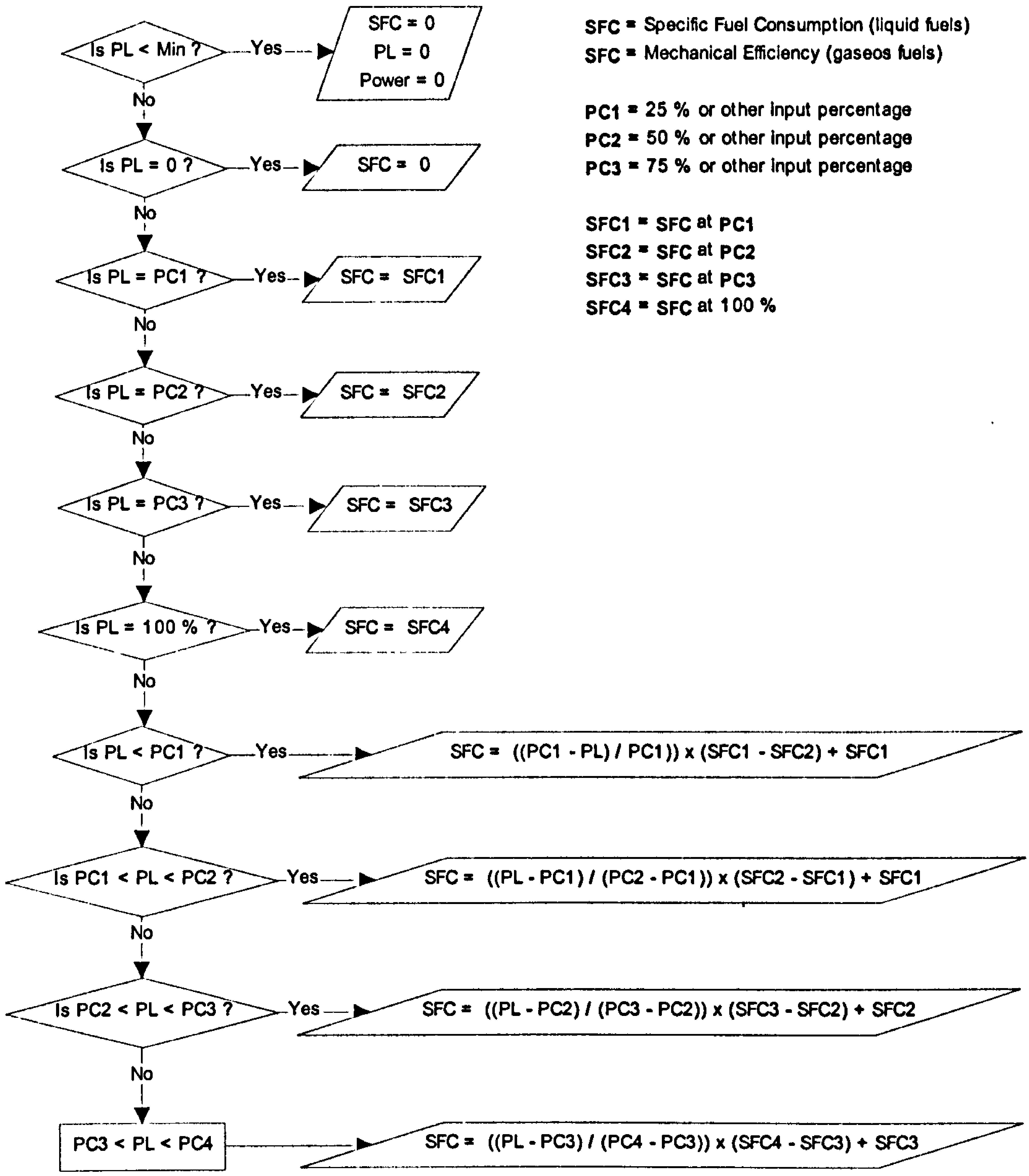
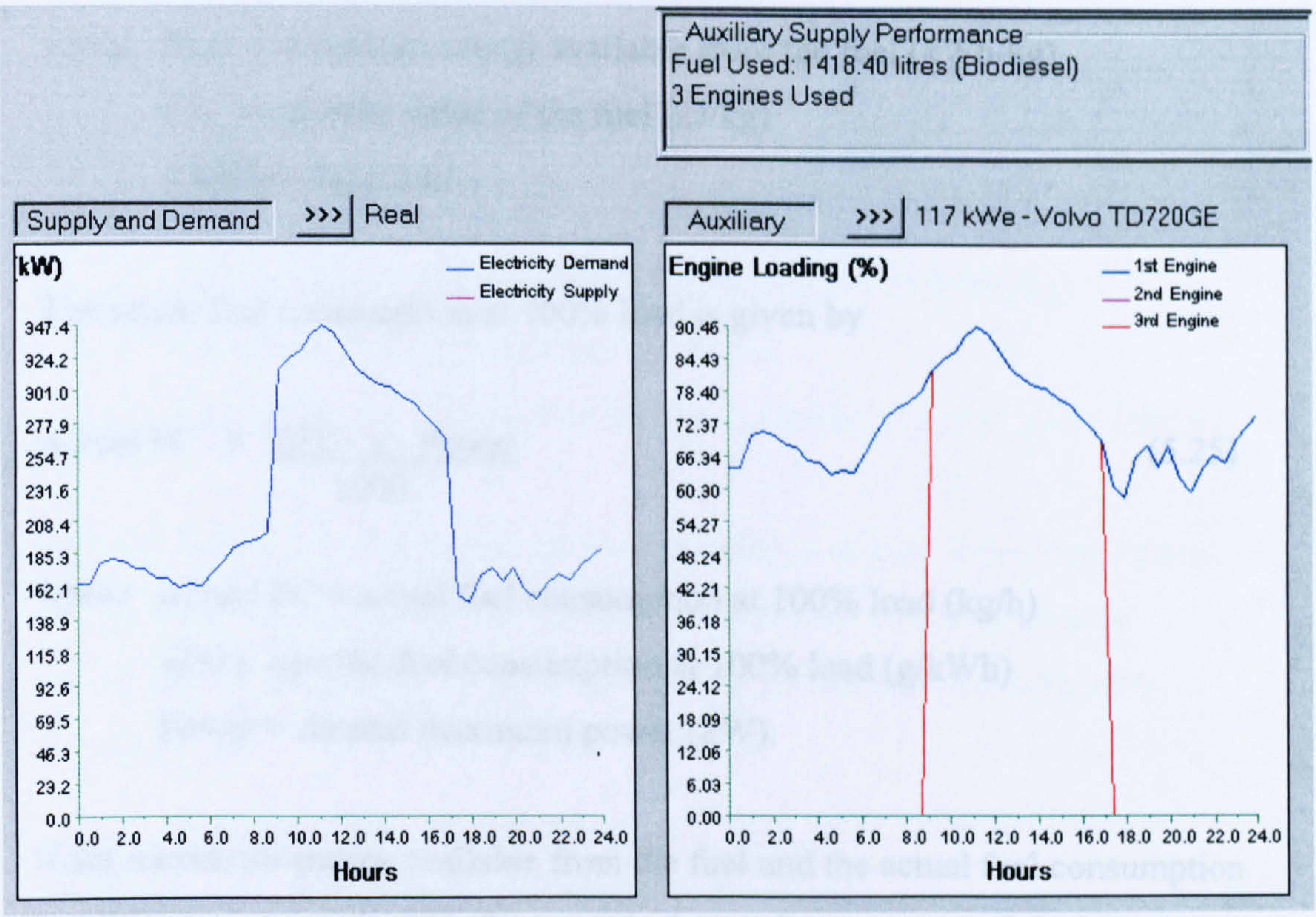


Figure 5.9 Specific Fuel Consumption or Efficiency Determination

As engines may be started and stopped at different times as demand increases and decreases, it is necessary to be able to see graphs showing the loading of all engines in order to assess the way in which they require to be used. As these graphs overlap, it is also necessary to state how many engines have been used to satisfy the peak demand. Figure 5.10 shows the output of a biodiesel run generator set, where three engines are required to meet the electricity demand. Two engines are running constantly at varying load, following the electricity demand, and a third is needed to help supply the peak demand between 0900 and 1700 hours.



Auxiliary Supply Performance
Fuel Used: 1418.40 litres (Biodiesel)
3 Engines Used

Supply and Demand >>> Real

Auxiliary >>> 117 kWe - Volvo TD720GE

Figure 5.10 Use of Multiple Engine Generator Sets

5.2.6 *Heat to Electricity Ratio*

The heat to electricity ratio at partial loads may be calculated in a number of ways. The options are available to estimate the ratio at partial loads using the assumptions outlined earlier, to input heat to electricity ratios at partial load percentages (e.g. 100%, 75%, 50%, and 25%) if this information is available, or to keep the ratio constant at partial loads. If values are input for specific percentage loads, the heat to electricity ratio is interpolated using these values. If CHP is not desired, then the engine may be run to generate electricity only, and the heat to electricity ratio is set to 0.

If the ratio is to be estimated, the calculations outlined below are used. If the specific fuel consumption is being used (liquid fuels), the maximum energy available from the fuel is given by

$$\text{Max} = \frac{\text{CV}}{3610.3} \tag{5.24}$$

where Max = maximum energy available from the fuel (kWh/kg)
CV = calorific value of the fuel (kJ/kg)
1 kWh = 3610.3 kJ.

The actual fuel consumption at 100% load is given by

$$\text{Actual FC} = \frac{\text{SFC} \times \text{Power}}{1000} \qquad (5.25)$$

where Actual FC = actual fuel consumption at 100% load (kg/h)
SFC = specific fuel consumption at 100% load (g/kWh)
Power = derated maximum power (kW).

If the maximum energy available from the fuel and the actual fuel consumption at 100% load are multiplied, the result is the total energy potential of the fuel used in kW. The percentage of this energy that is available for use at 100% load is given by

$$\text{Percentage} = \frac{(\text{Power} + (\text{Power} \times \text{Ratio})) \times 100}{\text{Potential}} \qquad (5.26)$$

where Percentage = percentage of energy available for use at 100% loading
Power = derated maximum power (kW)
Ratio = heat to electricity ratio at 100% loading
Potential = total energy potential of the fuel (kW).

The actual fuel used at the partial load is calculated using Equation 5.25, however, in this case, the specific fuel consumption must be that for the percentage load being considered, and the power is the required power at which the engine is operating, in kW. Assuming that the same percentage of the energy is available for use as at 100% loading (i.e. that the overall efficiency (heat and electricity) is constant), the total useful energy that this amount of fuel can produce is given by

$$\text{Total Energy} = \frac{\text{Max} \times \text{Fuel Used} \times \text{Percentage}}{100} \tag{5.27}$$

where Total Energy = total useful energy available from partial load fuel use (kW)

Max = maximum energy available from the fuel (kWh/kg)

Fuel Used = partial load fuel use (kg/h)

Percentage = percentage of energy available for use at 100% loading.

The part of this total useful energy that is available as heat is the total amount minus the electrical output, and the heat to electricity ratio may then be calculated from these two figures. This whole process may be reduced to Equation 5.28.

$$\text{Ratio}_{\text{part}} = \frac{\text{SFC}_{\text{part}}\ (1 + \text{Ratio}_{100\%})}{\text{SFC}_{100\%}} - 1 \tag{5.28}$$

where $\text{Ratio}_{100\%}$ = heat to electricity ratio at 100% load

$\text{Ratio}_{\text{part}}$ = heat to electricity ratio at partial load

$\text{SFC}_{100\%}$ = Specific Fuel Consumption at 100% load

SFC_{part} = Specific Fuel Consumption at partial load

If efficiency values are being used (gaseous fuels), the overall efficiency may be defined as

$$\text{Overall Efficiency} = \text{Efficiency} \times (\text{Ratio} + 1) \tag{5.29}$$

where Overall Efficiency = total heat and electrical efficiency

Efficiency = electrical efficiency at 100% load

Ratio = heat to electricity ratio at 100% load.

Assuming the overall efficiency is constant, the heat to electricity ratio at partial load may be calculated using

$$\text{Ratio}_{\text{part}} = \frac{(\text{Overall Efficiency} - \text{Efficiency}_{\text{part}})}{\text{Efficiency}_{\text{part}}} \tag{5.30}$$

where $\text{Ratio}_{\text{part}}$ = heat to electricity ratio at partial load

Overall Efficiency = total heat and electrical efficiency

$\text{Efficiency}_{\text{part}}$ = electrical efficiency at partial load.

Substituting for the overall efficiency gives

$$\text{Ratio}_{\text{part}} = \frac{\text{Efficiency}_{100\%}\ (1 + \text{Ratio}_{100\%})}{\text{Efficiency}_{\text{part}}} - 1 \qquad (5.31)$$

where $\text{Ratio1}_{100\%}$ = heat to electricity ratio at 100% load

$\text{Ratio}_{\text{part}}$ = heat to electricity ratio at partial load

$\text{Efficiency}_{100\%}$ = Specific Fuel Consumption at 100% load

$\text{Efficiency}_{\text{part}}$ = Specific Fuel Consumption at partial load

Therefore, if estimating the heat to electricity ratio at partial loads, Equation 5.28 is used if specific fuel consumption is being considered, and Equation 5.31 is used if efficiency values are being considered. The process of determining the heat to electricity ratio at different loads is outlined in Figure 5.11.

If the engine is following the heat demand, it is necessary to recalculate the required engine power. This is because the original calculation of the electrical load required to produce the desired amount of heat relied on the heat to electricity ratio at 100% loading. However, this ratio will increase at partial loading, decreasing the required engine power to meet the heat demand. Also, if the engine is following both electricity and heat demand, and the heat demand is currently being followed, this must, again, be recalculated. However, if the electricity demand is currently being followed, there is no need to recalculate as, if the electricity demand was more than the heat demand originally, the heat supply will only increase with decreased efficiency, therefore it will still require to follow the electricity demand. This process is shown in Figure 5.12.

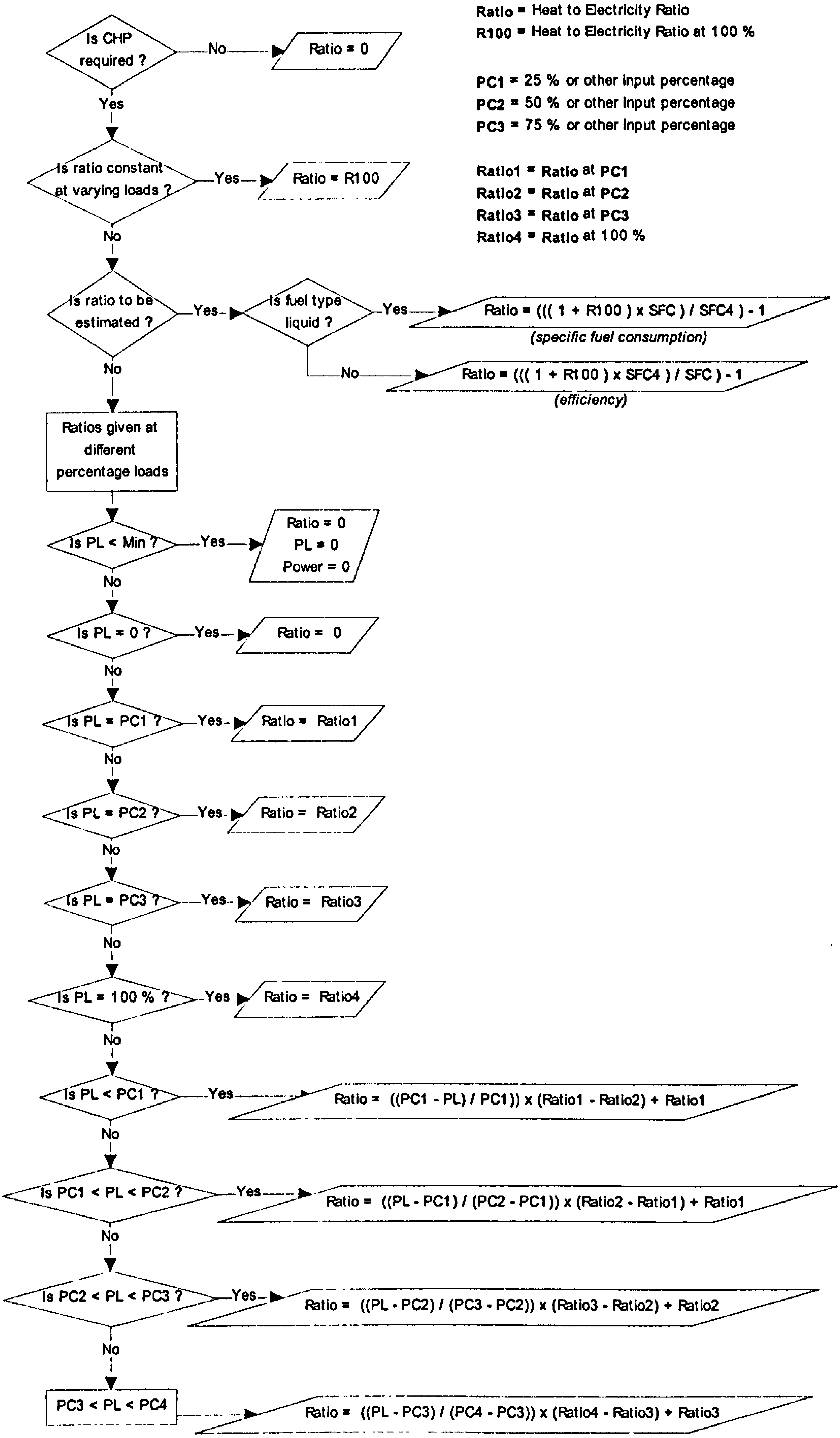


Figure 5.11 Heat to Electricity Ratio Determination

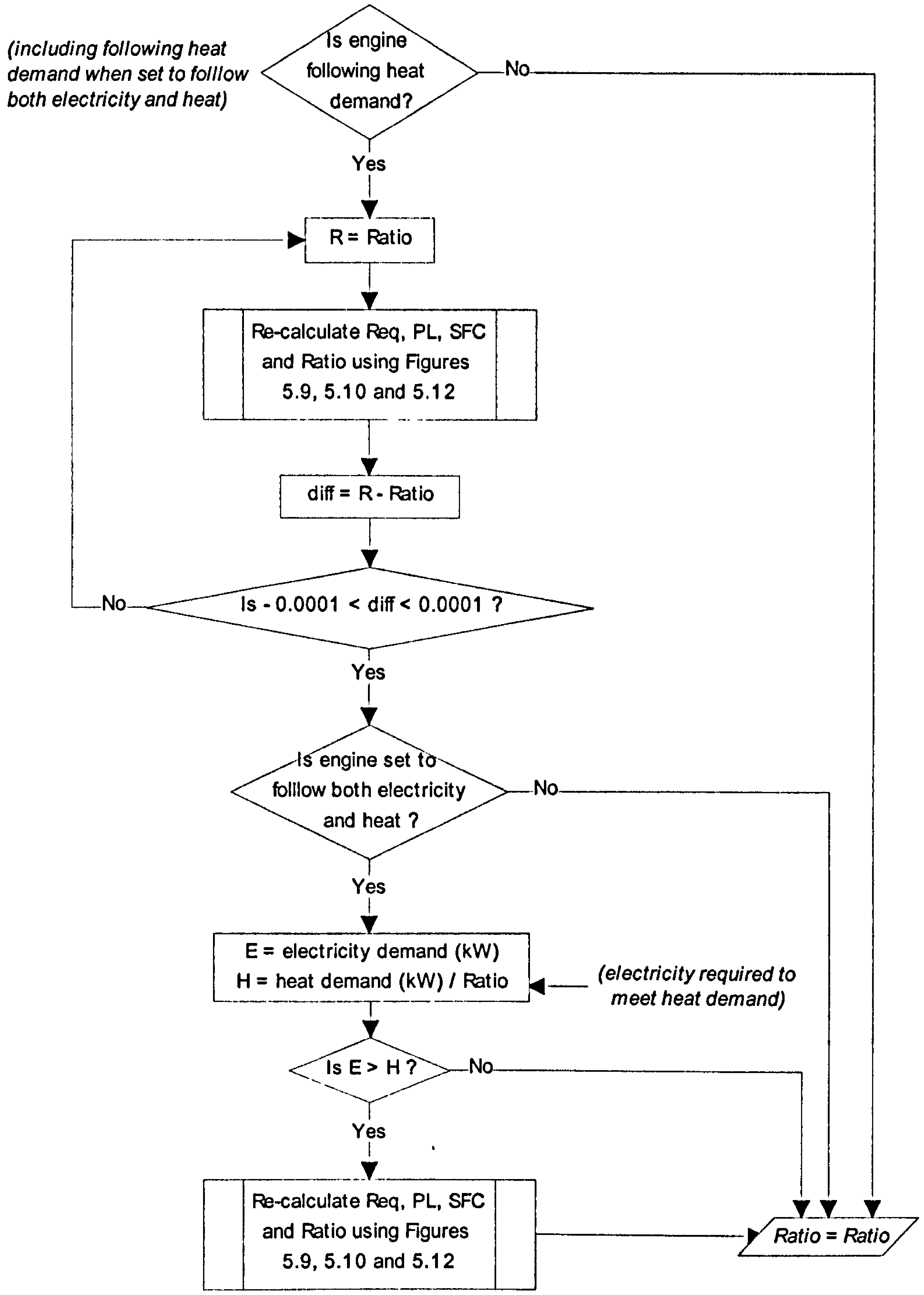


Figure 5.12 Re-Determination of Heat to Electricity Ratio

In order to find the revised heat to electricity ratio, the generator power required is recalculated by dividing the heat demand by the heat to electricity ratio just calculated for the current percentage load, and the power required from the engine is recalculated using Equation 5.22. The percentage load, specific fuel consumption or efficiency and heat to electricity ratio are calculated as before with this new required engine power. This process is repeated continuously using the recalculated heat to power ratio to determine the required engine power in order to satisfy the heat demand, until the difference between the last calculated ratio and the current calculated ratio is plus or minus 0.0001. If the engine is following both heat and electricity demand, once the final heat to electricity ratio has been determined, it is necessary to check if it is still better to be following the heat demand rather than the electricity demand. Again, the required generator powers to meet either demand are determined, and whichever value is highest is used in Equation 5.22 to find the required engine power. The percentage load, specific fuel consumption or efficiency and heat to electricity ratio are then calculated as before.

5.2.7 Actual Fuel Consumption

Once the final values for the percentage load, specific fuel consumption or efficiency, heat to electricity ratio and number of engines running have been determined, it is necessary to calculate the actual fuel consumption required. This can be done using Equations 5.32 to 5.36. The equation used depends on the desired unit for the fuel (kWh for gas, litres for liquid and kg for solid fuels), and whether specific fuel consumption or efficiency values are being used. Although solid fuels may not be used in either of these types of engine, they may be used in Stirling engines, which will be considered later in this chapter.

$$\text{Consumption (litres)} = \frac{\text{SFC} \times \text{Power}}{\text{Density} \times \text{Timesteps}} \tag{5.32}$$

$$\text{Consumption (litres)} = \frac{3610.3 \times 100 \times 1000 \times \text{Power}}{\text{Efficiency} \times \text{CV} \times \text{Density} \times \text{Timesteps}} \tag{5.33}$$

$$\text{Consumption (kg)} = \frac{\text{SFC} \times \text{Power}}{1000 \times \text{Timesteps}} \tag{5.34}$$

$$\text{Consumption (kg)} = \frac{3610.3 \times 100 \times \text{Power}}{\text{Efficiency} \times \text{CV} \times \text{Timesteps}} \tag{5.35}$$

$$\text{Consumption (kWh)} = \frac{100 \times \text{Power}}{\text{Efficiency} \times \text{Timesteps}} \tag{5.36}$$

where SFC = specific fuel consumption at partial load (g/kWh)
Power = required engine power (kW)
Density = density of the fuel (kg/m^3)
Timesteps = number of timesteps per hour
Efficiency = engine efficiency at partial load (%)
CV = calorific value of the fuel (kJ/kg)
1 kWh = 3610.3 kJ.

Once the actual fuel required has been calculated, this is multiplied by the number of engines being used, and this is checked against the amount of fuel available. If there is not enough fuel, a warning is given, and the percentage load at which the engine or engines are able to run with the available fuel is calculated. Although the generating set would not actually work in this way, this has been designed to give an idea of what would be available in a given circumstance, so the user can make a decision about either increasing the fuel production rate, or providing other means of supply to reduce reliance on the engine.

If the specific fuel consumption is being used, the algorithm for determining the fuel consumption and finding the percentage load that is possible with the available fuel as necessary is shown in Figure 5.13. The possible engine power achievable with the fuel available, and hence the percentage load, are determined using the current specific fuel consumption. This may be done by re-arranging Equation 5.32 or 5.34 as appropriate. If more than one engine set is available, and the possible percentage load is above 100%, the number of engines that may be run, and the percentage at which they may be run, are calculated, while not allowing them to go below minimum load. If the possible percentage load is above 400%, this is divided by 5, and, if this is not below the minimum load level, this is used as the percentage load for all five engines. If it is below minimum load, four engines are run at full power. This is repeated for above 300%, 200% and 100% (dividing by 4, 3 or 2, and with 4, 3 or 2

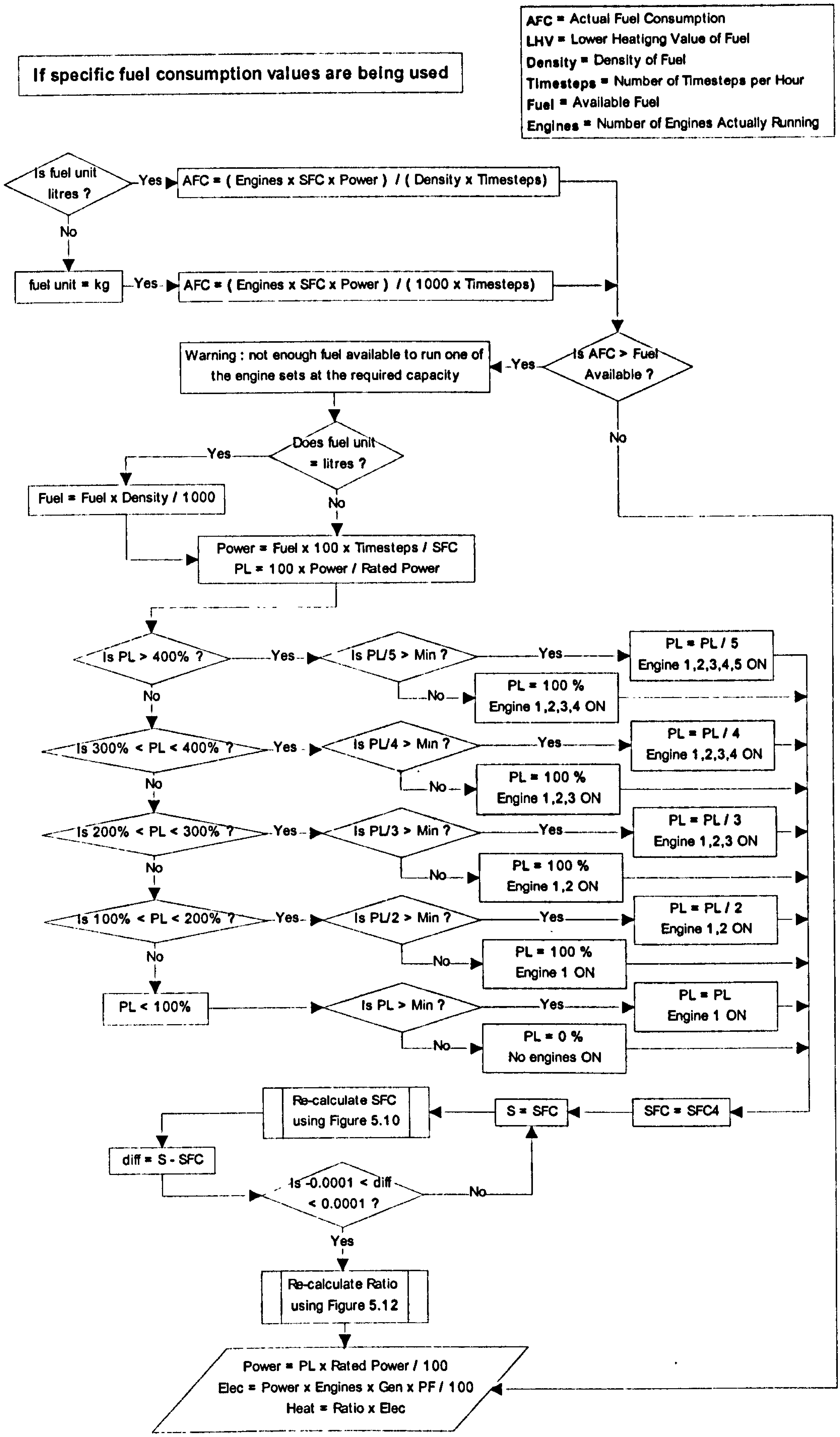


Figure 5.13 Fuel Consumption and Possible Load Determination (SFC)

engines running respectively). If the possible percentage load is below 100% and above minimum load, one engine is used at this percentage. The desired number of engines will always be available, otherwise, the condition that there was not enough fuel to meet the required consumption would not have been met. The specific fuel consumption must then be recalculated at this new percentage loading, and the process repeated until the difference between the last calculated specific fuel consumption and the current calculated specific fuel consumption is minimal (e.g. plus or minus 0.0001).

If the efficiency is being used, the above process cannot be followed, as the calculation of the possible engine power, which may be calculated by re-arranging Equations 5.33, 5.35 or 5.36 as appropriate, would result in ever decreasing operating powers. This is due to the fact that, in the equations, the efficiency is being multiplied by, rather than divided by, which is the case with the specific fuel consumption. Another approach has, therefore, been taken where the actual fuel consumptions at the percentages for which the efficiency values are quoted, are calculated, and the possible percentage load with the fuel available is calculated by interpolation between these points. If more than one engine is available, the fuel available is checked to see if it is above four times the 100% load fuel consumption. If so, the fuel available is divided by five, all five engines are used, and the percentage load possible with the available fuel is calculated. If this results in a loading less than the minimum load, four engines are run at full load. This is repeated for above three times the 100% load fuel consumption, above two times, and above the 100% load fuel consumption. If less than the 100% load fuel consumption is available, one engine is used, and the fuel consumption is calculated as before. This approach is slightly less accurate due to its use of linear variation between the percentage load points, but it is adequate for this purpose. The algorithm for determining the fuel consumption and finding the percentage load that is possible with the available fuel as necessary, if the efficiency is being used, is shown in Figure 5.14.

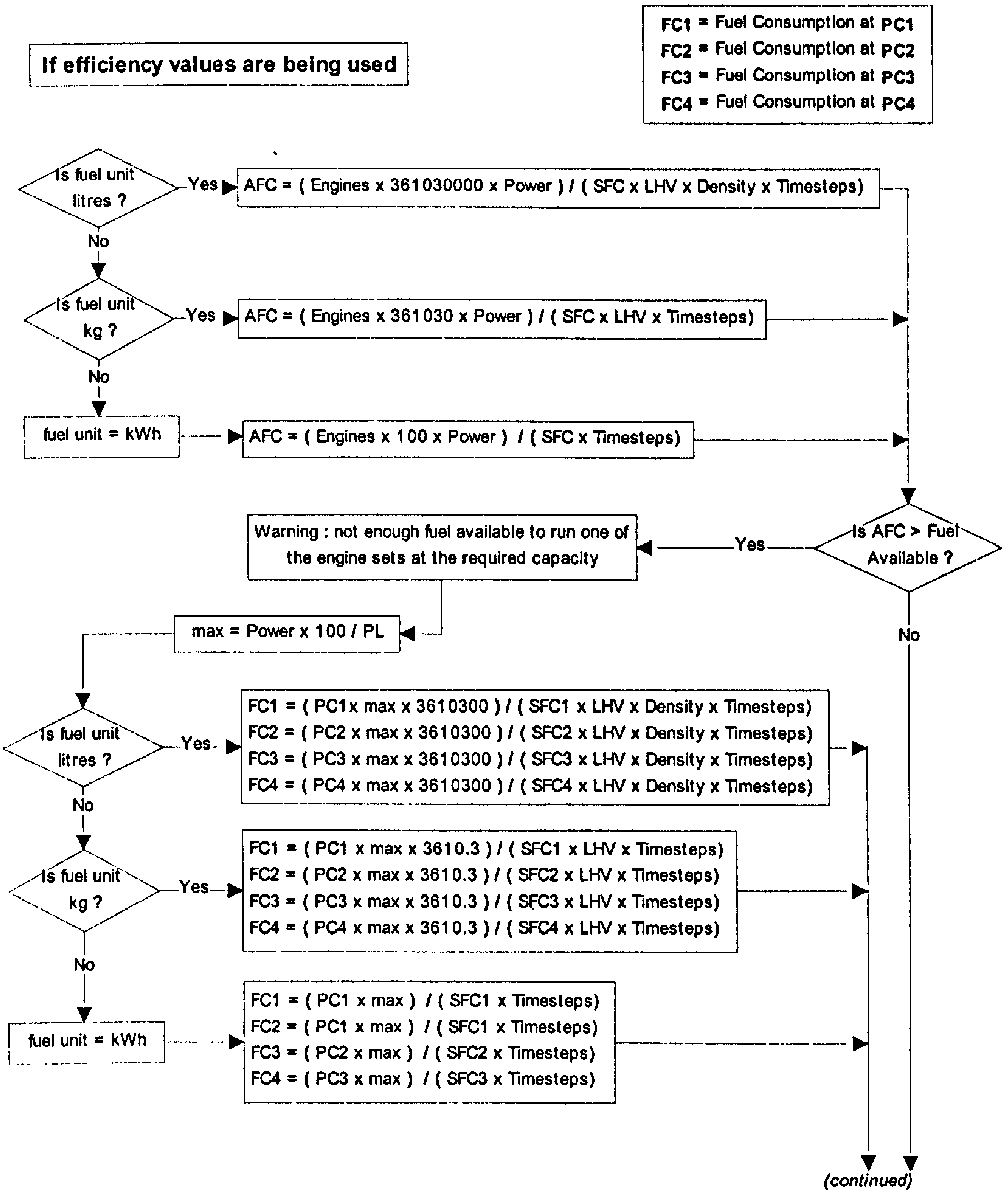


Figure 5.14 Fuel Consumption and Possible Load Determination (Efficiency)

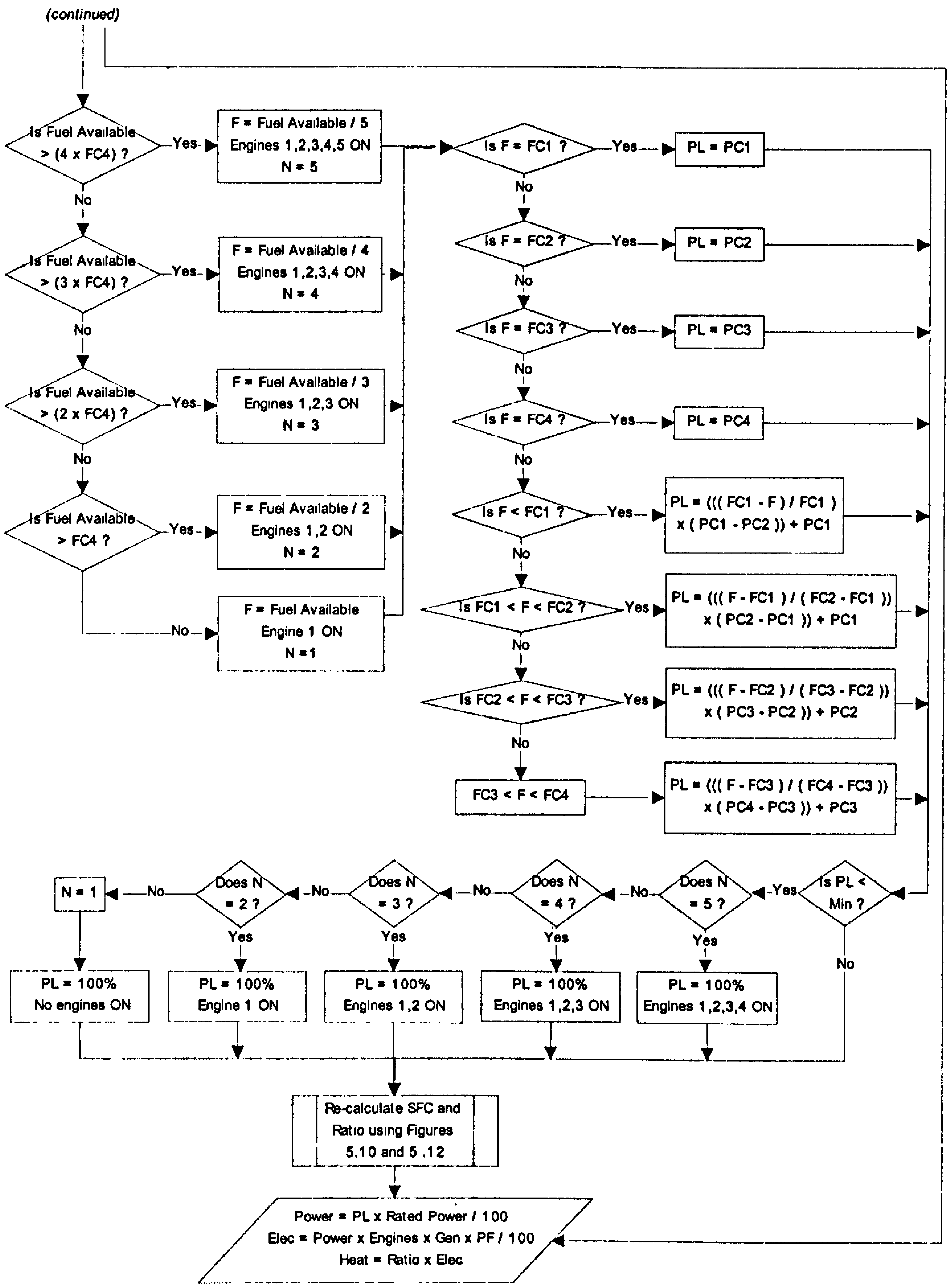


Figure 5.14 (cont) Fuel Consumption and Possible Load Determination (Efficiency)

After either process to find the possible percentage load with the fuel available, this should be checked to see if it is below the minimum load, and, if not, the specific fuel consumption and heat to electricity ratio should be recalculated as before.

5.2.8 Estimating Biodiesel Performance From Diesel Consumption

Testing of biodiesel performance in diesel engines shows that specific biodiesel consumption (in litres) is, typically, 10% more than diesel consumption in the same engine [12]. This increase is due to the reduced lower heating value (LHV) of biodiesel, despite its higher density. Taking into account the difference in density, the specific fuel consumption (g/kWh) of biodiesel is equal to the diesel specific fuel consumption increased by 15%. Heat to electricity ratios and overall efficiencies remain unaffected. If the efficiency is being used rather than the specific fuel consumption, the efficiency value does not require to be amended for varying lower heating values, as these will be taken into consideration when calculating the actual fuel consumption.

If the modelling of back-up supply using diesel, petrol or natural gas as fuels is required, this may be done using the 'other' fuel categories, and giving the required information for these fuels. It is necessary to specify whether these 'other' fuels are solid, liquid or gas, to allow the correct calculations to be made.

5.3 Stirling Engine Model

The performance of a Stirling engine is not affected by ambient temperature or altitude and, therefore, does not require derating. Otherwise, performance characteristics are quoted in a similar manner to other engines, with efficiency values being given. Again, efficiency decreases with partial load, as can be seen in Figure 5.15, while overall efficiency (electricity and heat) remains fairly constant. This allows this type of engine to be treated in the same manner as diesel engines and ICEs for performance modelling, as described in section 5.2. However, due to the external nature of the heat source, and their fairly slow start-up time, the options to follow heat demand, electricity demand or both are not appropriate for Stirling engines, and are, therefore, not available. Again, multiple engine sets may be used, and these are subject to a minimum recommended load. The output from this procedure is a graph of percentage engine loading, and fuel use is calculated and dealt with as before. An example of the definition window for a Stirling engine is given in Appendix 1, Figure A1.33.

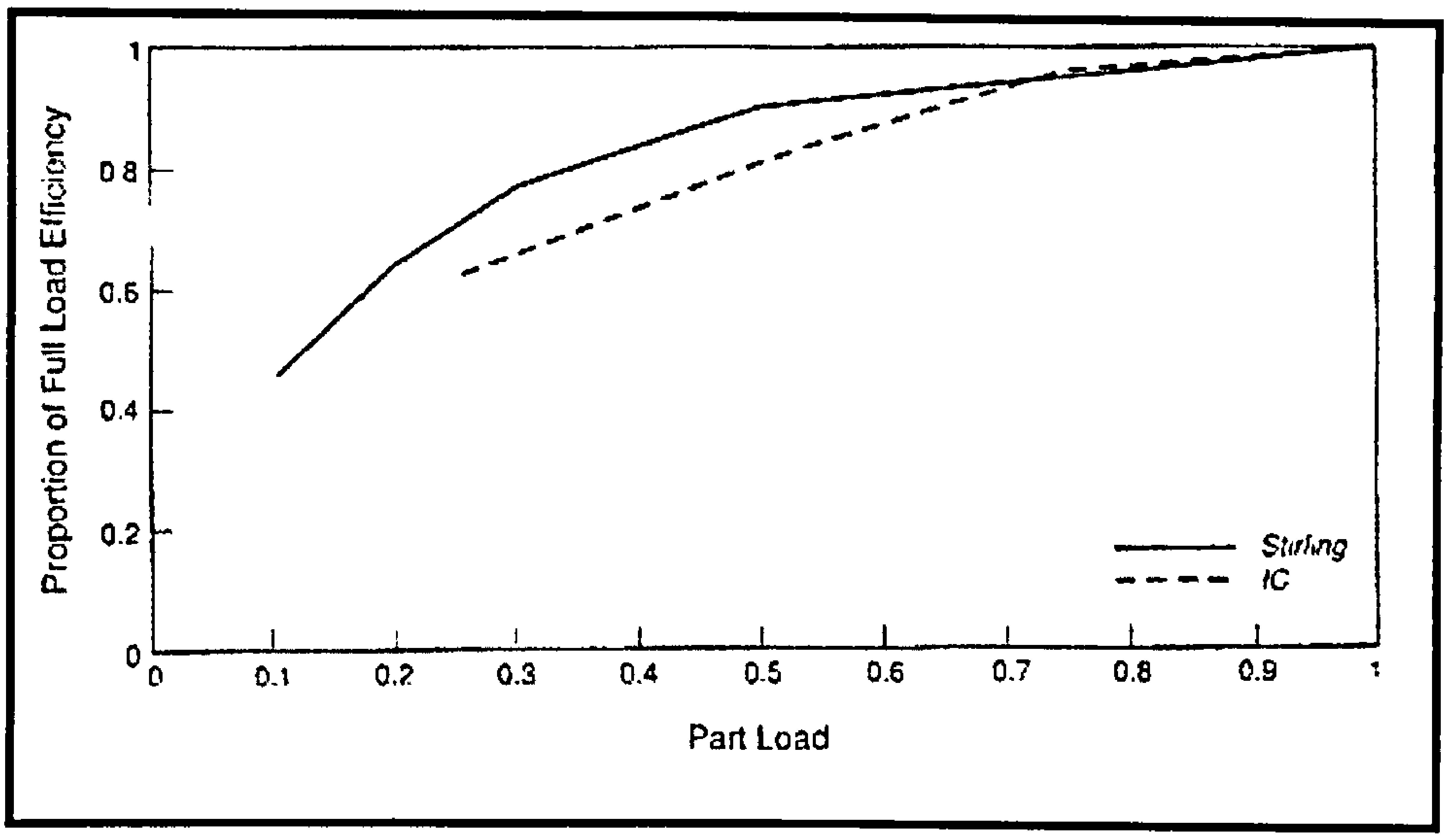


Figure 5.16 Theoretical Load Performance of Stirling and IC Engines [13]

5.4 Gas Turbine Model

Performance characteristics for gas turbines are generally quoted in charts similar to that shown in Figure 5.16. Ambient temperature derating factors may be determined from this chart by considering the 'power limit' line. From this line, the threshold temperature (the temperature at which the line changes from horizontal to sloping, above which derating should begin) and percentage rate of decrease per °C above this temperature may be determined. Although the rated power is generally quoted at the ISO standard of 15 °C, the generator terminal output power at the threshold temperature should be used as the basis for derating to allow accurate calculation of the maximum derated power available. Different turbines have different derating threshold temperatures and rates of decrease. As the threshold temperatures tend to be low (between –10 and 10 °C), it is important to consider this effect, as it can have a significant affect on the performance of the turbine. Site altitude can also affect the maximum output power, and this information will be included in manufacturers' data if required. Derating of the maximum available power may, therefore, be treated in the same way as for diesel and internal combustion engines, as described in section 5.2.

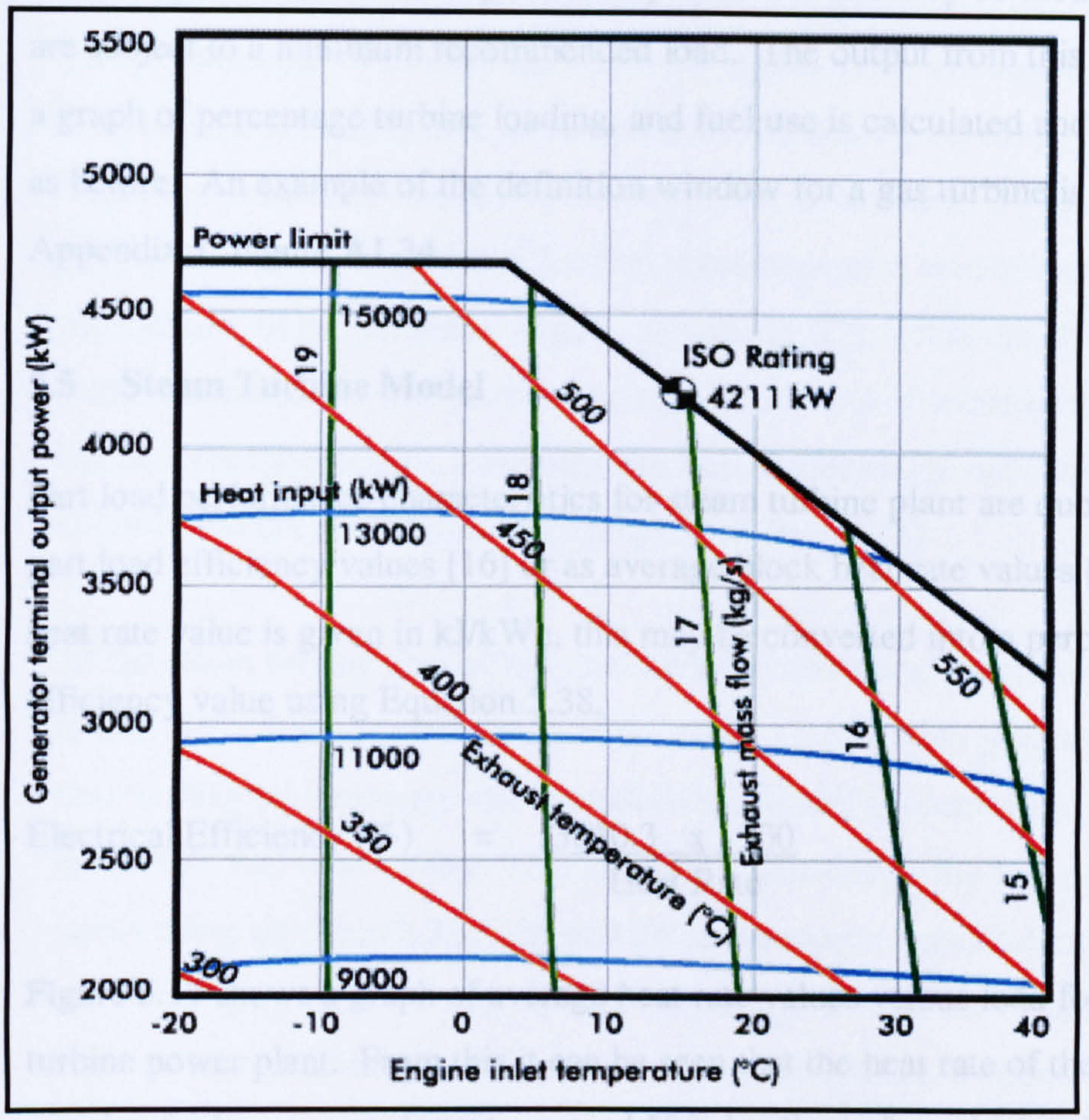


Figure 5.16 Gas Turbine Performance Chart – Alstom Typhoon 435 [14]

The generating set percentage electrical efficiency at full and partial loads may also be determined from gas turbine performance charts, using

$$\text{Efficiency (\%)} = \frac{\text{generator terminal output power (kW)} \times 100}{\text{heat input (kW)}} \qquad (5.37)$$

To find the average efficiency values at full and partial load, the ISO standard rated output at 15°C is taken as the full load rated output. When part load efficiencies are calculated, it can be seen that the efficiency decreases with partial load in a similar way as with the engines. The overall efficiency (heat and electricity) again remains fairly constant, typically at around 80%. Therefore, the calculation of percentage load and heat to electricity ratio may, again, be dealt with as previously described for diesel and internal combustion engines, as described in section 5.2. As gas turbines cope well with varying loads, and have a fast response time [15], they are suitable for load following and continuous operation. Again, multiple turbine sets may be used, and these are subject to a minimum recommended load. The output from this procedure is a graph of percentage turbine loading, and fuel use is calculated and dealt with as before. An example of the definition window for a gas turbine is given in Appendix 1, Figure A1.34.

5.5 Steam Turbine Model

Part load performance characteristics for steam turbine plant are quoted either as part load efficiency values [16] or as average block heat rate values [17]. If a heat rate value is given in kJ/kWh, this may be converted into a percentage efficiency value using Equation 5.38.

$$\text{Electrical Efficiency (\%)} \quad = \quad \frac{3610.3 \ \text{x} \ 100}{\text{Heat Rate}} \tag{5.38}$$

Figure 5.17 shows a graph of average heat rate values versus load for a steam turbine power plant. From this it can be seen that the heat rate of the plant remains fairly constant down to around 50% loading, after which it increases significantly. This increase in heat rate denotes a significant decrease in efficiency. This is typical behaviour for a steam turbine, although actual part load efficiency or heat rate figures will vary with the type and size of plant.

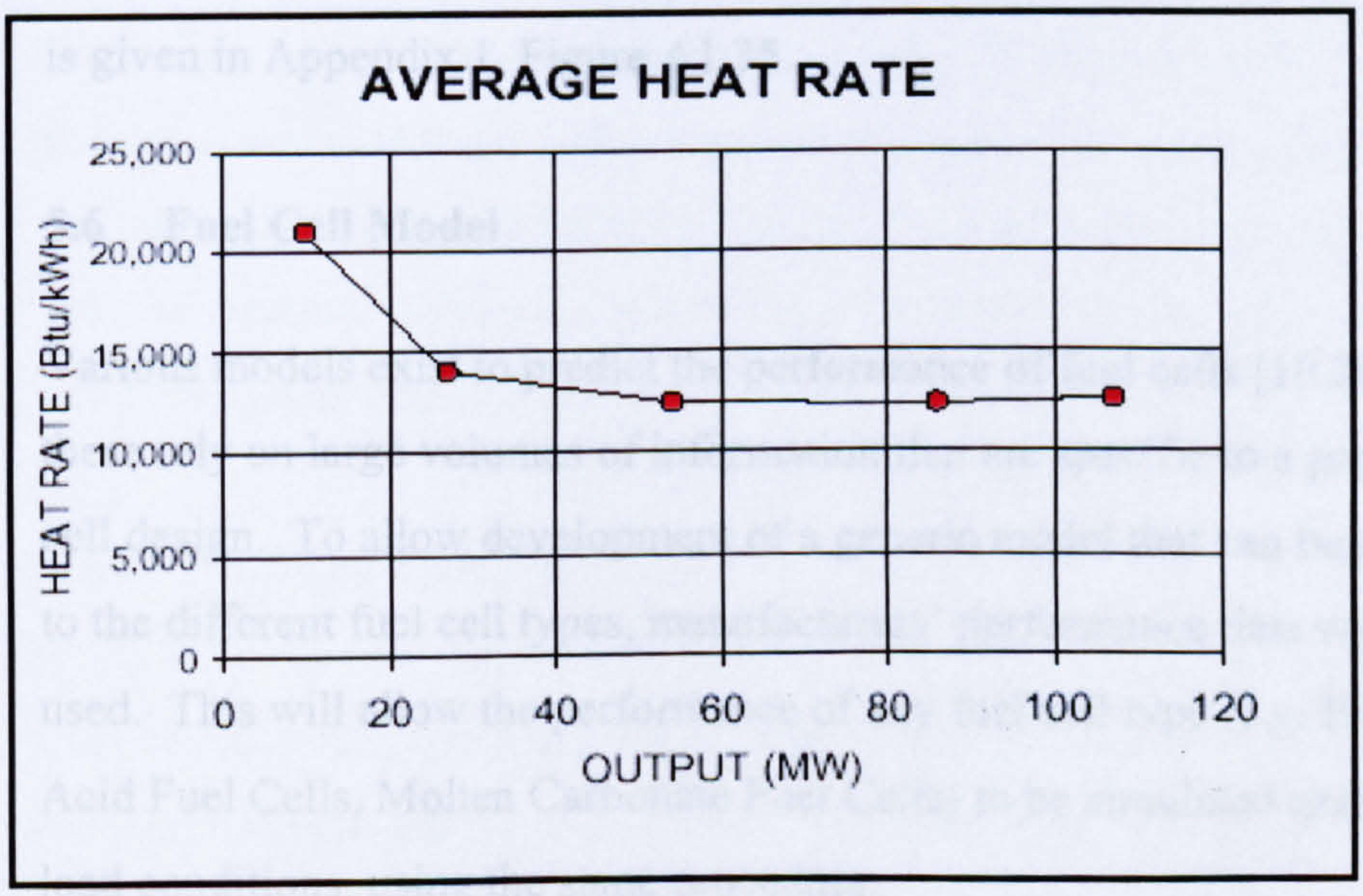


Figure 5.17 Average Heat Rate Versus Output for a Steam Turbine [17]

The performance of a steam turbine is not significantly affected by ambient temperature or altitude and, therefore, does not require derating [18]. Otherwise, steam turbine performance may be modelled in the same way as an ICE, as described in section 5.2, using percentage part load efficiency values as the measure of performance. Again, as with an ICE, while the efficiency of the steam turbine drops with partial loading, the amount of waste heat produced increases proportionally, increasing the heat to electricity ratio, and keeping the overall efficiency (heat plus electricity) fairly level [18].

As the steam turbine uses an external heat source to produce the steam necessary to turn the turbine, the efficiency of the boiler employed to produce the required heat to raise the necessary steam must be taken into account when calculating the overall fuel requirement. This is done by calculating the fuel consumption figure using Equation 5.33, 5.35 or 5.36 as appropriate, multiplying this by 100 and dividing by the percentage boiler efficiency. Due to the external nature of the heat source, and fairly slow start-up time, the options to follow heat demand, electricity demand or both are not appropriate for steam turbines, and are, therefore, not available. Again, multiple turbine sets may be used, and these are subject to a minimum recommended load. The output from this procedure is a graph of percentage turbine loading, and fuel use is calculated and dealt with as before in section 5.2. An example of the definition window for a steam turbine is given in Appendix 1, Figure A1.35.

5.6 Fuel Cell Model

Various models exist to predict the performance of fuel cells [19,20,21], but these rely on large volumes of information that are specific to a particular fuel cell design. To allow development of a generic model that can be easily applied to the different fuel cell types, manufacturers' performance data will again be used. This will allow the performance of any fuel cell type (e.g. Phosphoric Acid Fuel Cells, Molten Carbonate Fuel Cells) to be simulated under various load conditions, using the same procedure.

The performance of a fuel cell is not significantly affected by ambient temperature or altitude and, therefore, does not require derating. Otherwise, the electricity and heat production of a single fuel cell may be modelled in the same way as an ICE (as described in section 5.2), using percentage part load efficiency values as the measure of performance, and the output to the matching stage is also the same. As electricity is generated directly in a fuel cell, the generator efficiency and power factor considered in the ICE model are not required. Fuel cells also have fast response times, which make them ideal for following demand. There are no other factors that significantly affect the performance of a fuel cell at this level of modelling [22]. Examples of the definition window for a fuel cell system are given in Appendix 1, Figures A1.37 and A1.38. There are, however, some specific considerations that need to be taken into account when modelling fuel cells, and these are outlined below.

5.6.1 Operating Temperature

The required operating temperature of a fuel cell depends on the type of electrolyte used. The most common types of fuel cell used for stationary applications are the Phosphoric Acid Fuel Cell (PAFC), which operates at around 200°C, and the Alkaline Fuel Cell (AFC), which operates at around 80°C. This operating temperature is reached, initially, with the help of an external heat source, and is then maintained at a reasonably constant level by waste heat from the operation of the fuel cell. For the purposes of this model, it will be assumed that the fuel cell generating system is running fairly continuously, with some degree of loading, and therefore does not require external heating. Typically, several days of standby can be achieved without the need for external heating [22].

5.6.2 Fuel Cell Efficiency

Fuel cell generating systems can run either on pure hydrogen or on hydrogen rich fuels such as biogas or methanol. The latter type requires an internal reformer, which reduces the overall generating efficiency, and this effect is included in their quoted efficiency figures. The efficiency of a fuel cell also varies with the type of electrolyte being used, and its required working temperature, although scaling the same fuel cell design up or down has little effect on the efficiency.

Interestingly, the efficiency of a fuel cell stack alone increases at lower loads, as shown in Figure 5.18 [23]. This increase in efficiency, however, varies substantially with the overall plant design, and some fuel cell generating sets can show efficiency values that increase, decrease or stay reasonably constant at lower loadings [24]. This can be seen in the overall curve in Figure 5.18, which shows the fuel in to electricity out efficiency of an overall fuel cell configuration.

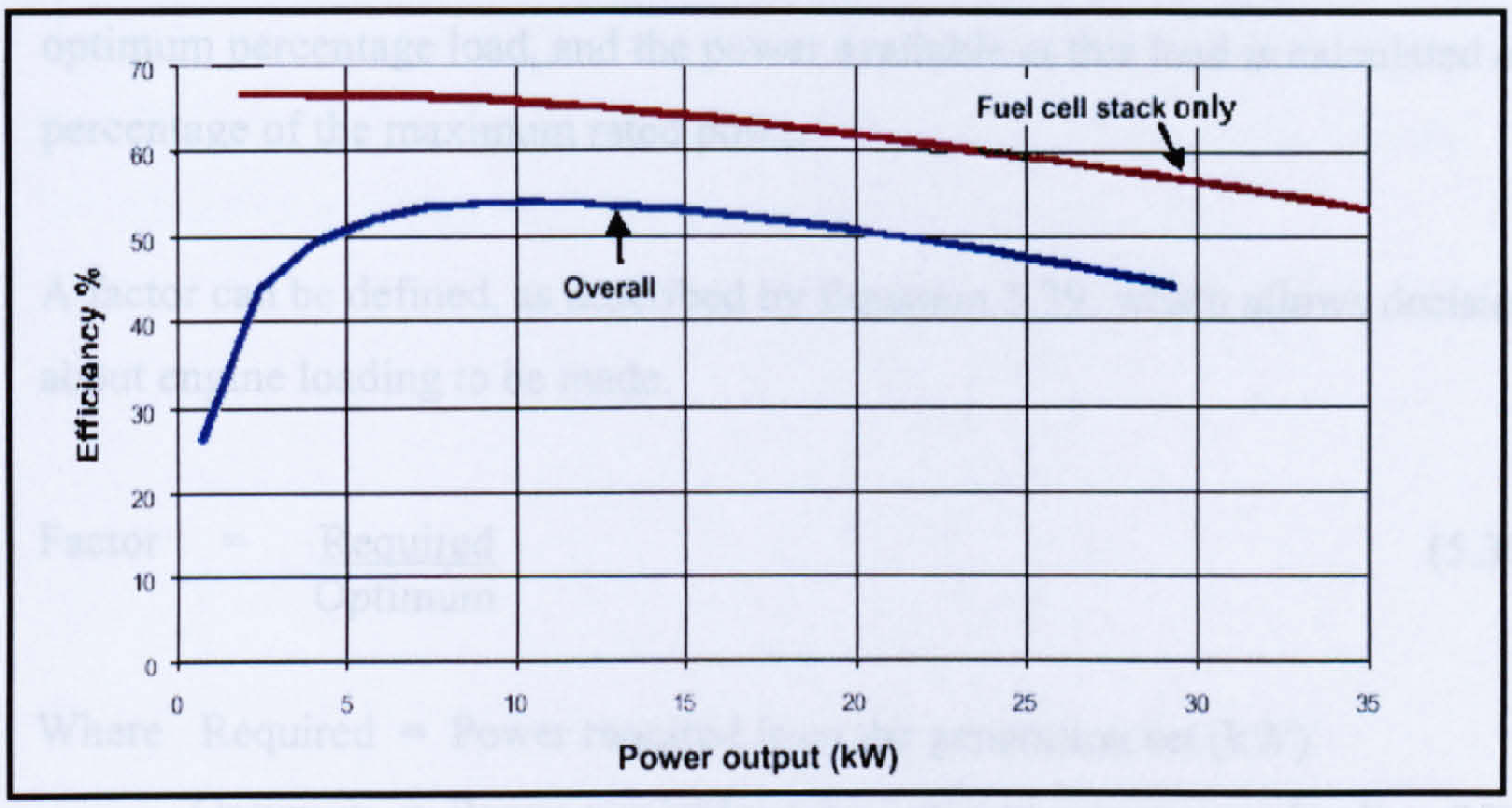


Figure 5.18 Typical Efficiency of a Fuel Cell Under Partial Loading [23]

5.6.3 *Multiple Fuel Cell Generation Sets*

As the efficiency of a fuel cell may increase under partial load, this must be taken into consideration when deciding the optimum share of load between multiple fuel cells when more than one is specified in a generating set. If efficiency decreases with partial load, the load share is determined as described for multiple engine sets in Section 5.2.5. If efficiency increases with decreasing load, as shown in Figure 5.18, a different approach must be taken. This is outlined below, and shown graphically in Figure 5.19. Again, it has been assumed that it is more efficient to run a number of fuel cells at the same percentage loading, rather than using a mixture of percentage loadings. This is due to the shape of the efficiency versus partial load graph (Figure 5.18), where the rate of change of the efficiency is much lower closer to optimum loading, and this increases as loading moves away from optimum in either direction. There would, therefore, be no real benefit in running one or more fuel cells at optimum loading and one or more at a different loading and lower efficiency, as this would give a lower overall efficiency.

In order to determine the optimum fuel cell load share, the efficiency values require to be specified at different partial loads, as before, and the efficiency value at the minimum load is determined from these by extrapolation or interpolation. These values are then compared with each other to find the optimum percentage load, and the power available at this load is calculated as a percentage of the maximum rated power.

A factor can be defined, as described by Equation 5.39, which allows decisions about engine loading to be made.

$$\text{Factor} = \frac{\text{Required}}{\text{Optimum}} \qquad (5.39)$$

Where Required = Power required from the generation set (kW)
Optimum = Power available at the optimum percentage loading (kW).

If the maximum of five fuel cell sets are specified, and the factor is greater than five, all five fuel cells are run. If the required power divided by the maximum rated power is greater than five, the generating set is not able to satisfy all the power requirement, and all five fuel cells are run at full power. If this is less than five, the power requirement is divided equally between the five fuel cells, and the percentage load is calculated from this.

If the factor is between four and five, the required power is divided by five, and the percentage load is calculated. If this is below minimum load, four fuel cells are run with the required power distributed evenly between them. Otherwise, the efficiency value this loading would give, with five fuel cells running, is calculated by interpolation, and the same calculation is made for four fuel cells running (dividing the power required by four). These efficiency values are compared, and the most efficient generation mix, using either four or five fuel cells, is chosen. If the factor is between three and four, two and three, or one and two, the same process is carried out to compare the efficiency values gained by running three or four, two or three, or one or two, fuel cells respectively. If the factor is less than one, the percentage load is calculated. If this is less than minimum load, no fuel cells are run. Otherwise, one fuel cell is run at the required load. If the factor is equal to an exact integer of five or below, that number of fuel cells may be run at their optimum percentage load. If four, three or two fuel cells are specified, the procedure outlined above is followed, checking first if the factor is greater than four, three or two respectively, rather than five. From this, the percentage load, the number of fuel cells running, and the efficiency at which they are running may be determined.

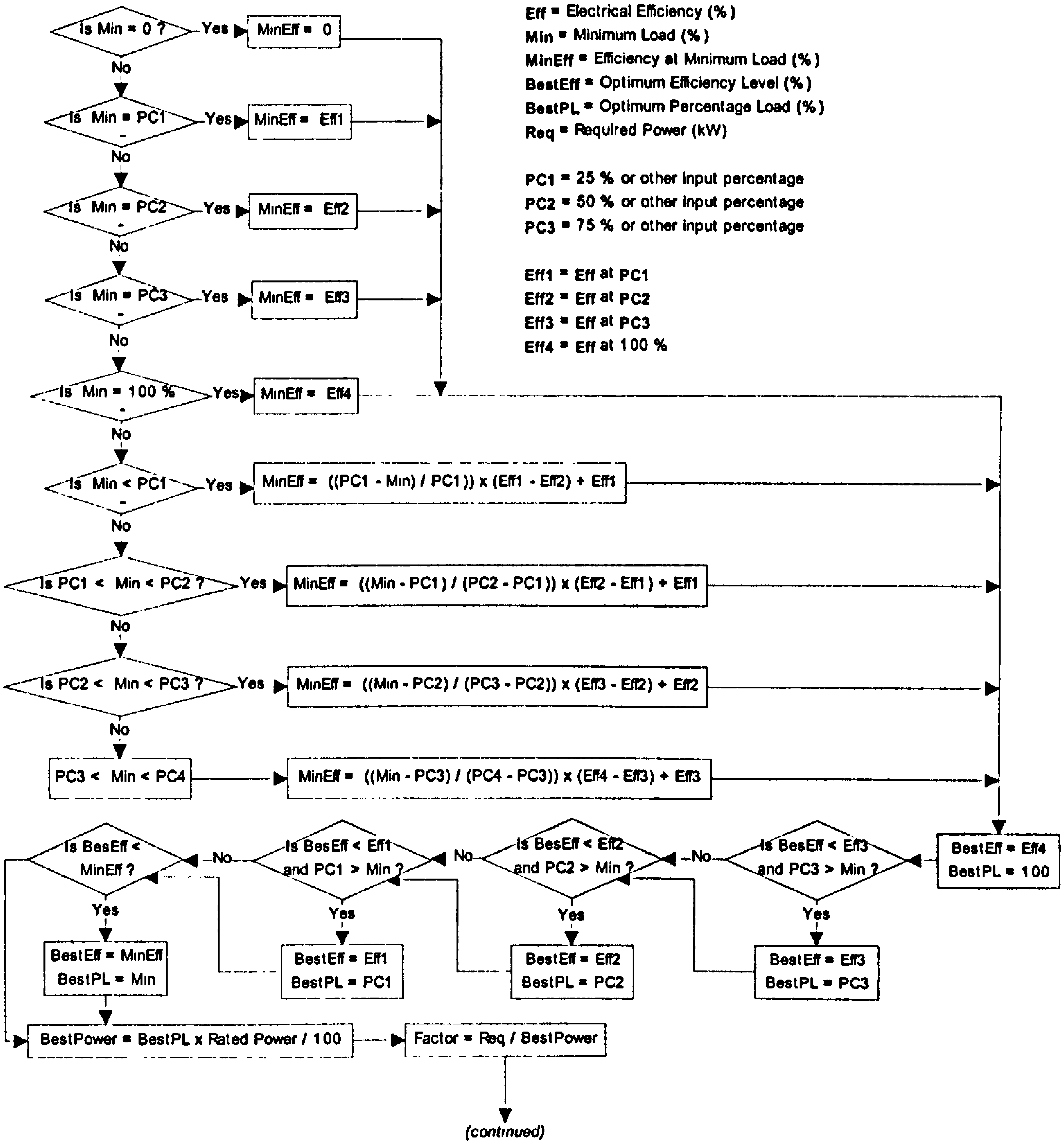


Figure 5.19 Determination of Percentage Load for a Fuel Cell

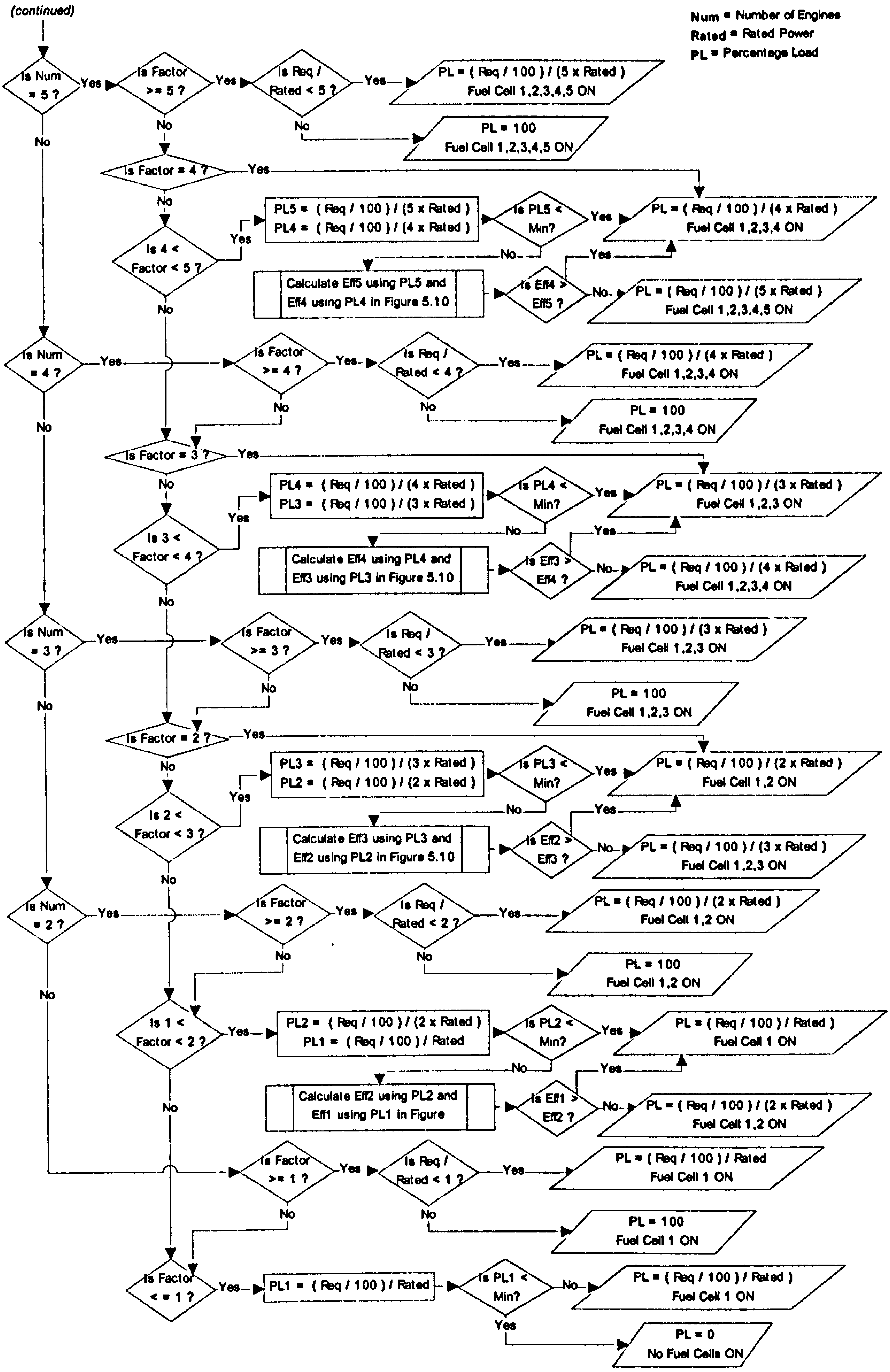


Figure 5.19 (cont) Determination of Percentage Load for a Fuel Cell

5.6.4 If Fuel Availability is Less Than Required

If there is less fuel than is required to run the fuel cells at the desired loading, the maximum output that may be achieved must be ascertained. If only one fuel cell has been specified, or if the efficiency is at a maximum at full load, the maximum output achievable with the available fuel is calculated in the same way as described for engines in Section 5.2.6. Otherwise, where the fuel cell efficiency increases with decreasing load, the method outlined below is used. This is shown graphically in Figure 5.20.

Firstly, the fuel consumption at the optimum percentage load and the other given percentage loads are calculated using Equation 5.33, 5.35 or 5.36 as appropriate. The optimum number of fuel cells amongst which the load may be divided can be determined using the factor calculated in Equation 5.40.

$$\text{Factor} = \frac{\text{Fuel Available}}{\text{Optimum Fuel Consumption}} \qquad (5.40)$$

Where Fuel Available = Amount of fuel available (litres, kg or kWh)
Optimum Fuel Consumption = Fuel consumption at the optimum percentage loading (litres, kg or kWh).

If five fuel cell sets have been specified, and this factor is equal to an exact integer of five or below, that number of fuel cells may be run at their optimum percentage load. If this factor is greater than five, the best load spread with the fuel available is achieved by dividing the fuel available equally between all five fuel cells. If the factor is between four and five, the available fuel is divided equally between four fuel cells, and the percentage load possible is calculated by interpolation between the fuel consumption figures calculated for the given percentage loads. If the factor is between three and four, two and three, or one and two, the same process is carried out to compare the efficiency values gained by running three or four, two or three, or one or two, fuel cells respectively. If the factor is less than one, the percentage load is calculated. If this is less than minimum load, no fuel cells are run. Otherwise, one fuel cell is run at the load possible with the available fuel.

If four, three or two fuel cells are specified, the procedure outlined above is followed, checking first if the factor is greater than four, three or two respectively, rather than five. In this way, the percentage load, the number of fuel cells running, and their efficiency at this load, may be determined, to provide the optimum use of the total fuel available.

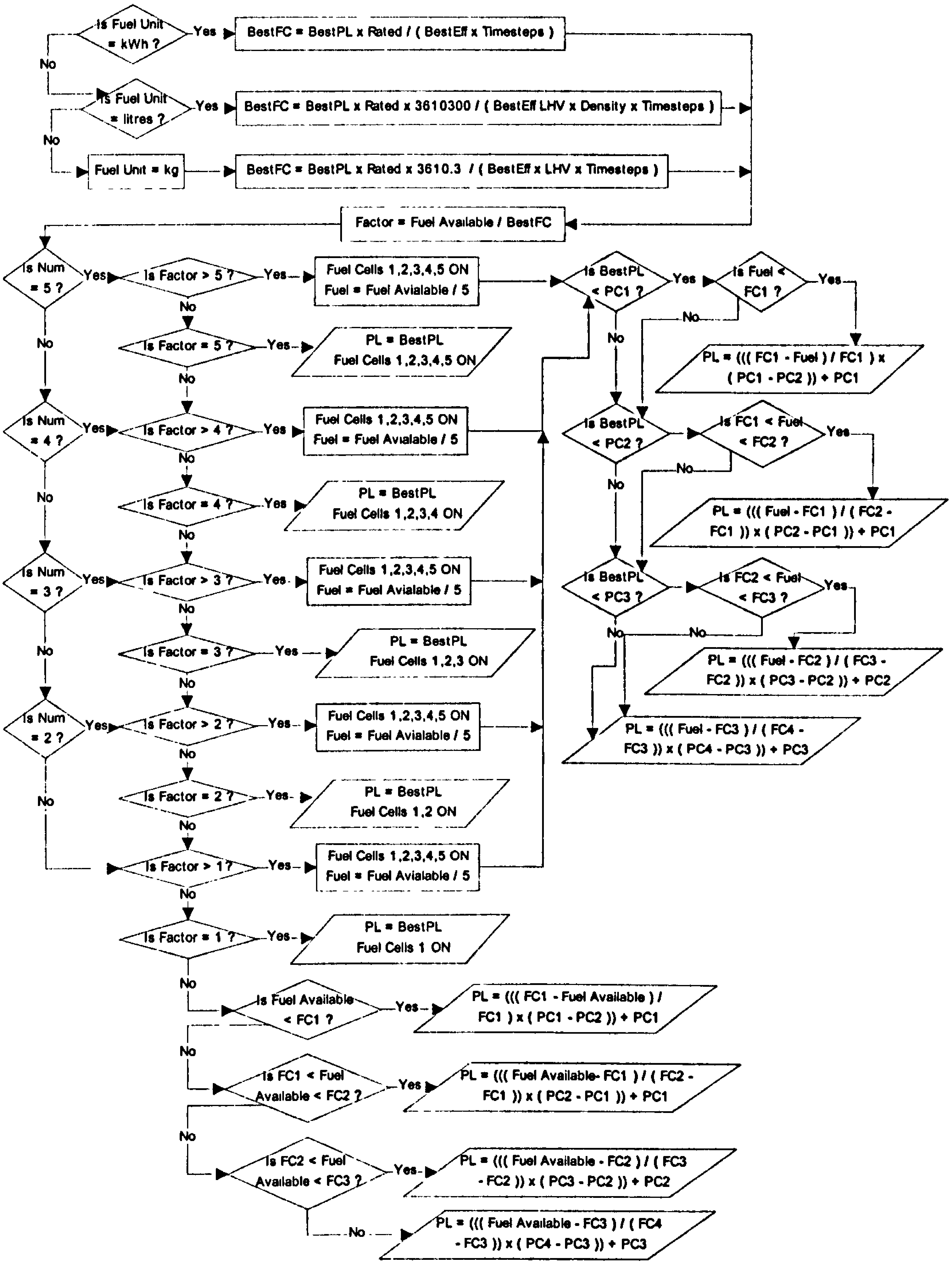


Figure 5.20 Possible Load Determination for a Fuel Cell

5.7 Electrolyser Model

An electrolyser uses excess electricity to create pure hydrogen from water, which may then be used for transport, for the production of heat or electricity, or stored for later use. It is, effectively, a fuel cell operating in reverse, and shows the same increase in efficiency at lower running levels. Again, complex models such as TRNSYS and SIMELINT do exist to predict the output of specific electrolysers [25,26], but these require large amounts of data specific to each electrolyser, and give more detail than is required here. Therefore, easily available manufacturers' data will again be used to provide a sufficient approximation of the performance of a range of electrolysers.

The performance of an electrolyser is defined by its electricity consumption (kWh/Nm^3), which varies at partial loads, and may be quoted at a range of percentage loads, and by its maximum hydrogen production rate (Nm^3/hour). The unit Nm^3 represents one normal cubic metre of hydrogen (measured at 0°C and 1 bar), which is equivalent to 3 kWh. The amount of water required is around one litre/Nm^3, and there is usually a minimum acceptable percentage load of around 25%. If the hydrogen produced is to be compressed or liquefied for storage, the energy required to do this must be taken into consideration, and this is also given in kWh/Nm^3. The performance of an electrolyser is not significantly affected by ambient temperature or altitude, and as it operates at ambient temperature, it does not require to run on standby. Little waste heat is produced, and this is not enough to be of use for CHP [27,28]. An example of the electrolyser definition window can be seen in Appendix 1, Figure A1.50.

5.7.1 Electrolyser Performance Algorithm

To determine the amount of hydrogen that may be produced, the amount of electricity available for use over each timestep must be known. Therefore, the rate at which electricity is available (kW) must be divided by the number of timesteps per hour to give the total amount of electricity available for use (kWh). The maximum amount of hydrogen that may be made over the timestep (Nm^3) must also be determined by dividing the maximum production rate by the number of timesteps per hour. From these, the amount of hydrogen that can actually be made, and the percentage load this would require, can be determined using Equations 5.41 and 5.42.

$$\text{Can Make} = \frac{\text{Electricity}}{\text{Consumption} + \text{Storage}} \tag{5.41}$$

$$\text{Percentage Load} = \frac{100 \times \text{Can Make}}{\text{Maximum}} \tag{5.42}$$

Where Can Make = Amount of hydrogen which can be made with the available electricity (Nm^3)

Electricity = Electricity available over that timestep (kWh)

Consumption = Electricity consumption at 100% load (kWh/Nm^3)

Storage = Energy required to put hydrogen into storage (kWh/Nm^3)

Maximum = Maximum amount of hydrogen that may be made during the timestep (Nm^3)

If the percentage load is less than the stated minimum load, the electrolyser is not run. If the percentage load is greater than 100%, the electrolyser is run at full load, and the electricity used, hydrogen made, and water used are calculated using Equations 5.43, 5.44 and 5.45.

$$\text{Electricity Used (kW)} = \text{Consumption} \times \text{Maximum} \times \text{Time} \tag{5.43}$$

$$\text{Hydrogen Made (kWh)} = \text{Maximum} \times 3 \tag{5.44}$$

$$\text{Water Used (litres)} = \text{Water} \times \text{Maximum} \tag{5.45}$$

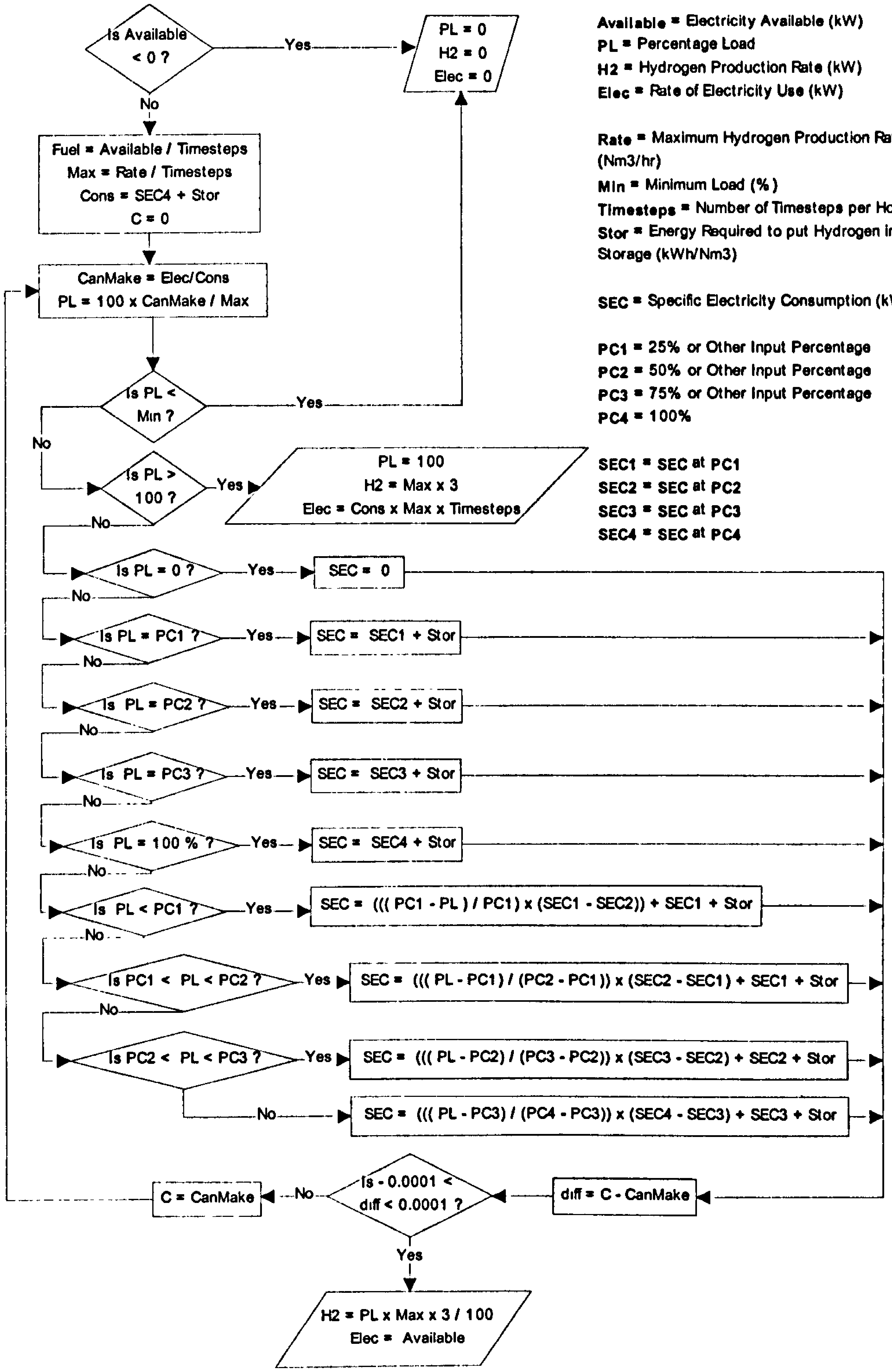
Where Time = Number of timesteps per hour

Water = Water required ($litre/Nm^3$)

1 Nm^3 of hydrogen = 3 kWh

If the percentage load is between minimum and maximum load, it is necessary to recalculate the amount of hydrogen that may be made (using the power consumption figure for the percentage load just calculated). This is because the original calculation of the amount of hydrogen that could be made with the available electricity used the power consumption rate at 100% load. The new power consumption figure at partial load may be found by interpolation between the part load percentage figures given. This process is repeated continuously, using the new percentage load calculated each time to ascertain the power consumption figure, until the difference between the current amount of hydrogen that can be made, and the new amount is negligible (e.g. less than 0.001). The new percentage load is then checked to see if it is below the minimum load, and, if not, the amount of hydrogen made is calculated by multiplying Equation 5.44 by the percentage load, and dividing by 100. All the electricity available is used, and the amount of water used is calculated by multiplying Equation 5.45 by the percentage load, and dividing by 100. This procedure is shown Graphically in Figure 5.21.

The output of this section to the matching stage is a graph of electrolyser percentage loading, a total amount of electricity and water used, and a total amount of hydrogen made. As the hydrogen is made, it is made available for use at that timestep, or stored for subsequent use by adding it to the available fuel profile in the same way that fuel used has been subtracted in other procedures.



Available = Electricity Available (kW)
PL = Percentage Load
H2 = Hydrogen Production Rate (kW)
Elec = Rate of Electricity Use (kW)

Rate = Maximum Hydrogen Production Rate (Nm3/hr)
Min = Minimum Load (%)
Timesteps = Number of Timesteps per Hour
Stor = Energy Required to put Hydrogen into Storage (kWh/Nm3)

SEC = Specific Electricity Consumption (kWh/Nm3)

PC1 = 25% or Other Input Percentage
PC2 = 50% or Other Input Percentage
PC3 = 75% or Other Input Percentage
PC4 = 100%

SEC1 = SEC at PC1
SEC2 = SEC at PC2
SEC3 = SEC at PC3
SEC4 = SEC at PC4

Figure 5.21 Electrolyser Algorithm

5.8 Regenerative Fuel Cell Model

A regenerative fuel cell is a fuel cell that may be run either as a fuel cell, or in reverse as an electrolyser. It is, essentially, a storage device, which takes in excess electricity and converts it to hydrogen, which it then stores in a tank until electricity is required, when the operation will reverse to create electricity from the stored hydrogen. A model for this can be created by amalgamating the fuel cell and electrolyser models, although extra consideration must be given to the amount of hydrogen storage that is available, and the initial storage level.

At the beginning of the procedure, the amount of hydrogen in the tank is calculated using the initial percentage storage level, and the maximum storage level. Then, at each timestep, it is determined whether there is a demand for or a supply of electricity. If there is a demand, the fuel cell model is employed as described in Section 5.6, using hydrogen from the dedicated storage rather than that available from the matching stage. The procedure checks to see if there is enough hydrogen available in the storage tank the same way as before, and the amount used is subtracted from the amount in the tank to give a new tank storage level. If there is a supply of electricity, the electrolyser model is used to determine the amount of hydrogen that may be produced, as described in Section 5.7, and this is added to the stored amount, taking care not to exceed the storage limitations. If the amount of hydrogen being produced will take the storage level over 100%, only the amount of hydrogen necessary to fill the tank will be produced, and the amount of electricity required to achieve this is calculated. If this would require the electrolyser to run below minimum load, no hydrogen is produced.

The output from this model is a graph of the percentage storage tank content, along with the amount of electricity produced, electricity used, heat produced, and water used. A regenerative fuel cell may be defined using the Fuel cell definition window, and an example of this can be seen in Appendix 1, Figure A1.39.

5.9 Instantaneous Space and Water Heating System Model

Space and water heating systems are provided here to allow the use of remaining fuels and excess electricity to help meet the demands for heat and hot water. Considered here are space heaters, which have an instantaneous action, instantaneous water heaters, and water heaters with some storage, which are capable of providing a full tank of hot water or more within a half hour period, depending on their rated power. Larger hot water storage systems will be considered later in this chapter.

This basic type of heating is simple to model, as efficiency of the plant does not vary significantly with partial load, and is not subject to minimum loads. This is due to the way in which a heating system is controlled – when the thermostatic control determines that heating is required, the heater is turned on at its full rated power, and turned off again when the correct temperature is reached. Therefore, the efficiency always remains the efficiency at rated power, and the heat supplied is the heat required. The information required to model instantaneous space or water heater performance is the number of heaters, their rated power and efficiency, and the type of fuel to be used. If a liquid fuel is being used, the lower heating value (kJ/kg) and density (kg/m^3) of the fuel are also required. The lower heating value only is required for a solid fuel. An example of the heating system definition window for this type of system can be seen in Appendix 1, Figure A1.49.

The maximum heat or hot water that may be supplied is equal to the rated power of the heater multiplied by the number of heaters. If demand is greater than this, there will be a residual demand, and the heaters will run at full load. If demand is less, the heater will supply only the required amount. The amount of fuel required is then calculated using Equations 5.33, 5.35 or 5.36 as appropriate, multiplied by the number of heaters. If there is not enough fuel, the amount of heat that can be supplied with the available fuel is calculated, and the user is alerted that there was not enough fuel to run the heater at the desired capacity. The profile shown on matching is a graph of percentage heater loading with time. Figure 5.22 gives a graphical representation of this procedure for a system following the heat demand. To follow the hot water demand, simply substitute the hot water required for the heat required.

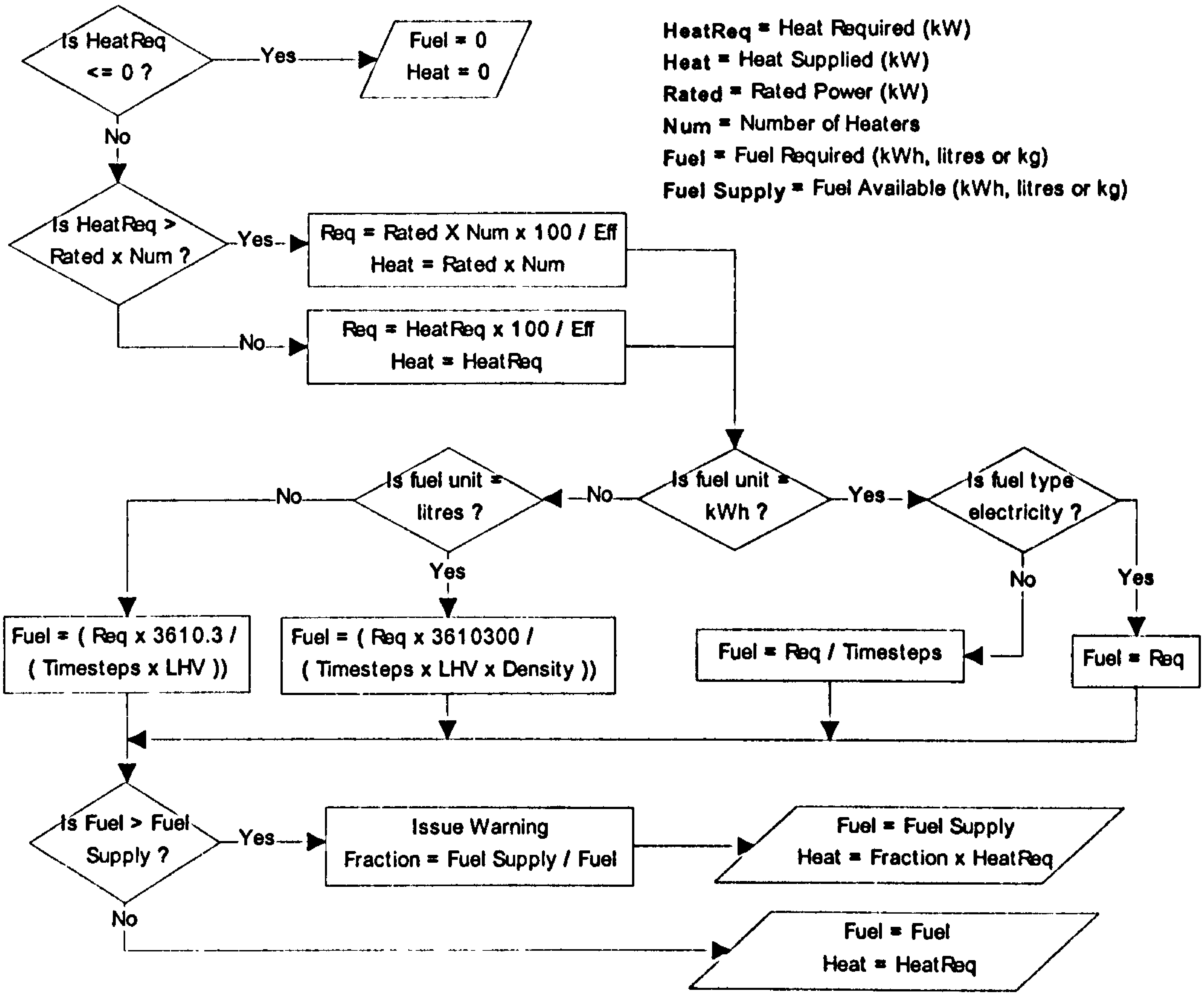


Figure 5.22 Instantaneous Heater Algorithm

5.10 Space Heating Storage Heater Model

Storage heaters have a rated capacity (kW), which limits the rate at which electricity may be converted to heat and stored in the bricks, and a maximum storage level (kWh). There is also a limit to the rate at which the heat may be given out from the bricks. This is generally given as a minimum length of time, in hours, for a full discharge of heat from the bricks [29]. A small amount of heat will be lost from the bricks over time, and the amount lost depends on the amount of heat stored. This heat loss may be quoted as the percentage of the heat stored that is lost per hour. Although this heat will be lost into the room, and will therefore serve some useful purpose in offsetting future heat demand, It will be assumed that this heating effect is negligible as it occurs at times when heating is not required. An example of the heating system definition window for a space heating storage heater can be seen in Appendix 1, Figure A1.48.

To calculate the performance of a storage heater, the initial and maximum storage levels must be given, and then, for each timestep, the algorithms outlined in Figure 5.23 and 5.24 must be followed.

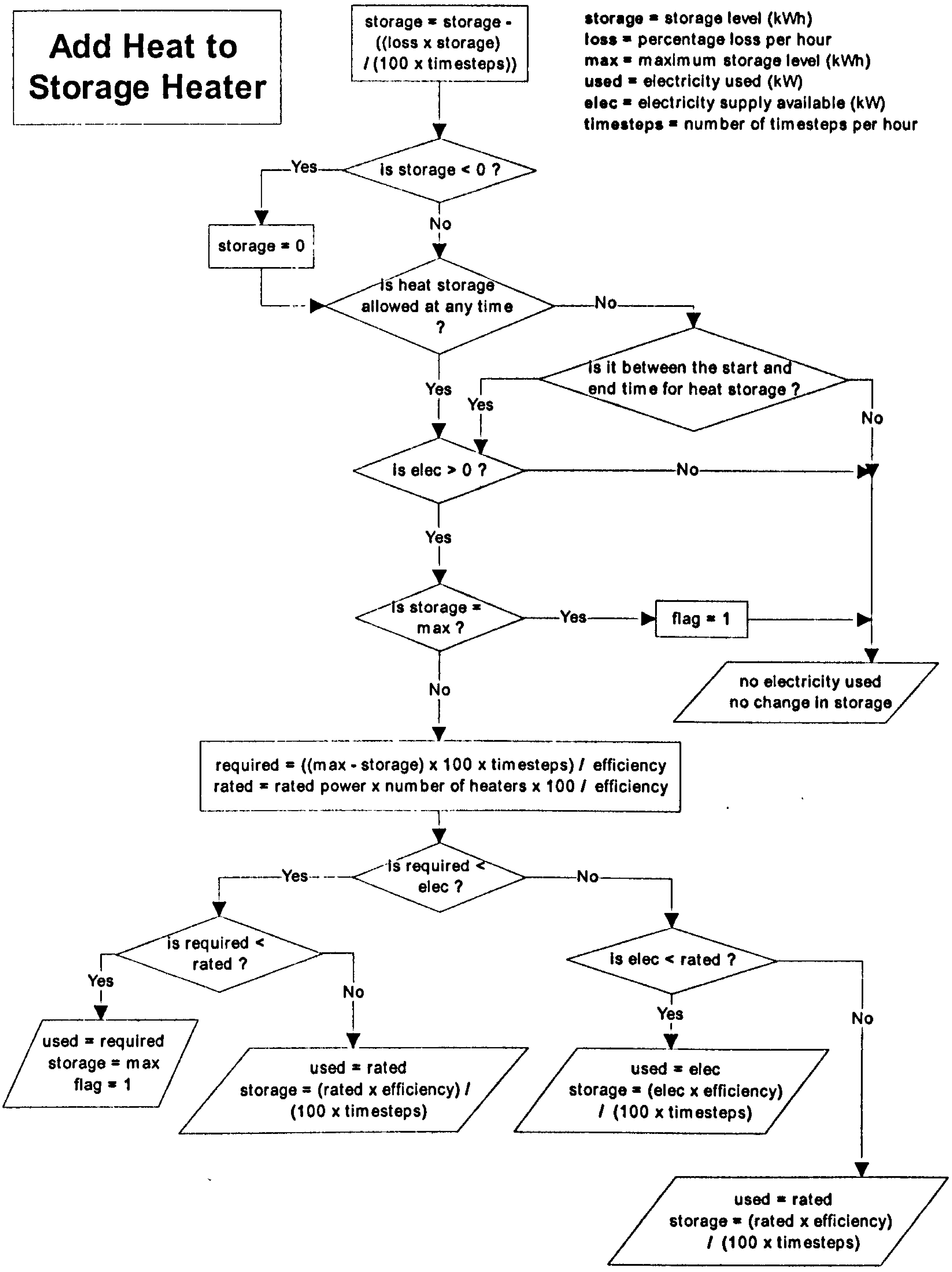


Figure 5.23 Algorithm for Adding Heat to a Storage Heater

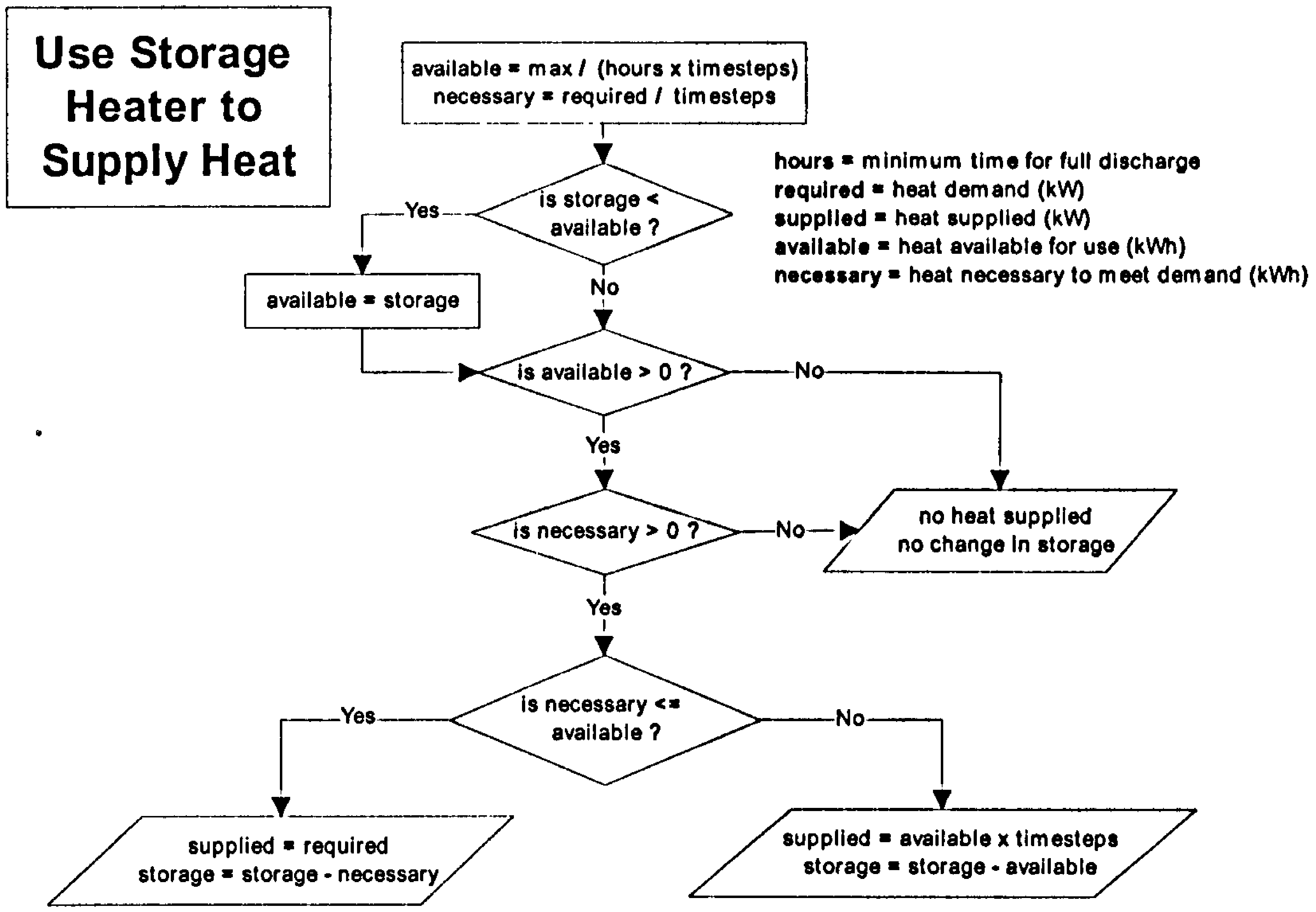


Figure 5.24 Algorithm for Using Stored Heat to Supply Heat Demand

If all the available or allowed electricity (rated power x number of heaters), whichever is least, has not been used (i.e. flag = 1), and the storage level is not at maximum, these two algorithms are repeated until one of these conditions has been met. This allows for simultaneous intake and supply of heat. Each time the procedure is repeated, the available electricity and allowed electricity must be reduced by the amount already used. The profile shown on matching is a graph of percentage heat stored with time. Information is also given about the total amount of electricity used, and the total amount of heat given out.

5.11 Hot Water Storage System Model

Hot water heating systems have been placed in this procedure as a separate model as they may then be used as an outlet for excess electricity from any source, to store excess heat from CHP systems or other sources for later use, or both (see Appendix 1, Figure A1.47). They may also be supplied by a dedicated fuelled heater, which runs continuously (see Appendix 1, Figure A1.46). This hot water may then be used to supply space heat, hot water or both in any size of system. If considering the supply of both heat and hot water, two tanks would be used in a real system – a closed loop system for space heating, and an open system to supply hot water. However, as water from one of these tanks would be used to heat the other tank, both tanks would come to the same temperature. Therefore, these two tanks may be treated as one equivalent tank with a combined storage capacity. As hot water storage systems may be used on any scale (from a small domestic system, to a large district heating system) this procedure will allow necessary tank sizes and rated outputs to be determined for a wide variety of different situations.

In a hot water storage system, it is necessary to know the temperature inside the tank for a number of reasons:

- hot water should be supplied at or above a given temperature (generally around 60°C) to ensure bacteria are not present,
- the water replacing the used hot water will be supplied at a fairly low temperature (typically around 10°C),
- there will be a maximum temperature above which water should not be stored or supplied (generally around 80°C),
- if stored water is at or below room temperature (generally around 20°C), it can not be used for space heating.

These temperatures must, therefore, be specified for a system.

However, as both the supply and demand for heat is given in kW, and tanks may be of varying sizes, the amount of heat stored in the hot water will be calculated in kWh. Equation 5.46 gives the heat stored in kJ.

$$\text{Heat Stored (kJ)} = m\,C_p\,\Delta T \tag{5.46}$$

where m = mass of water (kg)

C_p = specific heat capacity of water (kJ/kgK)

ΔT = temperature difference (K)

As 1 kWh = 3610.3 kJ, and using litres as the measure of volume of water stored in the tank, rather than kg as a measure of weight, the heat stored in kWh may be calculated using

$$\text{Heat Stored (kWh)} = \frac{V\,D\,C_p\,\Delta T}{3610.3} \tag{5.47}$$

where V = storage tank volume (litres)
D = density of water (kg/litre).

Using Equation 5.39, the threshold temperatures defined above may be expressed in their equivalent amount of stored heat for a given storage tank size. The water inlet temperature is taken as the lowest temperature that the tank will experience, and the amount of heat stored at this temperature is zero. Room temperature (below which heat can not be supplied to a room) is calculated as a heat stored equivalent by using Equation 5.47, where ΔT is equal to room temperature minus the water inlet temperature. To calculate the heat stored equivalent of the minimum hot water supply temperature, ΔT is equal to the minimum hot water supply temperature minus the water inlet temperature. To calculate the maximum amount of heat that may be stored in the tank, ΔT is equal to the maximum tank temperature minus the water inlet temperature. To calculate the initial heat storage level, ΔT is equal to the initial tank temperature minus the water inlet temperature. These threshold heat storage values are then used to decide whether or not heat may be added or supplied using the procedures outlined below.

Figure 5.25 outlines the algorithm for adding heat to the hot water storage tank using excess heat, electricity or both. It is assumed that, when waste heat is used to heat the stored water, that this is supplied at or above the maximum tank temperature. This allows all the available heat (in kWh) to be transferred to the tank, with no reduction in tank water temperature.

Some of the terms used in Figures 5.25 and 5.26 are explained below. As with electric space heating storage heaters, there will be some loss due to radiation from the storage tank. The scale of this loss depends on the level of insulation, and the temperature of the water in the tank. Again, this may be expressed as a percentage loss of heat stored over time, and only occurs if the water temperature is above room temperature.

storage = storage level (kWh)
loss = percentage loss from tank per hour (above room temperature)
max = maximum storage level (kWh)
HWCutOff = lowest storage level to allow hot water supply (kWh)
SHCutOff = lowest storage level to allow space heating supply (kWh)
heatused = heat used (kW)
elecused = electricity used (kW)
heat = heat supply available (kW)
elec = electricity supply available (kW)
timesteps = number of timesteps per hour
AtoW = hot air to water heat exchanger efficiency (%)
efficiency = electric water heater efficiency (%)

HWrequired = hot water demand (kW)
Heatrequired = heat demand (kW)
HWsupplied = hot water supplied to meet demand (kW)
Heatsupplied = heat supplied to meet demand (kW)
HWnecessary = hot water necessary to meet hot water demand (kWh)
Heatnecessary = hot water necessary to meet heat demand (kWh)

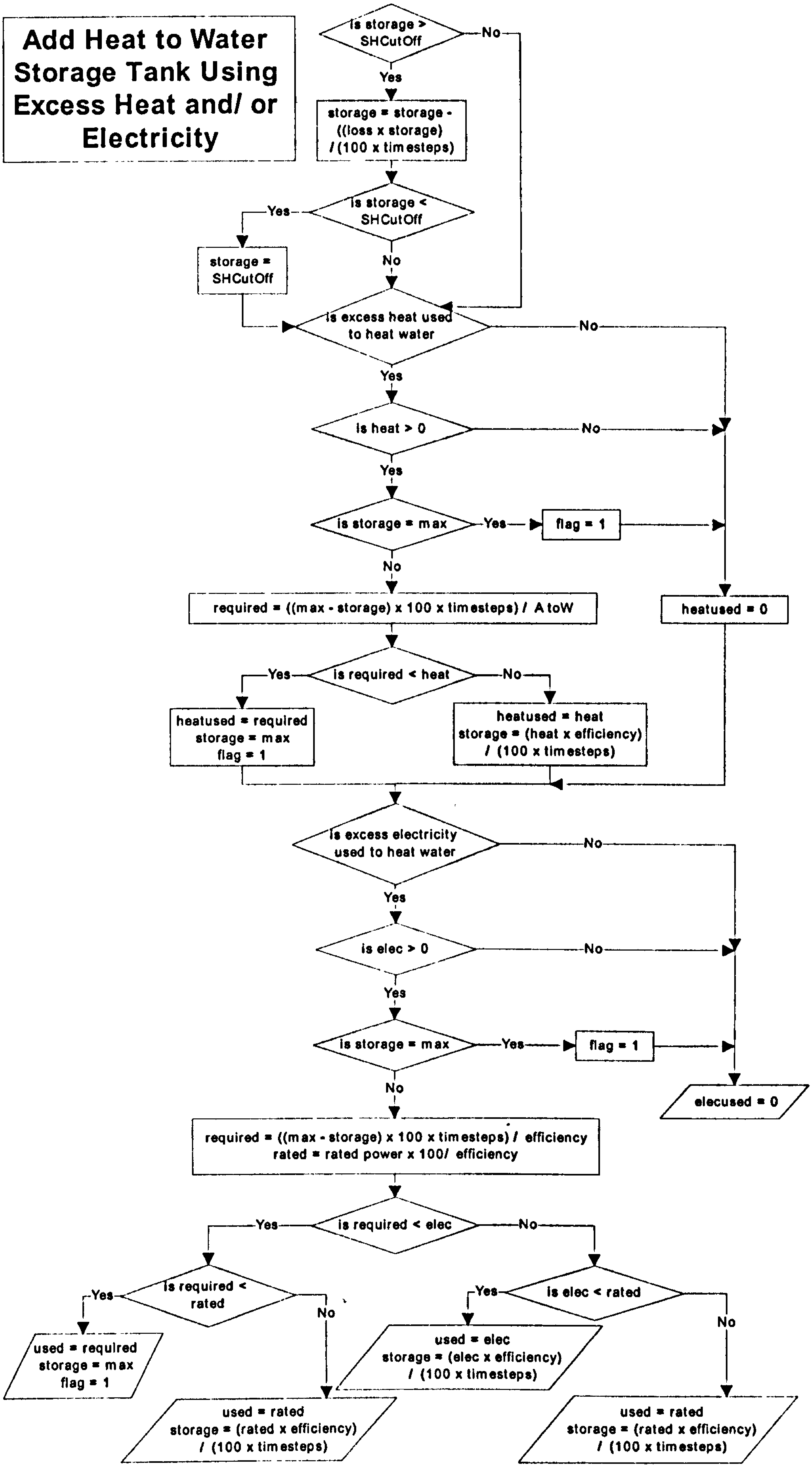


Figure 5.25 Stored Hot Water Heating Using Excess Heat or Electricity

If a dedicated supply is used, for example a straw fired boiler, which runs continuously despite demand, the heat lost from the tank is calculated as before. The actual fuel consumption required to run the heater at maximum capacity must then be determined. If electricity is being used, the required supply rate (kW) is calculated using Equation 5.48.

$$\text{Supply} = \frac{\text{Power} \times \text{Number} \times 100}{\text{Efficiency}} \tag{5.48}$$

where Supply = electricity supply rate (kW)
Power = heater rated power (kW)
Number = number of heaters
Efficiency = heater efficiency (%)

The actual required fuel consumption for gaseous, liquid and solid fuels may be calculated using Equations 5.33, 5.35 or 5.36 as appropriate, and multiplying the result by the number of heaters. If there is not enough fuel to run the heater at its rated capacity, the amount of heat which can be supplied with the available fuel is calculated, and the user is alerted that there was not enough fuel to run the heater at its maximum capacity.

The amount of heat being supplied is then added to the storage tank. If this causes the amount stored to go above the maximum level, the excess heat is wasted. This wasted heat is calculated by subtracting the maximum storage level from the new storage level, which is then set at maximum.

Whether using excess electricity and/or heat, or a dedicated supply, the stored hot water is then used to meet the demands for heat and/or hot water as desired. Figure 5.26 outlines this procedure.

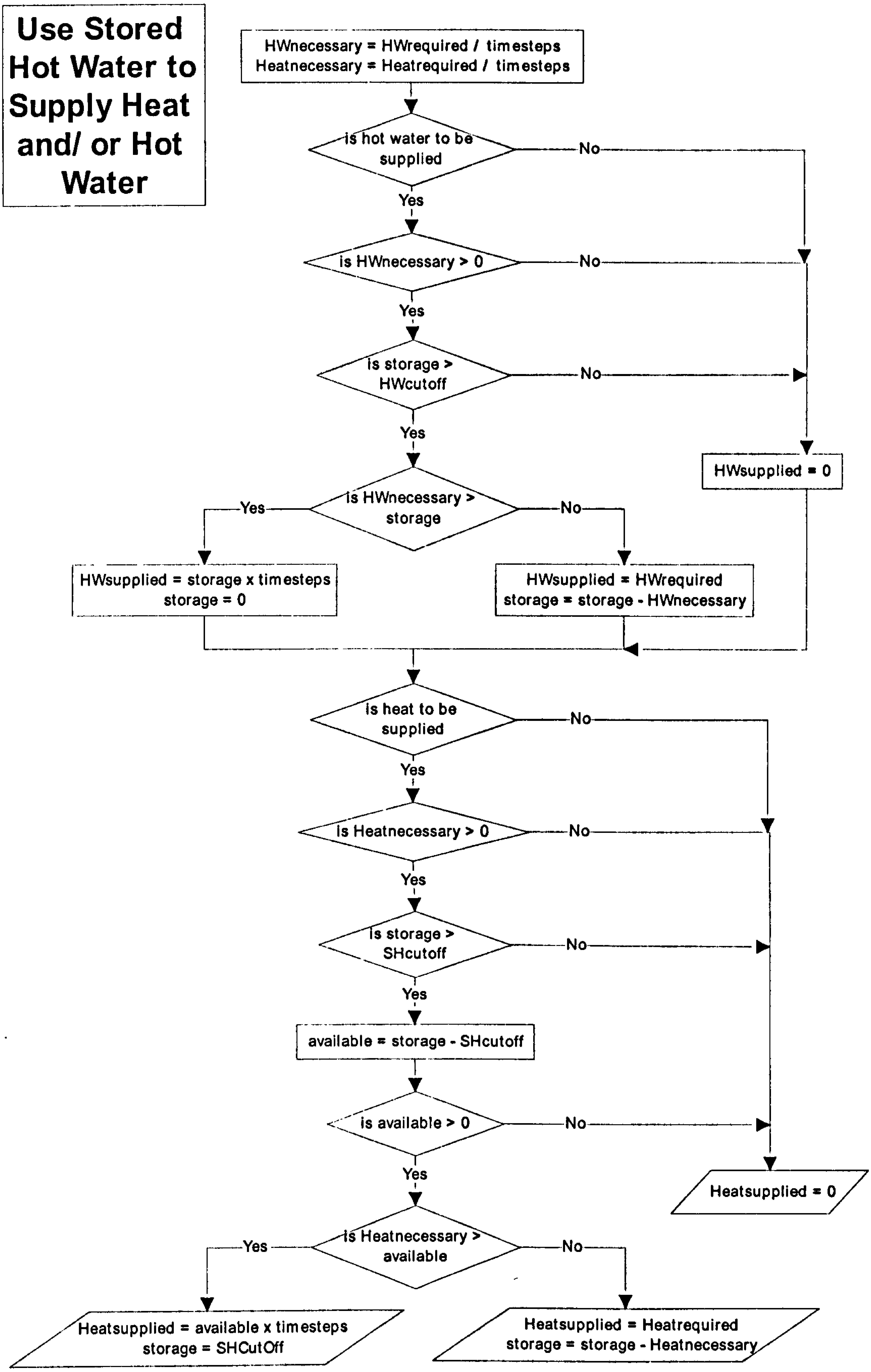


Figure 5.26 Using Stored Hot Water to Meet Heat and Hot Water Demands

If using excess electricity and/or heat, if all the allowed supply has not been used (i.e. flag = 1), and the storage level is not at maximum, the two processes outlined in Figures 5.25 and 5.26 are repeated until one of these conditions has been met. This allows for simultaneous production and supply. Each time the procedure is repeated, the available electricity, allowed electricity (rated value available), and available heat must be reduced by the amount already used.

If a dedicated supply is being used, the amount of waste heat that was produced, if any, is added to the storage value. If this is then greater then the maximum allowed storage value, the maximum value is subtracted from the storage value, and this becomes the new waste amount. If there is still a demand for heat and/or hot water to be met, the procedure shown in Figure 5.26 is followed again. This process continues until either there is no residual demand, or no more waste is being produced. This, again, is to allow for simultaneous production and supply.

The profile shown on matching is a graph of the tank water temperature with time. The water temperature may be calculated by re-arranging Equation 5.47 to give Equation 5.49.

$$T_{water} = \frac{H \times 3610.3}{V\,D\,C_p} - T_{inlet} \tag{5.49}$$

where T_{water} = water temperature (°C)

T_{inlet} = inlet temperature (°C)

H = heat stored (kWh)

V = storage tank volume (litres)

D = density of water (kg/litre)

C_p = specific heat capacity of water (kJ/kgK)

If using excess electricity and/or heat to supply the tank, information is given about the total amount of heat and/or electricity used, and also about the total amount of heat and/or hot water supplied. If a dedicated supply is used, information is given about the overall fuel consumption, the total heat and/or hot water supplied, and the total amount of heat wasted.

This chapter described the algorithms used to estimate the performance of various load following supplies, based on residual demand, supply and fuel availability information sent by the matching process. Chapter 6 describes the algorithms used to create fuel supply and related energy use profiles for specified derived fuels.

5.12 References

[1] Vehicle Certification Agency (VCA) "New Car Fuel Consumption and Emission Figures" January 2001, www.vca.gov.uk

[2] "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems" General Motors Corporation, Argonne National Laboratory, BP, Exxon Mobil and Shell, April 2001

[3] Accu Oerlikon Ltd, www.accuoerlikon.com

[4] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001

[5] European Electric Road Vehicle Association, www.avere.org

[6] "Ethanol as an aviation fuel", The International Energy Agency, CADDET, www.caddet.org

[7] R. VonWedel, "Technical handbook for marine biodiesel in recreational boats", CytoCulture Environmental Biotechnology, April 1999, www.cytoculture.com

[8] R. A. Proeschel, "Afterburning Ericsson Cycle Engine", Future Transportation Technology Conference and Exposition, Conta Mesa, California, August 17-19, 1999

[9] L. C. Wilbur, "Handbook of Energy Systems Engineering – Production and Utilisation" John Wiley & Sons 1985

[10] Volvo Penta, "Sales Guide – Generating Set Engines – 2001/2002", www.volvopenta.com

[11] Personal correspondence, Claire Kelly, Sales Department, Jenbacher AG, www.jenbacher.com

[12] Personal correspondence, Dr Stefan Schlag, Traffic and Environment, Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology

[13] Energy Efficiency Best Practice Programme, "A Technical and Economic Assessment of Small Stirling Engines for Combined Heat and Power", Energy Efficiency Office, Department of the Environment, January 1993, www.energy-efficiency.gov.uk, 0800 585794

[14] Gas Turbine Performance Specifications, Alstom Power, www.power.alstom.com

[15] Personal correspondence, Martin Prickett, Regional Sales Manager, Centrax Gas Turbines, www.centrax.eu.com

[16] Combined Cycle Turbine Performance Information, Alstom Power, www.power.alstom.com

[17] Joel B. Klein, "The Use of Heat Rates in Production Cost Modeling and Market Modeling", Electricity Analysis Office, California Energy Commission, April 17, 1998

[18] Personal correspondence, Samuel Fällman, Area Sales Manager, Industrial Steam Turbines, ALSTOM Power, Finspong, Sweden, www.power.alstom.com

[19] O. Ulleberg, S. O. Morner, "TRNSYS Simulation Models for Solar-Hydrogen Systems" Solar Energy, Vol. 59, No 4-6, pp. 271-279, 1997

[20] N. F. Bessette, W. J. Wepfer, "Prediction of Solid Oxide Fuel Cell Power System

Performance Through Multi-Level Modelling", Journal of Energy Resources Technology, Vol.117, pp. 307-317, December 1995

[21] J.C. Amphlett, R. M. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, "Performance Modelling of the Ballard Mark IV Solid Polymer Electrolyte Fuel Cell", J. Electrochem. Soc., Vol. 142, No.1, pp. 1-8, Jan 1995

[22] Personal correspondence, Edwin Foong, Marketing Manager, Ceramic Fuel Cells Ltd, www.cfcl.com.au

[23] K. Foger, B. Godfrey, "System Demonstration Program at Ceramic Fuel Cells Ltd in Australia", Fuel Cells 2000, Lucerne, Switzerland, 10-14 July 2000, www.cfcl.com.au

[24] S. W. Angrist, "Direct Energy Conversion", Fourth Edition, Allyn and Bacon Inc., 1982

[25] "PV-Hydrogen System Simulator", Solar Energy Laboratory, University of Wisconsin-Madison, sel.me.wisc.edu

[26] A. G. Dutton, J. A. M. Bleijs, H. Dienhart, M. Flachetta, W Hug, D. Prischich, A. J. Ruddell, " Experience in the design, sizing, economics and implementation of autonomous wind-powered hydrogen production systems", International Journal of Hydrogen Energy, 25 (2000), pp 705 - 722

[27] Personal correspondence, Liesbet Geboers, sales assistant, Hydrogen Systems, www.hydrogensystems.com

[28] Stuart Energy, www.stuartenergy.com

[29] Personal correspondence, Connie Aman, Regional Sales Manager, Steffes Corporation, www.steffes.com

6 Derived Fuel Production Algorithms

In this chapter the algorithms used to determine the outputs of the various biomass and waste processing procedures, introduced in Chapter 2, are described in detail. For each process considered, easily available manufacturers' data, feedstock availability, and basic process parameters are input. The algorithms step through each timestep of the chosen simulation period in turn, in order to build up a half-hourly profile, for the chosen simulation period, of the production rate of the derived fuel or fuels (in kg/hr for solid fuels, litres/hour for liquid fuels and kW for gases). Also produced is a half-hourly profile of the energy requirements for the process (for electricity, heat and hot water, in kW). Other significant inputs and outputs are also considered, and information is given about their overall use or production for the simulation period being considered.

Due to the complications with the transport demand profiles described in Chapter 4, any extra demand for transport arising from the processes described (e.g. transport of feedstock, agricultural vehicle use) should be defined separately. If a seasonal fuel production profile is defined, and the simulation being run is for less than a whole year, the user is warned that this may give rise to misleading results.

6.1 Gasification and Pyrolysis

Although complex models exist to predict the output of gasification and pyrolysis systems, these require substantial amounts of complex, proprietary, and not easily available information [1]. A more generic approach has, therefore, been taken, which is based on available manufacturers' information for specific systems with specific feedstocks. As process batches are short (generally less than 30 minutes) this process is treated as a continuous process. Only one feedstock type at a time is considered as different feedstocks can give significantly different results, even with the same equipment [2]. An example of the gasification and pyrolysis definition window is given in Appendix 1, Figure A1.14.

6.1.1 Feedstock Availability

If the feedstock supply is constant throughout the year (e.g. tyres, household waste) the feedstock availability is given as the amount available each day in kg. This amount is put into a store on the first timestep of each day, and is then available for use by the gasification or pyrolysis system as described in section 6.1.2. The amount in store at any given time is given in kg. A specified degradation rate (percentage loss of weight per day) is applied, where necessary, to whatever fuel is left in the store at the start of each day before any new fuel is added. This allows any weight loss of feedstock due to organic degradation to be taken into account. This will only occur with certain types of feedstock, and can be kept to a minimum by using appropriate storage methods. If any pre-processing of feed is required (e.g. shredding, chipping), the electricity required for this is calculated using Equation 6.1 or 6.2 as appropriate.

If pre-processing is carried out 24 hrs per day

$$\text{Electricity required (kW)} \quad = \quad \frac{\text{Feed} \;\; \text{x} \;\; \text{Elec}}{24} \qquad (6.1)$$

If pre-processing is carried out between specified times during each day

$$\text{Electricity required (kW)} \quad = \quad \frac{\text{Feed} \;\; \text{x} \;\; \text{Elec}}{\text{Hours}} \qquad (6.2)$$

Where Feed = Feedstock per day (kg/day)
Elec = Electricity required for process (kWh/kg feedstock)
Hours = Number of hours machine is working per day

For seasonal feedstock supplies (e.g. energy crops, agricultural waste), a harvest period is defined, and an even harvest is assumed across this period. The feedstock availability per day is calculated using Equation 6.3.

$$\text{Feedstock per day (kg/day)} = \frac{\text{Land} \times \text{Yield}}{\text{Days}} \qquad (6.3)$$

Where Land = Available land (ha)

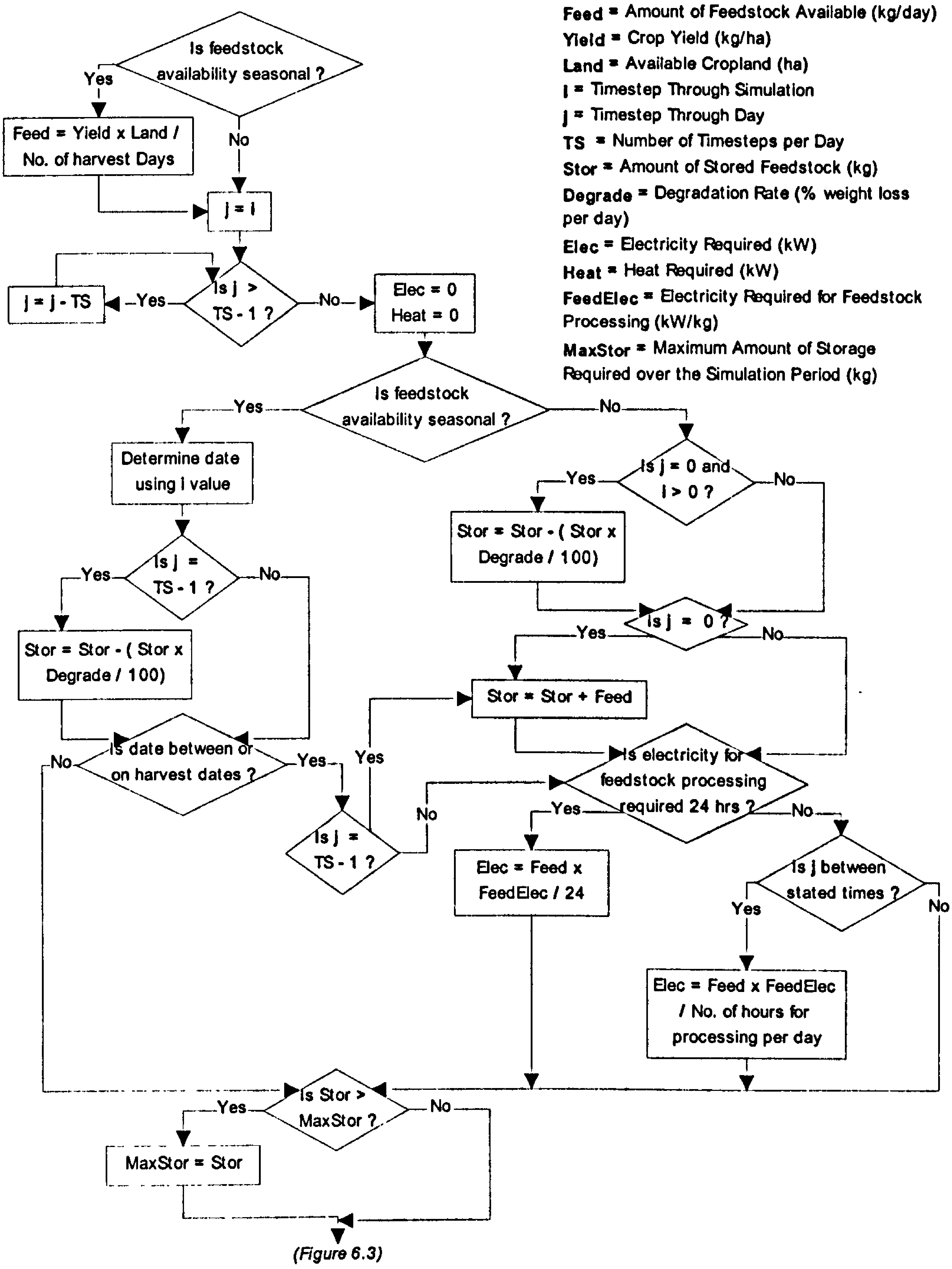
Yield = Crop Yield (kg/ha)

Days = Number of days in harvest period

This feedstock is put into a store on the last timestep of each day it is available, to allow for harvesting and feedstock processing, and, again, a degradation rate is applied, where appropriate, to any feedstock remaining in store before this new amount is added. The electricity required for feedstock pre-processing is calculated as before, and it is assumed that feedstock is processed, where necessary, as it is harvested, as this makes it easier to store, and often greatly reduces any possible degradation. If this is not the case, any required electricity demand can be added to the process requirements discussed in section 6.1.2. The algorithm dealing with the feedstock availability is shown in Figure 6.1. This is followed for each timestep in turn.

Although the fuel is only available to put into storage during the harvest period, it can be used from this store at a much slower rate, if desired, allowing fuel production beyond the harvest period. If there is excess feedstock left over in the store at the end of the simulation period, and this is more than the minimum required for the fuel production process, the entire simulation period is analysed again, in the same manner, but starting with the excess stored amount of feedstock available for processing. Using the results from this second simulation period allows the inclusion of fuel derived from feedstock remaining at the end of the first period. This is shown in Figure 6.2, where the feedstock remaining at the end of the year, from the June to September harvest, continues to be available into the next year, until finally running out in April. If there continues to be an excess of feedstock at the start of the next harvest period, the process will not be able to exceed its maximum feed rate, so there will continue to be an excess of feedstock, and production will be constant throughout the year. Care should be taken to match the feedstock availability to the process feedstock feed rate (kg/hr), either to ensure that all of the available feedstock is being used each day for a continuous supply, or that the feedstock availability is stretching across the desired time period for seasonal supplies.

Along with the graph of fuel production over time, information is given about the amount of unprocessed feedstock remaining at the end of the simulation, and the maximum amount of feedstock that has required storage at any one time throughout this period. Again, when using seasonal supplies, it is misleading to simulate anything less than a year.



Feed = Amount of Feedstock Available (kg/day)
Yield = Crop Yield (kg/ha)
Land = Available Cropland (ha)
i = Timestep Through Simulation
j = Timestep Through Day
TS = Number of Timesteps per Day
Stor = Amount of Stored Feedstock (kg)
Degrade = Degradation Rate (% weight loss per day)
Elec = Electricity Required (kW)
Heat = Heat Required (kW)
FeedElec = Electricity Required for Feedstock Processing (kW/kg)
MaxStor = Maximum Amount of Storage Required over the Simulation Period (kg)

Figure 6.1 Gasification and Pyrolysis Feedstock Availability Algorithm

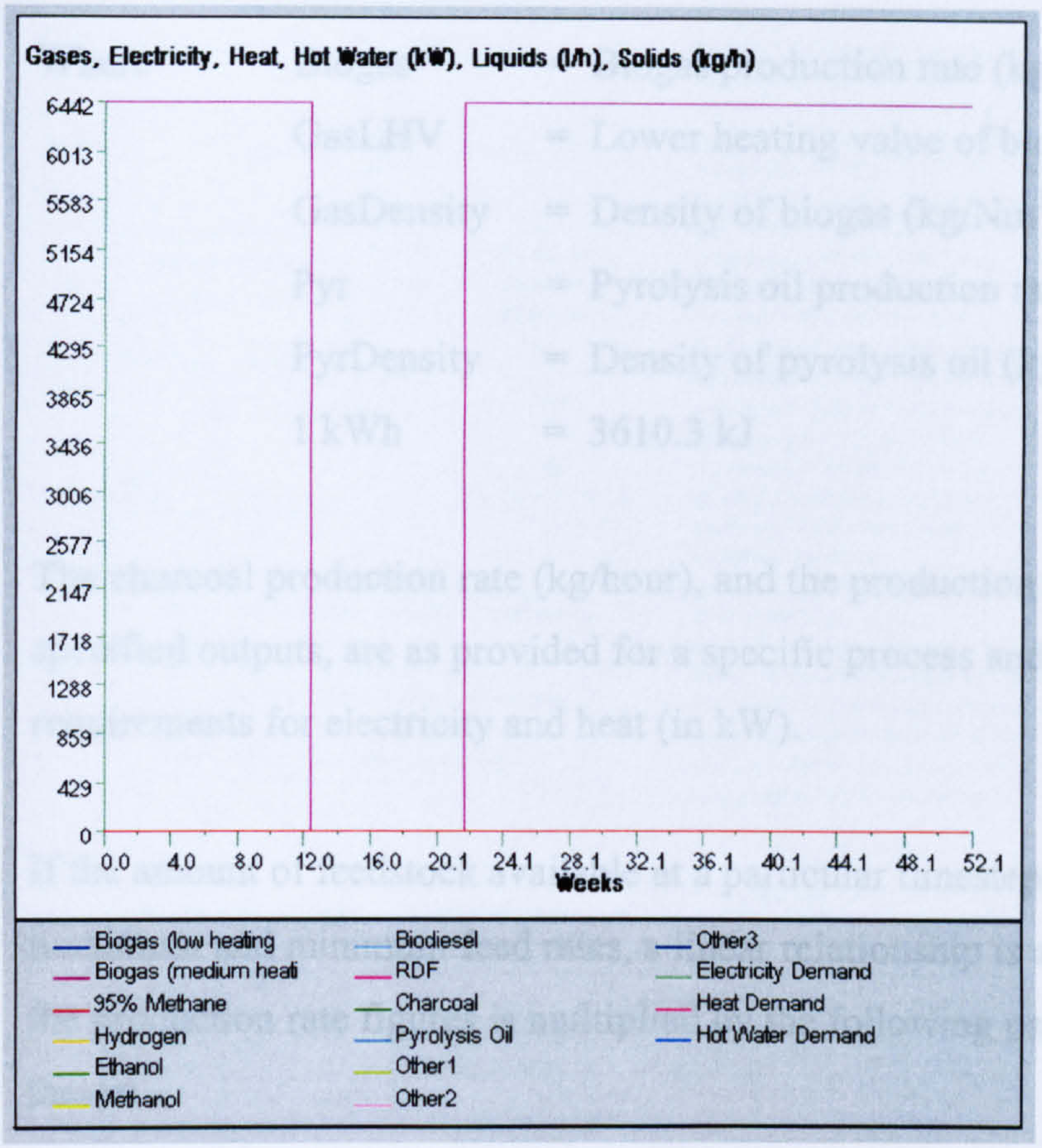


Figure 6.2 Seasonal Biogas Supply

6.1.2 Process Characteristics

The continuous gasification or pyrolysis process may be run either twenty-four hours per day, or between a specific start and end time each day. If the timestep being considered falls within an operating period, and there is enough feedstock in store to allow operation, the production rates (in kg/hr) for biogas, pyrolysis oil and charcoal are calculated from available information for a specific process and feedstock. If more feedstock is available than the maximum feed rate for that time period (maximum feed rate per hour / number of timesteps per hour),

$$\text{Biogas Production Rate (kW)} = \frac{\text{Biogas} \times \text{GasLHV}}{\text{GasDensity} \times 3610.3} \qquad (6.4)$$

$$\text{Pyrolysis Oil Production Rate (litres/hour)} = \frac{\text{Pyr} \times 1000}{\text{PyrDensity}} \qquad (6.5)$$

Where Biogas = Biogas production rate (kg/hr)
GasLHV = Lower heating value of biogas (kJ/Nm^3)
GasDensity = Density of biogas (kg/Nm^3)
Pyr = Pyrolysis oil production rate (kg/hr)
PyrDensity = Density of pyrolysis oil (kg/m^3)
1 kWh = 3610.3 kJ

The charcoal production rate (kg/hour), and the production rates of any other specified outputs, are as provided for a specific process and feedstock, as are the requirements for electricity and heat (in kW).

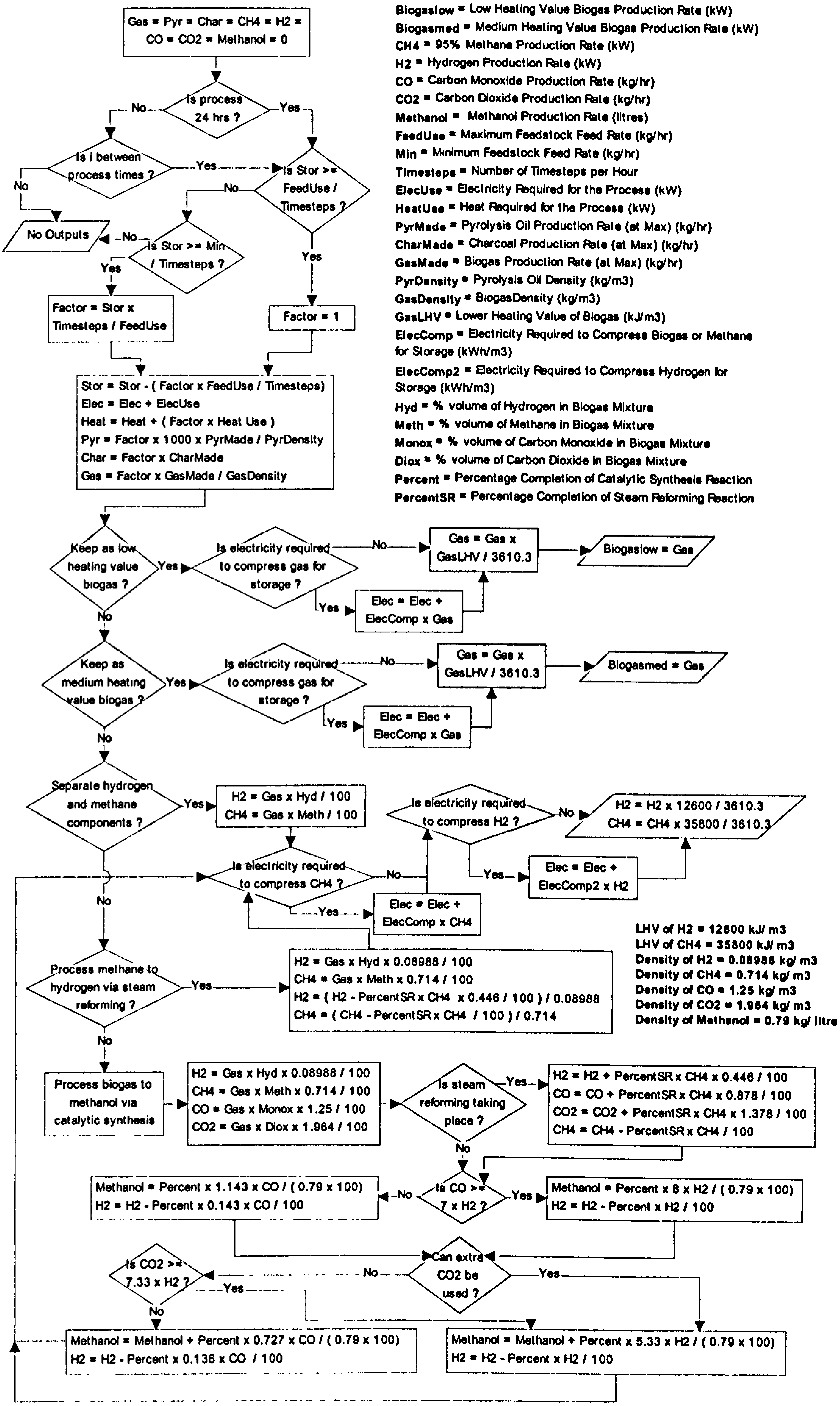
If the amount of feedstock available at a particular timestep is between the maximum and minimum feed rates, a linear relationship is assumed, and each of the production rate figures is multiplied by the following partial production factor: -

$$\text{Partial Production Factor} = \frac{\text{Feed} \times \text{Timesteps}}{\text{FeedRate}} \qquad (6.6)$$

Where Feed = Amount of feedstock available (kg)
Timesteps = Number of timesteps per hour
FeedRate = Feedstock feed rate (kg/hr).

The heat requirement is also multiplied by this factor, as this will vary with the amount of feedstock. The electricity requirement, however, is not reduced, as this will remain the same, despite the reduction in feedstock. When used, the amount of feedstock left in the store is reduced accordingly, and a tally is kept of the overall feed used (kg), outputs made and heat and electricity required (kWh). This information is displayed along with the final output graph.

This procedure is shown graphically in Figure 6.3, where each timestep is considered in turn, in order to determine the fuel production rates for the different fuels being produced, and the related energy requirements.



Biogaslow = Low Heating Value Biogas Production Rate (kW)
Biogasmed = Medium Heating Value Biogas Production Rate (kW)
CH4 = 95% Methane Production Rate (kW)
H2 = Hydrogen Production Rate (kW)
CO = Carbon Monoxide Production Rate (kg/hr)
CO2 = Carbon Dioxide Production Rate (kg/hr)
Methanol = Methanol Production Rate (litres)
FeedUse = Maximum Feedstock Feed Rate (kg/hr)
Min = Minimum Feedstock Feed Rate (kg/hr)
Timesteps = Number of Timesteps per Hour
ElecUse = Electricity Required for the Process (kW)
HeatUse = Heat Required for the Process (kW)
PyrMade = Pyrolysis Oil Production Rate (at Max) (kg/hr)
CharMade = Charcoal Production Rate (at Max) (kg/hr)
GasMade = Biogas Production Rate (at Max) (kg/hr)
PyrDensity = Pyrolysis Oil Density (kg/m3)
GasDensity = BiogasDensity (kg/m3)
GasLHV = Lower Heating Value of Biogas (kJ/m3)
ElecComp = Electricity Required to Compress Biogas or Methane for Storage (kWh/m3)
ElecComp2 = Electricity Required to Compress Hydrogen for Storage (kWh/m3)
Hyd = % volume of Hydrogen in Biogas Mixture
Meth = % volume of Methane in Biogas Mixture
Monox = % volume of Carbon Monoxide in Biogas Mixture
Diox = % volume of Carbon Dioxide in Biogas Mixture
Percent = Percentage Completion of Catalytic Synthesis Reaction
PercentSR = Percentage Completion of Steam Reforming Reaction

LHV of H2 = 12600 kJ/ m3
LHV of CH4 = 35800 kJ/ m3
Density of H2 = 0.08988 kg/ m3
Density of CH4 = 0.714 kg/ m3
Density of CO = 1.25 kg/ m3
Density of CO2 = 1.964 kg/ m3
Density of Methanol = 0.79 kg/ litre

Figure 6.3 Gasification and Pyrolysis Algorithm

6.1.3 Use of Biogas

Various options are available for the use of the biogas produced. The algorithms described are shown graphically in Figure 6.3.

1. Keep as a low or medium heating value biogas

The biogas production rate is calculated using Equation 6.4 (applying the partial production factor as necessary), which calculates the rate of production of biogas by measuring its energy content (kW). If this gas is to be put into storage, the electricity required to do this is calculated using,

$$\text{Electricity Required (kW)} = \frac{\text{Biogas} \times \text{Elec}}{\text{GasDensity}} \qquad (6.7)$$

Where Biogas = Biogas production rate (kg/hr)

Elec = Electricity to compress or liquefy biogas (kWh/Nm^3)

GasDensity = Density of biogas (kg/Nm^3).

2. Separate the hydrogen and methane components

The composition of the biogas produced from a specific process and feedstock is generally quoted as the percentage, by volume, of specific important gases in the total mixture. The amount of a specified gas in the mixture is, therefore, calculated using Equation 6.8, and the electricity required to put either or both gases into storage, if required, is calculated using Equation 6.9. The partial production factor is applied as necessary.

$$\text{Specified Gas Production Rate (kW)} = \frac{\text{Biogas} \times \text{Percentage} \times \text{LHV}}{\text{GasDensity} \times 100 \times 3610.3} \qquad (6.8)$$

$$\text{Electricity Required (kW)} = \frac{\text{Biogas} \times \text{Percentage} \times \text{Elec}}{\text{GasDensity} \times 100} \qquad (6.9)$$

Where Biogas = Biogas production rate (kg/hr)

Percentage = Percentage of specified gas in mixture (by volume)

LHV = Lower heating value of specified gas (kJ/Nm^3)
GasDensity = Density of biogas (kg/Nm^3)
Elec = Electricity to compress or liquefy biogas (kWh/Nm^3)

The total amounts of hydrogen and methane produced throughout the simulation period are given along with the final production rate graphs. Any excess energy requirements arising from the separation process may be added to the overall process energy requirements considered in section 6.1.2.

3. Make hydrogen, from the methane component, via steam reforming

Hydrogen may be made, via the steam reforming of methane, according to the following chemical equation: -

$$2CH_4 + 3H_20 \longrightarrow CO + CO_2 + 7H_2$$

$$64\ \text{kg}\ CH_4 + 108\ \text{kg}\ H_20 \longrightarrow 56\ \text{kg}\ CO + 88\ \text{kg}\ CO_2 + 28\ \text{kg}\ H_2$$

By considering the molecular weights of each component, it can be determined that 64 kg of methane are required to produce 28 kg of hydrogen. In practice, however, this reaction will not go to completion, so a completion percentage must be applied [3].

To determine the total amount of hydrogen that is made, the rates of production by weight (in kg/hr) of hydrogen and methane are calculated using Equation 6.10, and the partial production factor is applied as necessary.

$$\text{Specified Gas Production Rate (kg/hr)} = \frac{\text{Biogas} \times \text{Percentage} \times \text{Density}}{\text{GasDensity} \times 100} \qquad (6.10)$$

Where Biogas = Biogas production rate (kg/hr)
Percentage = Percentage of specified gas in mixture (by volume)
Density = Density of specified gas (kg/Nm^3)
GasDensity = Density of biogas (kg/Nm^3)

The amount of hydrogen that can be produced from this weight of methane is calculated by direct proportion, using the weights given in the above chemical equation, and the completion percentage is applied to find the weight actually produced. This is then added to the weight of hydrogen already in the biogas mixture to determine the total hydrogen production rate in kg/hr. If desired, the weight of methane remaining can also be calculated by direct proportion, in the same manner as for hydrogen, and the percentage applied should be 100 minus the completion percentage.

The production rate of hydrogen and methane (in kW) is calculated using Equation 6.11, and the electricity required to put either or both gases into storage is calculated using Equation 6.12.

$$\text{Specified Gas Production Rate (kW)} = \frac{\text{Gas} \times \text{LHV}}{\text{Density} \times 3610.3} \qquad (6.11)$$

$$\text{Electricity Required (kW)} = \frac{\text{Gas} \times \text{Elec}}{\text{Density}} \qquad (6.12)$$

Where Gas = Specified gas production rate (kg/hr)
LHV = Lower heating value of specified gas (kJ/Nm^3)
Density = Density of specified gas (kg/Nm^3)
Elec = Electricity to compress or liquefy specified gas (kWh/Nm^3)

Again, the total amount of hydrogen, and methane if desired, produced throughout the simulation period is given along with the final production rate graphs. The heat required to raise the steam necessary for this process may be added to the overall process energy requirements considered in section 6.1.2.

4. Make methanol, via catalytic conversion

As the biogas mixture produced will typically contain a mixture of hydrogen, carbon dioxide and carbon monoxide, this allows the production of methanol, via catalytic conversion, according to the following chemical equations [3]: -

$$CO + 2H_2 \longrightarrow CH_3OH$$

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

That is

$$56\text{ kg } CO + 8\text{ kg } H_2 \longrightarrow 64\text{ kg } CH_3OH$$

$$88\text{ kg } CO_2 + 12\text{ kg} H_2 \longrightarrow 64\text{ kg } CH_3OH + 36\text{ kg } H_2O$$

Further hydrogen, carbon monoxide and carbon dioxide for these reactions may also be derived from the methane content of the biogas if desired, via steam reforming as described previously. The production rates by weight (in kg/hr) of hydrogen, and the other gases, are determined as described previously, and the extra gases produced via steam reforming of methane are added to these if desired. The methanol production reactions will not, in practice, go to completion so a completion percentage must, again, be applied.

Firstly the amount of methanol that can be derived from the carbon monoxide and hydrogen present is determined. If there is excess carbon monoxide (i.e. there is more than 7 (56 divided by 8) times the weight of hydrogen), the amount of methanol produced (in kg/hr) is calculated, using direct proportion, from the weight of hydrogen present. If there is excess hydrogen, the weight of methanol produced is calculated, using direct proportion, from the weight of carbon monoxide present. In either case, the completion percentage is applied, and the remaining weight of each gas is determined.

The weight of methanol that can be derived from the carbon dioxide and hydrogen present is then determined, and added to the previous amount, in the same manner, using the second chemical equation. It is common practice to introduce extra carbon dioxide into this reaction in order to increase the hydrogen use. If this is desired, the weight of methanol that can be made from the hydrogen present is calculated, from the second chemical equation, using direct proportion, and the weight of extra CO2 required is determined. The completion percentage must, again, be applied.

The production rate of methanol in litres/hr is calculated by dividing the production rate (in kg/hr) by the density of methanol (in kg/m^3), and multiplying by 1000. The production rate of any remaining hydrogen and methane (in kW) is calculated using Equation 6.11, and the electricity required to put either or both gases into storage, if desired, is calculated using Equation 6.12.

Again, the total amount of methanol, hydrogen and methane produced, and the amount of extra carbon dioxide used throughout the simulation period, is given along with the final production rate graphs. Any excess energy requirements arising from this process may be added to the overall process energy requirements considered in section 6.1.2.

6.1.4 General Comments

Many pyrolysis and gasification systems are linked directly with combined heat and power (CHP) production plants as the waste heat that these produce can be used for the fuel production process, allowing a high degree of process integration, maximising efficiency [2]. As it may be difficult to separate the process outputs and energy requirements of such plant, it is also possible to model their operation using the generic engine/turbine model described in Chapter 5. An example of the definition window for such a system is shown in Appendix 1, Figure A1.36. In order to do this, the rated electrical output, heat to electricity ratio, and efficiency at partial load must be known. Direct wood gasifier stoves may also be modelled as heating systems.

Some or all of the required process heat and electricity is often derived from a portion of the output fuel. If this is the case, these outputs, and the corresponding energy demands, can be subtracted from the totals input into the simulation.

As the lower heating value of the pyrolysis oil produced from the pyrolysis of plastic and tyres is significantly higher than that of the oil produced from wood, the option is available to change the pyrolysis oil type to one of the 'other' categories for the occasion where these two different pyrolysis feedstock types are desired.

6.2 Anaerobic Digestion

Existing models are available which predict the output of anaerobic digestion systems. These, however, either require substantial amounts of complex, proprietary, and not easily available information, or look only at the overall production for a year, not taking into account possible changes in feedstock type and amount [4]. Therefore, a more generic and flexible approach has again been taken, which is based on basic process parameters and typical feedstock performances. An example of the anaerobic digestion definition window is given in Appendix 1, Figure A1.15. A graphical representation of the algorithm described in this section can be seen in Figure 6.4, where each timestep value is input in turn.

6.2.1 Process Characteristics

The anaerobic digestion process is, by its nature, a continuous process, where feedstock is introduced periodically (generally daily) and resides in the digester for 10 to 40 days while the digestion process takes place. Over this retention time, biogas is given off at a steady rate, which is defined by the volume of biogas given off during this period per tonne of feedstock. The required retention time varies with the operating temperature of the digester, but the overall amount of gas that is produced per tonne of feedstock will remain the same, though this will vary with different feedstock types [5].

As the digester should remain active where possible, and as different types and amounts of feed may be available at different times of the year, up to five different feedstock supplies may be specified. These are defined by how much feedstock is available (tonnes per day), how much biogas the feedstock will produce in total (Nm^3 per tonne feedstock), and what dates it is available between. The required retention time, and either the percentage of methane in the biogas produced, or the lower heating value of the biogas (kJ/Nm^3) must also be given. Feedstock cannot be kept in store for times of low or no production, as it will degrade too quickly.

For each feedstock availability time period specified, if the digester has been running with the same level of input, for that particular feedstock, for longer than the retention time, then the volume of biogas produced at a particular timestep may be calculated using Equation 6.13.

$$\text{Biogas Produced (Nm}^3) = \frac{\text{Biogas} \times \text{Feed}}{24 \times \text{TS}} \qquad (6.13)$$

Where Biogas = Biogas produced (Nm^3/tonne feedstock)
Feed = Feedstock available (tonnes per day)
TS = Number of timesteps per hour

If it is the first timestep introducing the new feedstock, the amount of biogas produced is zero, and the amount of biogas produced at each subsequent timestep, until the retention time is reached, is equal to the previous timestep production value from that feedstock, plus the following incremental production increase,

$$\text{Production Increase (Nm}^3) = \frac{\text{Biogas} \times \text{Feed}}{24 \times \text{TS} \times 24 \times \text{TS} \times \text{Retention}} \qquad (6.14)$$

Where Retention = Retention time (days).

When the end of the specific feedstock availability time has been reached, the amount of biogas produced is decreased incrementally, at each timestep, by the same amount, until the retention time is reached.

If the first day of feedstock availability is the first day of the year, or fuel availability has been specified as continuous, then it is assumed that full production is carried on from the previous period, and no build up time is required. If the simulation period starts in the middle of the build up time, then the amount of biogas produced at the first timestep is calculated by multiplying Equation 6.14 by the number of days elapsed since the start of the fuel availability time period, and the amount produced at each subsequent time step is increased incrementally as before. This should not happen, however, as it is not realistic to model seasonal supplies over anything less than a full year.

This process is carried out for each specific feedstock availability time period, and the amount of biogas produced from each period, for each timestep, is added together to determine the total biogas (Nm^3) output for each timestep.

The amount of fertiliser made over the simulation period may be calculated using Equation 6.15, and this information is given, along with the overall electricity and heat use, with the final production rate graphs.

$$\text{Fertiliser Made (kg)} = \text{Feed} - (\text{Biogas} \times \text{Density}) \qquad (6.15)$$

Where Feed = Total feedstock added to digester (kg)
Biogas = Total biogas produced (Nm^3)
Density = Density of biogas (kg/Nm^3)

6.2.2 Energy Requirements

The electricity requirements for the anaerobic digestion process can be split into two components. If energy is required for mixing the contents of the digester, this is required constantly, and is not a function of the amount of feedstock being input. This electricity requirement is, therefore, specified directly in kW, and is added directly to the timestep electricity demand. Electricity for fuel pre-processing and pumping will be required only at specific times during the day, before and during feedstock input. This is calculated using Equation 6.16, and added to the timestep electricity requirement if it falls within the specified operating times.

$$\text{Electricity (kW)} = \frac{\text{Elec} \times \text{Feed}}{\text{Hours}} \qquad (6.16)$$

Where Elec = Electricity required (kWh/tonne feedstock input)
Feed = Total feedstock input (tonnes per day)
Hours = Number of operating hours per day

If the contents of the digester are being heated, this heat is required, constantly throughout the days of the feedstock availability period plus a time equal to the retention time after feedstock input has finished. This heat requirement is calculated using Equation 6.16, using the heat required instead of electricity required, and 24 as the number of operating hours. If feedstock heating is being used, heat is required only during specified times before the feedstock is input. This heat requirement is, again, calculated using Equation 6.15, substituting the heat requirement for the electricity requirement. The use of well-insulated tanks ensures that the performance of the digester and its energy requirements are not significantly affected by ambient temperature [6].

6.2.3 Use of Biogas

The biogas produced from this process typically contains 60% methane and 40% carbon dioxide, though these amounts may vary. Again, various options are available for the use of the biogas produced, though the processes involved are slightly different to those used after gasification, due to the difference in biogas composition.

1. Keep as a medium heating value biogas

The biogas production rate for each timestep is calculated using Equation 6.17, and the electricity required to put the gas into storage, if required, is calculated using Equation 6.18.

$$\text{Biogas Production Rate (kW)} = \frac{\text{Biogas} \times \text{TS} \times \text{LHV}}{3610.3} \tag{6.17}$$

$$\text{Electricity Required (kW)} = \text{Biogas} \times \text{Elec} \times \text{TS} \tag{6.18}$$

Where Biogas = Biogas produced (Nm^3)
LHV = Lower heating value of biogas (kJ/Nm^3)
TS = Number of timesteps per hour
Elec = Electricity to compress or liquefy biogas (kWh/Nm^3)

The total amount of biogas produced (kWh) throughout the simulation period is given along with the final production rate graphs.

2. Upgrade biogas to 95% methane

To allow use in vehicles and certain other plant, the carbon dioxide content of the biogas mixture must be reduced to give 95% methane content (equivalent to natural gas). The energy content of the gas remains the same, and is calculated using Equation 6.17. Electricity, however, is required to process the gas, and this is calculated using Equation 6.18, with Elec equal to the amount of electricity required to process the gas. If the gas is to be compressed or liquefied for storage, the electricity required is calculated using Equation 6.18. Again, total amount of biogas produced (kWh) throughout the simulation period is given along with the final production rate graphs.

3. Make hydrogen via steam reforming

The methane production rate by weight (in kg/hr) is determined using Equation 6.19.

$$\text{Methane Production Rate (kg/hr)} = \frac{\text{Biogas} \times 3610.3}{\text{LHV}} \qquad (6.19)$$

Where Biogas = Biogas production rate (kW) (from Equation 6.17)
LHV = Lower heating value of methane (kJ/Nm^3).

Hydrogen may be made, via the steam reforming of methane, according to the chemical equation given in section 6.1.3, and the production rate of hydrogen, by volume (in Nm^3/hr) is calculated by direct proportion,

$$\text{Hydrogen Production Rate (Nm}^3\text{/hr)} = \frac{28 \times \text{Methane} \times \text{Percent}}{64 \times \text{Density} \times 100} \qquad (6.20)$$

Where Methane = Methane Production Rate (kg/hr)
Percent = Reaction Completion Percentage
Density = Density of Hydrogen (kg/Nm^3)

If desired, the remaining production rate of methane (in Nm^3/hr) can be calculated by dividing the remaining methane production rate by the density of methane. To determine the production rates of both of these gases in kW, multiply the production rate in Nm^3/hr by the lower heating value of the gas in kJ/Nm^3, and divide by 3610.3.

The electricity required to put either or both gases into storage is calculated by multiplying the amount of gas made (in Nm^3) by the electricity required (in kWh/Nm^3). Electricity and heat requirements for the process are calculated by multiplying the specific energy requirements (kWh/Nm^3 methane) by the methane production rate (Nm^3/hr). The total amount of hydrogen produced (kWh) throughout the simulation period is given along with the final production rate graphs.

4. Make methanol via catalytic conversion

The two-stage process of converting methane to methanol is characterised by the following chemical equation when no carbon dioxide is available [3],

$$2CH_4 + 2H_2O \longrightarrow 2CH_3OH + 2H_2$$

$$(\ 64\ \mathrm{kg}\ CH_4 + 108\ \mathrm{kg}\ H_2O \longrightarrow 128\ \mathrm{kg}\ CH_3OH + 8\ \mathrm{kg}\ H_2O\ )$$

and by the following equation if carbon dioxide is available,

$$6CH_4 + 4H_2O + 2CO_2 \longrightarrow 8CH_3OH$$

$$(\ 192\ \mathrm{kg}\ CH_4 + 144\ \mathrm{kg}\ H_2O + 176\ \mathrm{kg}\ CO_2 \longrightarrow 512\ \mathrm{kg}\ CH_3OH\ )$$

The methane production rate by weight (in kg/hr) is again determined using Equation 6.19, and the production rate of carbon dioxide is calculated using,

$$\text{CO}_2\text{ Production Rate (kg/hr)} = \frac{\text{Methane} \times (100 - \%\text{Methane}) \times \text{CO}_2\text{Density}}{\text{CH}_4\text{Density} \times \%\text{Methane}} \qquad (6.21)$$

Where Methane = Methane production rate (kg/hr)
%Methane = Percentage of methane in biogas by volume
CO_2Density = Density of carbon dioxide (kg/m^3)
CH_4Density = Density of methane (kg/m^3)

If there is sufficient carbon dioxide to allow the second equation to be used, or if extra carbon dioxide may be used as necessary, the methanol production rate is calculated using Equation 6.22, and any extra carbon dioxide required is calculated in a similar manner.

$$\text{Methanol Production Rate (litres/hr)} = \frac{512 \times \text{Methane} \times \text{Percent}}{192 \times \text{Density} \times 100} \qquad (6.22)$$

Where Methane = Methane Production Rate (kg/hr)
Percent = Reaction Completion Percentage
Density = Density of Methanol (kg/litre)

If there is not sufficient carbon dioxide present, and extra may not be utilised, the amount of methanol that can be made with the carbon dioxide present is calculated using,

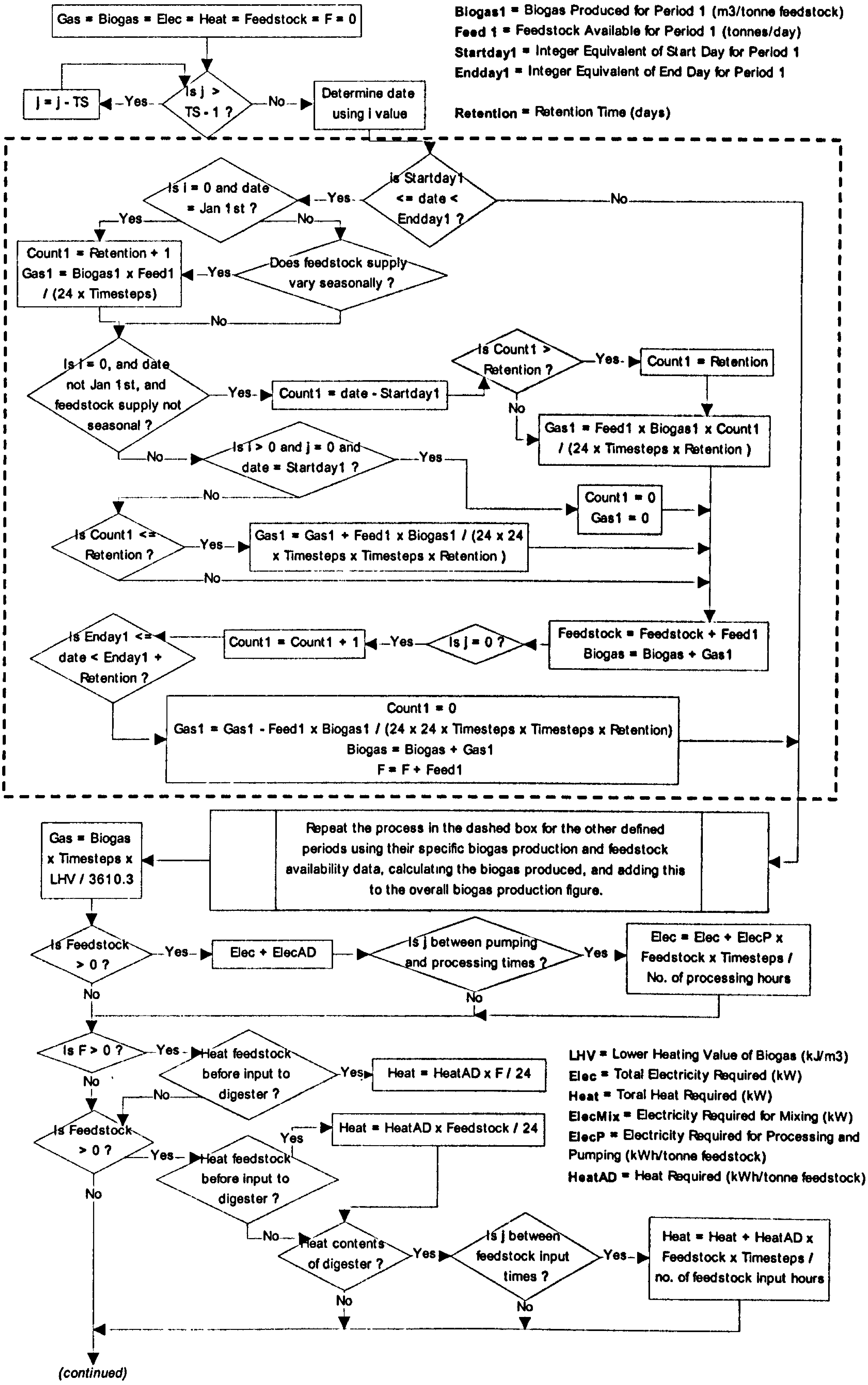
$$\text{Methanol Production Rate (litres/hr)} = \frac{512 \times CO_2 \times \text{Percent}}{176 \times \text{Density} \times 100} \quad (6.23)$$

Where CO_2 = CO_2 Production Rate (kg/hr),

and the remaining, unused methane is calculated using,

$$\text{Remaining Methane (kg/hr)} = \text{Methane} - \frac{(196 \times CO_2 \times \text{Percent})}{(176 \times 100)} \quad (6.24)$$

The methanol that can be made using the first chemical reaction is then determined in the same manner, by direct proportion using the first chemical equation, and added to the methanol production rate for that timestep. If desired, the remaining methane production rate may be calculated as described for hydrogen production, as can the process electricity and heat requirements and the electricity required for gas storage. The total amount of methanol produced (litres) throughout the simulation period, and any extra carbon dioxide required, is given along with the final production rate graphs.

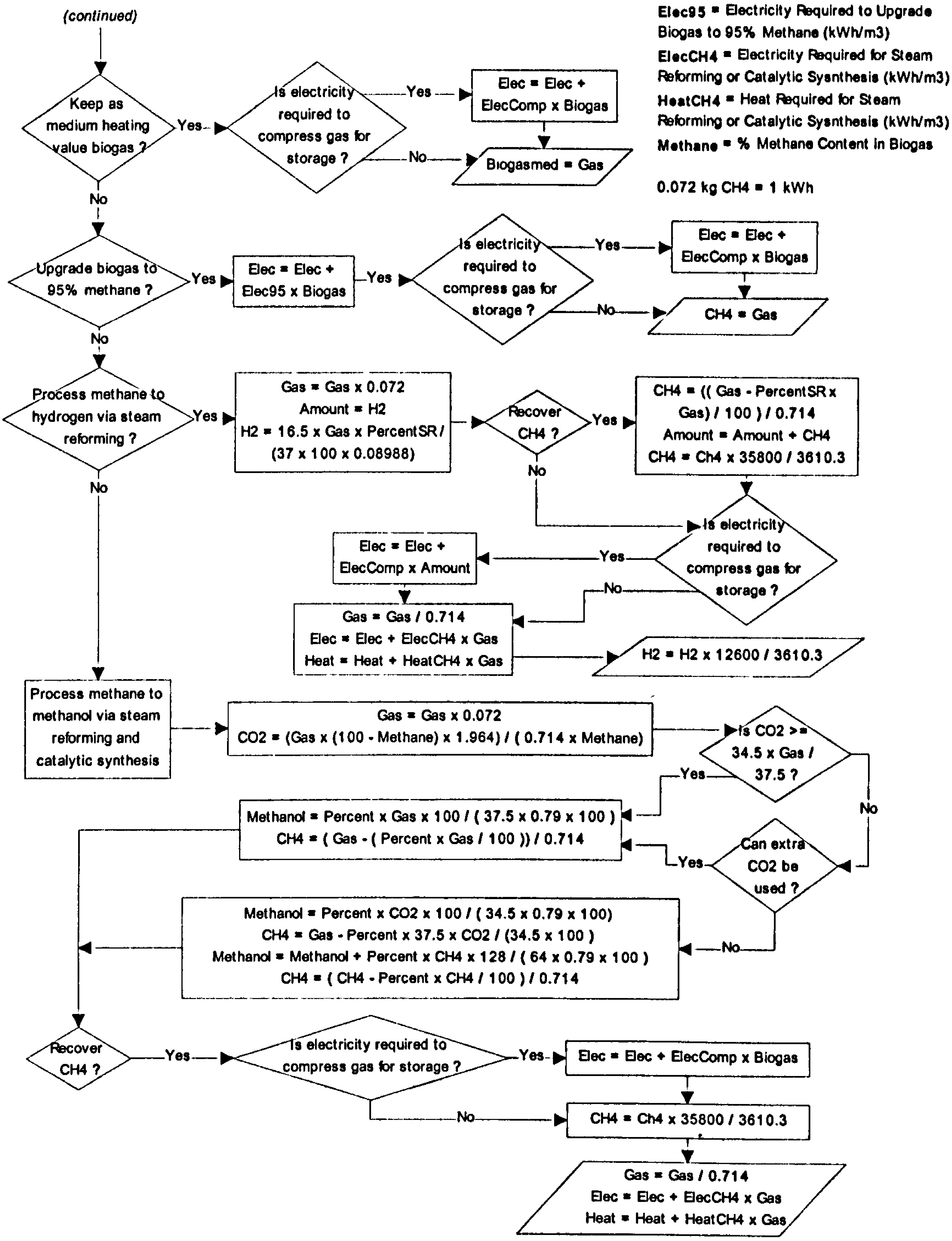


Biogas1 = Biogas Produced for Period 1 (m3/tonne feedstock)
Feed 1 = Feedstock Available for Period 1 (tonnes/day)
Startday1 = Integer Equivalent of Start Day for Period 1
Endday1 = Integer Equivalent of End Day for Period 1

Retention = Retention Time (days)

LHV = Lower Heating Value of Biogas (kJ/m3)
Elec = Total Electricity Required (kW)
Heat = Toral Heat Required (kW)
ElecMix = Electricity Required for Mixing (kW)
ElecP = Electricity Required for Processing and Pumping (kWh/tonne feedstock)
HeatAD = Heat Required (kWh/tonne feedstock)

Figure 6.4 Anaerobic Digestion Algorithm



Elec95 = Electricity Required to Upgrade Biogas to 95% Methane (kWh/m3)
ElecCH4 = Electricity Required for Steam Reforming or Catalytic Sysnthesis (kWh/m3)
HeatCH4 = Heat Required for Steam Reforming or Catalytic Sysnthesis (kWh/m3)
Methane = % Methane Content in Biogas

0.072 kg CH4 = 1 kWh

Figure 6.4 (cont) Anaerobic Digestion Algorithm

6.3 Transesterification

Transesterification is the production of methyl or ethyl esters (biodiesel) from animal or vegetable oils. The feedstock for this process may be continuously available (waste vegetable or animal oils), or seasonal (energy crops). Small-scale production is batch-wise, and larger scale continuous processes are being developed [7]. An example of the transesterification system definition window is given in Appendix 1, Figure A1.16.

6.3.1 Feedstock Availability

Feedstock availability, for continuous and seasonal supplies, is dealt with in a similar manner to that described in Section 6.1.1. For seasonal supplies, the oil availability per day is calculated using Equation 6.3, where the crop yield is in litres of oil per hectare. The electricity and heat required for oil extraction from energy crops, if necessary, are calculated using Equation 6.1 or 6.2 (substituting the heat requirement where appropriate), and are applied during the appropriate times. As it is common to use the same equipment to process oils from different harvest crops at different times of the year, to allow a more continual use, up to five different seasonal supplies may be defined for use by the same processing equipment. These are all added into the same store, as they become available, as the performance of the processing equipment and process requirements are not significantly affected by the use of different feedstocks. This process is shown in Figure 6.5.

Again, the rate of use of oil from seasonal supplies may be slower than the production rate to allow fuel production beyond the harvest periods. For seasonal supplies, if there is excess feedstock left over in the store at the end of the simulation period, and this is more than the minimum required for the fuel production process, the entire simulation period is analysed again, and the results from this second simulation period are used.

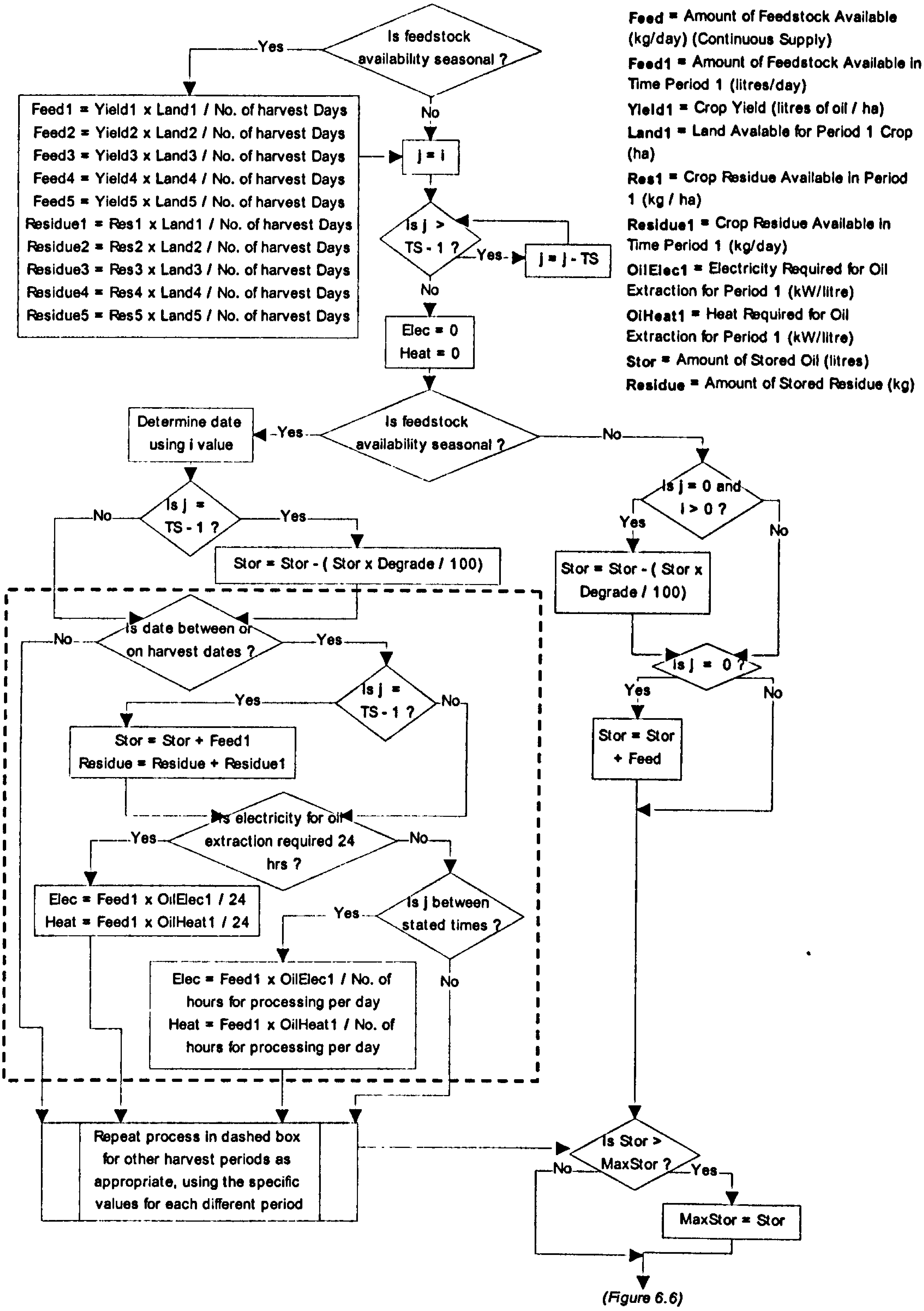


Figure 6.5 Transesterification Feedstock Availability Algorithm

6.3.2 Continuous Process Characteristics

As the continuous process cannot be easily started and stopped, it must run continuously throughout the day, and not between set times. The process information required to create the temporal fuel production and energy use profiles includes the maximum and minimum oil feed rates (litres/hr), the alcohol and catalyst types and feed rates (litres/hr and kg/hr respectively), the biodiesel and glycerine production rates (litres/hr), and the electricity and heat demands (kW). The methanol or ethanol requirement may also be made into a temporal profile and taken through to the matching procedure as a demand, if desired. This process is shown in Figure 6.6.

For each timestep, if more oil than necessary (oil feed rate / timesteps per hour) is available for that timestep, the process outputs, inputs and energy use are as input. If the amount of available oil is between the maximum and minimum oil required for that timestep, a partial production factor is calculated using Equation 6.6, and is applied to all inputs and outputs. The partial production factor is also applied to the heat demand, as this would vary with the amount of feedstock. It is not applied to the electricity demand, as this would not vary with the amount of feedstock. If there is not enough oil available, the process is not run. Oil is subtracted from the stored volume as it is used.

At the end of the simulation, graphs of the biodiesel production rate, ethanol or methanol requirement (if desired), and energy demands are created. Information about the overall consumption of oil, alcohol, catalyst, electricity and heat, and the overall production of biodiesel, glycerine and crop residue are given. The amount of unprocessed oil remaining and maximum storage required at any given time throughout the simulation are also presented.

6.3.3 Batch Process Characteristics

The batch process for biodiesel production is the most common, and can be run continuously throughout the day, or as a number of batches per day, starting at given time. The process information required to create the temporal fuel production and energy use profiles includes the time for one batch (hours), the maximum and minimum oil input per batch (litres), the alcohol and catalyst types and amount required at maximum load (litres and kg respectively), and the biodiesel and glycerine produced at maximum load (litres). Again, the methanol or ethanol requirement may also be made into a temporal profile and taken through to the matching procedure as a demand. This process is also shown in Figure 6.6.

The energy requirements for the batch process occur at different times throughout the process, and may include the following demands.

- Heat to boil off any water in the feedstock oil. This is given in kW for a specified number of minutes from the start of the process. This may be added to the heat demand or a 100% efficient electric heater may be used.

- Electricity for mixing (kW) for a specified number of minutes from the end of the previous boiling process.

- Electricity for biodiesel cleaning (for mixing or for bubbling air through to clean out any soap formed). This is given in kW for a specified number of minutes before the end of the batch.

The number of minutes for these energy demands may only be specified in multiples of 30 minutes. These specified times are translated into the equivalent number of timesteps using

$$\text{Number of Timesteps} = \frac{\text{Time} \times \text{Timesteps}}{60} \qquad (6.25)$$

Where Time = Specified time (minutes)
Timesteps = Number of timesteps per hour

The length of time required for one batch is translated into the equivalent number of timesteps necessary using

$$\text{Number of Timesteps} = \text{Time} \times \text{Timesteps} \tag{6.26}$$

Where Time = Length of batch (hours)

If the process is continuous throughout the day, the process will start at the first timestep where sufficient oil is available. If more oil is available than the maximum oil input, the process will run at full load. If the oil available is between the maximum and minimum input amounts, a partial production factor is calculated using Equation 6.6, and is applied to all inputs. The oil used (litres) is removed from the store at this timestep, and a timestep count is initiated to chart progress through the batch. The ethanol or methanol demand is also attributed to this timestep, if desired, and is translated into a production rate (litres/hr) by multiplying by the number of timesteps per hour.

For the subsequent timesteps, if the count is greater than or equal to zero, and less than the timestep equivalent of the heating time, then the energy required for this is applied for that timestep (directly in kW). This may be kept as a heat demand, or made directly into an electricity demand if a 100% efficient electric heater is used. The partial production factor is applied as necessary, as the amount of energy required is in direct proportion to the amount of oil being heated.

If the timestep count is greater than or equal to the timestep equivalent of the heating time (which may be zero), and less than the timestep equivalent of the time required for mixing, then the electricity required is applied for that timestep (directly in kW). If the timestep count is greater than or equal to the timestep equivalent of the batch length minus the timestep equivalent of the time required for biodiesel cleaning (which may be zero), and less than the timestep equivalent of the batch length, then the electricity required is applied for that timestep (directly in kW). The partial production factor is not applied to either of these electricity demands, as they would be independent of the amount of oil used.

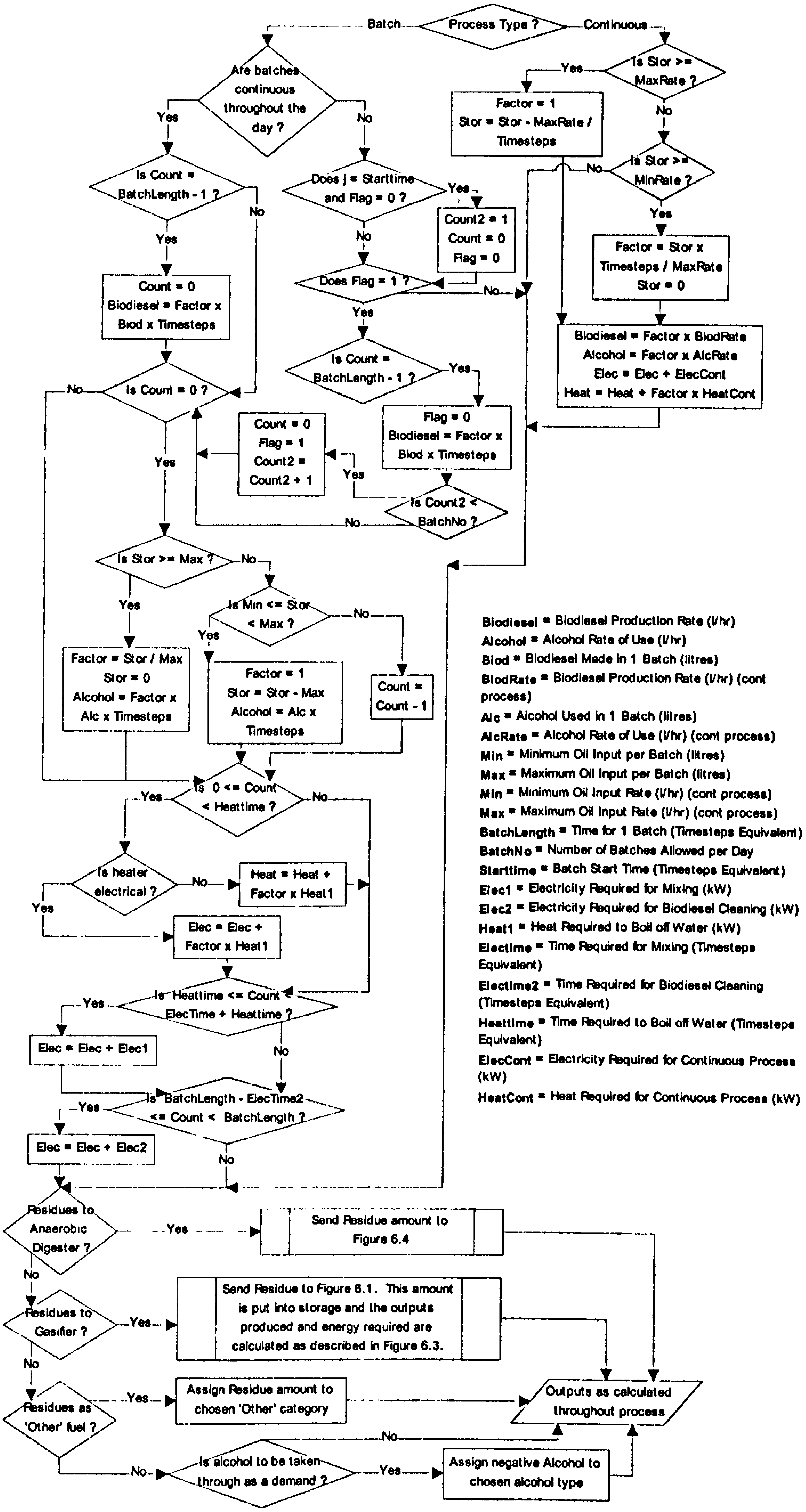
If it is the last timestep of the process, the amount of biodiesel made is added to the production profile for that timestep. The partial production factor is applied as necessary, and the amount of biodiesel produced, in litres, is translated into a production rate (litres/hr) by multiplying it by the number of timesteps per hour. The process is then free to start again provided there is enough oil available.

If a number of batches per day with a starting time have been specified, the batch can only be started after a given time each day, if no batch production is currently in progress, and if the maximum number of batches allowed each day has not been exceeded. Otherwise, the procedure outlined above is followed. The outputs of the batch process simulation are the same as for the continuous process described in Section 6.3.2.

6.3.4 Use of Crop Residue

If energy crops are used, a certain amount of crop residue, left over after oil extraction, will be available. This may be used as cattle feed, sent to an anaerobic digester or gasifier, or burned directly to produce heat and/or electricity, depending on the residue type, and other system requirements. The amount of residue made is calculated using Equation 6.3, with the yield being the crop residue (kg/ha), and this is made available at the last timestep of every day during the harvest season.

If the crop residue is to be made available for use in boilers, engines or turbines, a temporal production rate graph for a specified "other" category of fuel is produced. If the anaerobic digestion or gasification process is to be used, the feedstock availability for these processes is defined by the production of the crop residue, which is made available at the last timestep of each day. This feedstock is used immediately for the digestion process, or may be added to a store, for use at any time, for the gasification process. This can be done because the type of residue suitable for gasification will be much drier than that suitable for anaerobic digestion, and therefore will not suffer from the problem of degradation if stored properly.



Biodiesel = Biodiesel Production Rate (l/hr)
Alcohol = Alcohol Rate of Use (l/hr)
Biod = Biodiesel Made in 1 Batch (litres)
BiodRate = Biodiesel Production Rate (l/hr) (cont process)
Alc = Alcohol Used in 1 Batch (litres)
AlcRate = Alcohol Rate of Use (l/hr) (cont process)
Min = Minimum Oil Input per Batch (litres)
Max = Maximum Oil Input per Batch (litres)
Min = Minimum Oil Input Rate (l/hr) (cont process)
Max = Maximum Oil Input Rate (l/hr) (cont process)
BatchLength = Time for 1 Batch (Timesteps Equivalent)
BatchNo = Number of Batches Allowed per Day
Starttime = Batch Start Time (Timesteps Equivalent)
Elec1 = Electricity Required for Mixing (kW)
Elec2 = Electricity Required for Biodiesel Cleaning (kW)
Heat1 = Heat Required to Boil off Water (kW)
Electime = Time Required for Mixing (Timesteps Equivalent)
Electime2 = Time Required for Biodiesel Cleaning (Timesteps Equivalent)
Heattime = Time Required to Boil off Water (Timesteps Equivalent)
ElecCont = Electricity Required for Continuous Process (kW)
HeatCont = Heat Required for Continuous Process (kW)

Figure 6.6 Transesterification Algorithm

For each process, the process characteristics (except for the fuel availability information) are defined in a separate window, in the same manner as described previously for the different processes. This window appears when the option to use the process is chosen, and examples of these windows are given in Appendix 1, Figure A1.18 and A1.19. The outputs and energy use are calculated in the same manner as described in Section 6.1 for gasification, and Section 6.2 for anaerobic digestion, and the various options for processing the resulting gas are also available. The relevant production rate graphs are given along with the biodiesel production graph and the relevant overall production and use figures are also given. The maximum required storage and the amount of feedstock remaining are given for the gasification process, and a second simulation period is, again, analysed, as required, if there is a substantial amount of feedstock remaining at the end of the period.

6.4 Fermentation

Fermentation is the production of ethanol from sugary, starchy or cellulosic materials. The feedstock for this process may be continuously available (waste fruit, newspapers etc), or seasonal (energy crops). Small-scale production is batch-wise, and larger scale production may be achieved through various continuous processes [7,8]. An example of the fermentation system definition window is given in Appendix 1, Figure A1.17.

6.4.1 Feedstock Availability

Feedstock availability, for continuous and seasonal supplies, is dealt with as described in Section 6.1.1 and Figure 6.1. The electricity and heat required for the pre-processing of feedstock, however, are not calculated here as these are considered later as part of the ethanol production process. Only one type of feedstock may be used in a particular process simulation, as the process outputs and requirements vary with different feedstocks. It is possible, however, to have a number of different harvests of the same energy crop per year, so up to five different harvest times may be specified for the one feedstock type.

Again, the rate of use of the feedstock from seasonal supplies may be slower than the production rate to allow fuel production beyond the harvest periods. For seasonal supplies, if there is excess feedstock left over in the store at the end of the simulation period, and this is more than the minimum required for the fuel production process, the entire simulation period is analysed again, and the results from this second simulation period are used.

6.4.2 Continuous Process Characteristics

As the continuous process cannot be easily started and stopped, it must run continuously throughout the day, and not between set times. The following process information is required to create the temporal fuel production and energy use profiles.

- The maximum and minimum feedstock feed rates (kg/hr).
- Any other inputs (e.g. yeast, water, malt), type, amount and units per hour.
- The ethanol production rate (litres/hr).
- The wet and dry animal feed production rates (kg/hr).
- Any other outputs (e.g. carbon dioxide), type, amount and units per hour.
- The electricity and heat demands (kW).

For each timestep, if more feedstock than necessary (feedstock feed rate / timesteps per hour) is available for that timestep, the process outputs, inputs and energy use are as input. If the amount of available feedstock is between the maximum and minimum feedstock required for that timestep, a partial production factor is calculated using Equation 6.6, and is applied to all inputs and outputs. The partial production factor is also applied to the heat demand, as this would vary with the amount of feedstock. It is not applied to the electricity demand, as this would not vary with the amount of feedstock. If there is not enough feedstock available, the process does not run. Feedstock is subtracted from the stored volume as it is used.

At the end of the simulation, graphs of the ethanol production rate and energy demands are created. Information about the overall consumption of feedstock, other inputs, electricity and heat, and the overall production of ethanol, other outputs, and crop residue are given. The amount of unprocessed feedstock remaining and maximum storage required at any given time throughout the simulation are also presented. This process is shown in Figure 6.7.

6.4.3 Batch Process Characteristics

The batch process for ethanol production is started each day at a specified time, provided there is sufficient feedstock and equipment available. As the fermentation process may take between two to four days to complete, it is common to have a number of different fermenters available, to allow new batches to be started each day. The following process information is required to create the temporal fuel production and energy use profiles.

- The time for one batch (hours).
- The number of fermenters available.
- The maximum and minimum feedstock input per batch (litres).
- Any other inputs required (e.g. yeast, water, malt), type, amount and units.
- The ethanol output (litres).
- The wet and dry animal feed outputs (kg).
- Any other outputs (e.g. carbon dioxide), type, amount and units.

The energy requirements for the batch process occur at different times throughout the process, and may include the following demands, in this order.

- Electricity for the crushing or milling of the feedstock (kW).
- Heat for cooking and/or electricity for mixing (kW).
- Heat for hydrolysis and/or electricity for mixing (kW).
- Cooling requirement (heat or electricity) during fermentation (kW).
- Heat for distillation (kW)

- Heat and/or electricity for by-product preparation (kW).

Each of these stages is given a number of minutes or hours duration (which may be zero), and these are translated into the equivalent timestep values using Equation 6.25 or 6.26.

The process will start at the start time for each day provided sufficient feedstock and equipment are available. If more feedstock is available than the maximum oil input, the process will run at full load. If the feedstock available is between the maximum and minimum input amounts, a partial production factor is calculated using Equation 6.6, and is applied to all inputs. The feedstock used (kg) is removed from the store at this timestep, and a timestep count is initiated to chart progress through the batch. A separate count is initiated, and partial production factor calculated (as appropriate), for each fermenter being used, up to a maximum of five fermenters.

The energy demands are applied to the relevant timesteps throughout the batch process in a similar manner to that described in Section 6.3.3. The partial production factor is only applied to the heat demands, and there is the option to translate these heat demands directly into electricity demands (if electric heaters are being used). Distillation and by-product preparation take place after the end of the fermentation process, allowing the equipment to be used for the next batch. A separate count is, therefore, initiated for these stages, for each fermenter. Some of these processes may specify a time, but not an energy demand, if residues are being used to provide some of the process requirements.

If it is the last timestep of the fermentation process, the amount of ethanol made is added to the production profile for that timestep. The partial production factor is applied as necessary, and the amount of ethanol produced, in litres, is translated into a production rate (litres/hr) by multiplying it by the number of timesteps per hour. The process is then free to start again, for that particular fermenter, at the next start time, provided there is enough feedstock available.

As the time required for one batch is generally between two and four days, the batch process will run through a number of days longer than the batch length before starting to record data, when a continuous feedstock supply is being used. This allows the batches to start working through so that the ethanol production and energy requirements will start from the beginning, for the different batches running simultaneously. This is also done in the transesterification process if the batch length is longer than 24 hours, but this is not generally the case. The outputs of the batch process simulation are the same as for the continuous process described in Section 6.4.2. This process is also shown in Figure 6.7.

6.4.4 Use of Residues

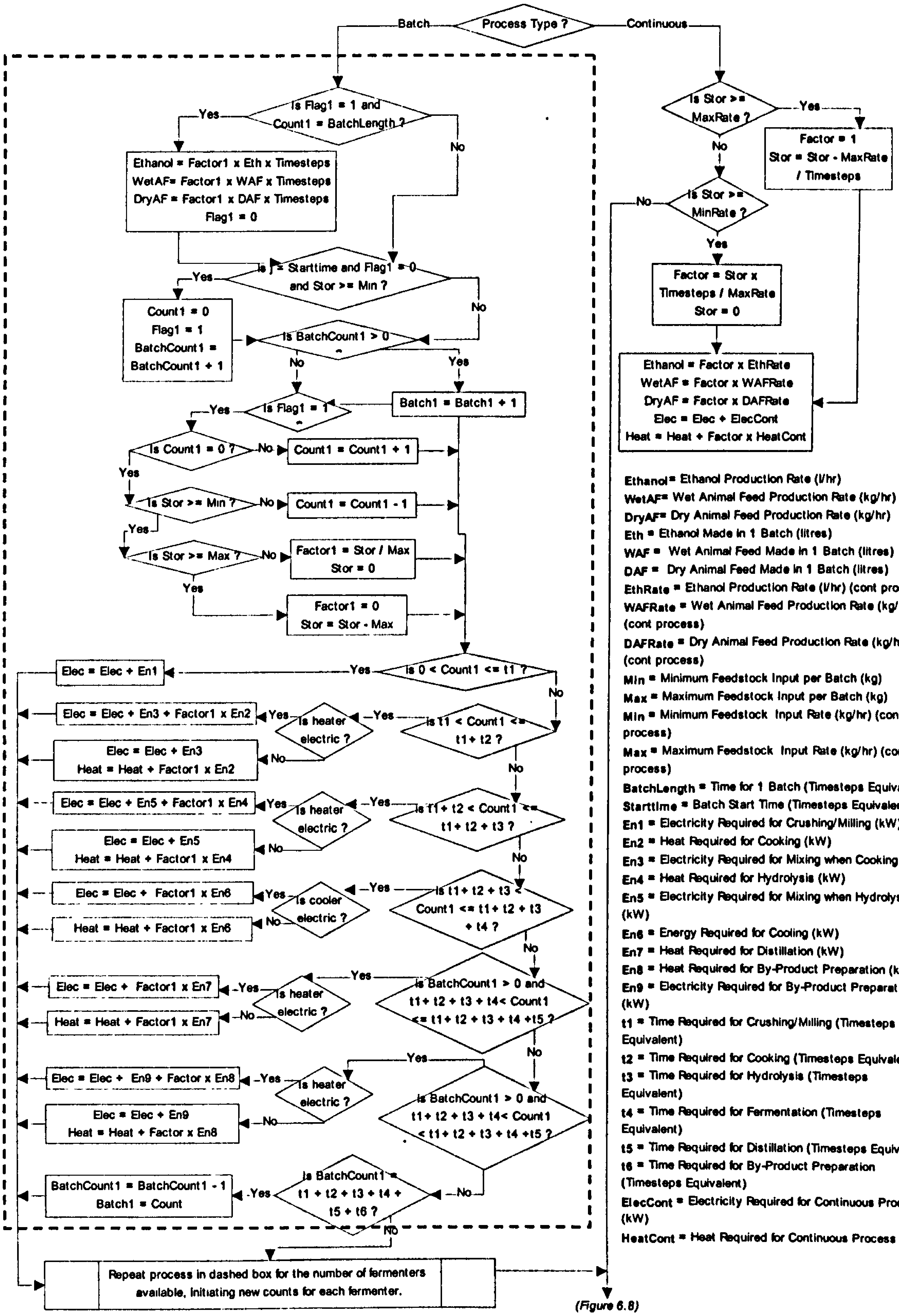
If energy crops are used, a certain amount of crop residue may be available. This may, again, be used as cattle feed, sent to an anaerobic digester or gasifier, or burned directly to produce heat and/or electricity, depending on the residue type, and other system requirements. The processes for dealing with this type of residue are as described in Section 6.3.4. If these crop residues are used to meet some or all of the process energy needs, the input energy requirements and amount of residue produced are reduced accordingly.

If a dry animal feed is produced, this can be used or processed in the same way as the energy crop residues. Determining the feedstock availability for this residue, however, is more difficult than for the crop residues, as it is produced more erratically. This is not a problem when gasification is being considered, as the feedstock is put into a store when available, and used from that store when possible. The gasification process characteristics are defined, and the outputs and energy use are calculated, in the same manner as described in Section 6.1, and the various options for processing the resulting gas are also available. If the dry animal feed is to be made available for use in boilers, engines or turbines, a temporal production rate graph for a specified "other" category of fuel is produced.

If a wet animal feed is produced, this may be sent, if desired, to an anaerobic digester. This is also an option for the dry animal feed. The erratic nature of both these feedstock supplies, however, poses a problem for this process, as it requires a single daily input. If a continuous process is being used, the feedstock produced is collected and stored to allow one input each day at a set time. If a batch process is used, and there are enough fermenters to allow a daily production of the feedstock, then this amount is input into the digester each day. The process characteristics are defined, and the outputs and energy use are calculated in the same manner as described in Section 6.2.

If there are not sufficient fermenters to allow a daily production of the feedstock, the number of days each batch requires to run is determined, and the number of fermenters available is divided by this number of days to determine the fraction of the feedstock from one batch which would be available for input to the digester each day. This amount of feedstock may then be input into the digester each day for the number of days each batch requires to run. If further feedstock is available, the process continues. If it is not available, the process slows down as described in Section 6.2. The build-up period and options for the use of the biogas are also dealt with as described in Section 6.2.

All the specific fuel production rates calculated using these procedures (i.e. methanol, 95% methane), for each timestep, from each process, are added together to make one production rate profile for each fuel type produced. The relevant production rate graphs are given along with the ethanol production graph and overall energy use graphs, and the relevant overall production and use figures are also given. The maximum required storage is given for the gasification process, and a second simulation period is, again, analysed, as required, if there is a substantial amount of feedstock remaining at the end of the simulation period. The procedures described in this section are shown in Figure 6.8.



Ethanol= Ethanol Production Rate (l/hr)
WetAF= Wet Animal Feed Production Rate (kg/hr)
DryAF= Dry Animal Feed Production Rate (kg/hr)
Eth = Ethanol Made in 1 Batch (litres)
WAF = Wet Animal Feed Made in 1 Batch (litres)
DAF = Dry Animal Feed Made in 1 Batch (litres)
EthRate = Ethanol Production Rate (l/hr) (cont process)
WAFRate = Wet Animal Feed Production Rate (kg/hr) (cont process)
DAFRate = Dry Animal Feed Production Rate (kg/hr) (cont process)
Min = Minimum Feedstock Input per Batch (kg)
Max = Maximum Feedstock Input per Batch (kg)
Min = Minimum Feedstock Input Rate (kg/hr) (cont process)
Max = Maximum Feedstock Input Rate (kg/hr) (cont process)
BatchLength = Time for 1 Batch (Timesteps Equivalent)
Starttime = Batch Start Time (Timesteps Equivalent)
En1 = Electricity Required for Crushing/Milling (kW)
En2 = Heat Required for Cooking (kW)
En3 = Electricity Required for Mixing when Cooking (kW)
En4 = Heat Required for Hydrolysis (kW)
En5 = Electricity Required for Mixing when Hydrolysis (kW)
En6 = Energy Required for Cooling (kW)
En7 = Heat Required for Distillation (kW)
En8 = Heat Required for By-Product Preparation (kW)
En9 = Electricity Required for By-Product Preparation (kW)
t1 = Time Required for Crushing/Milling (Timesteps Equivalent)
t2 = Time Required for Cooking (Timesteps Equivalent)
t3 = Time Required for Hydrolysis (Timesteps Equivalent)
t4 = Time Required for Fermentation (Timesteps Equivalent)
t5 = Time Required for Distillation (Timesteps Equivalent)
t6 = Time Required for By-Product Preparation (Timesteps Equivalent)
ElecCont = Electricity Required for Continuous Process (kW)
HeatCont = Heat Required for Continuous Process (kW)

Figure 6.7 Fermentation Algorithm

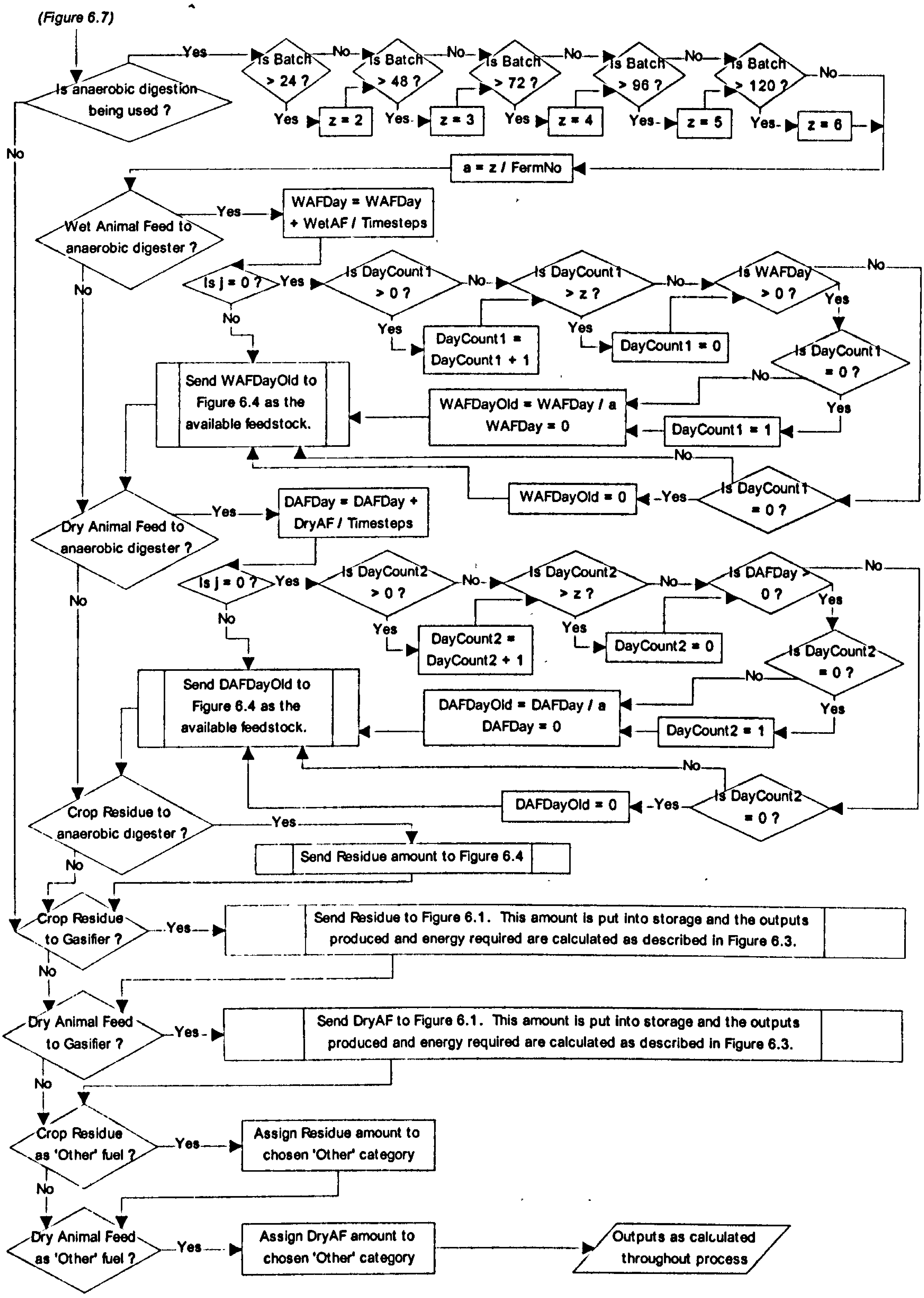


Figure 6.8 Fermentation Use of Residues Algorithm

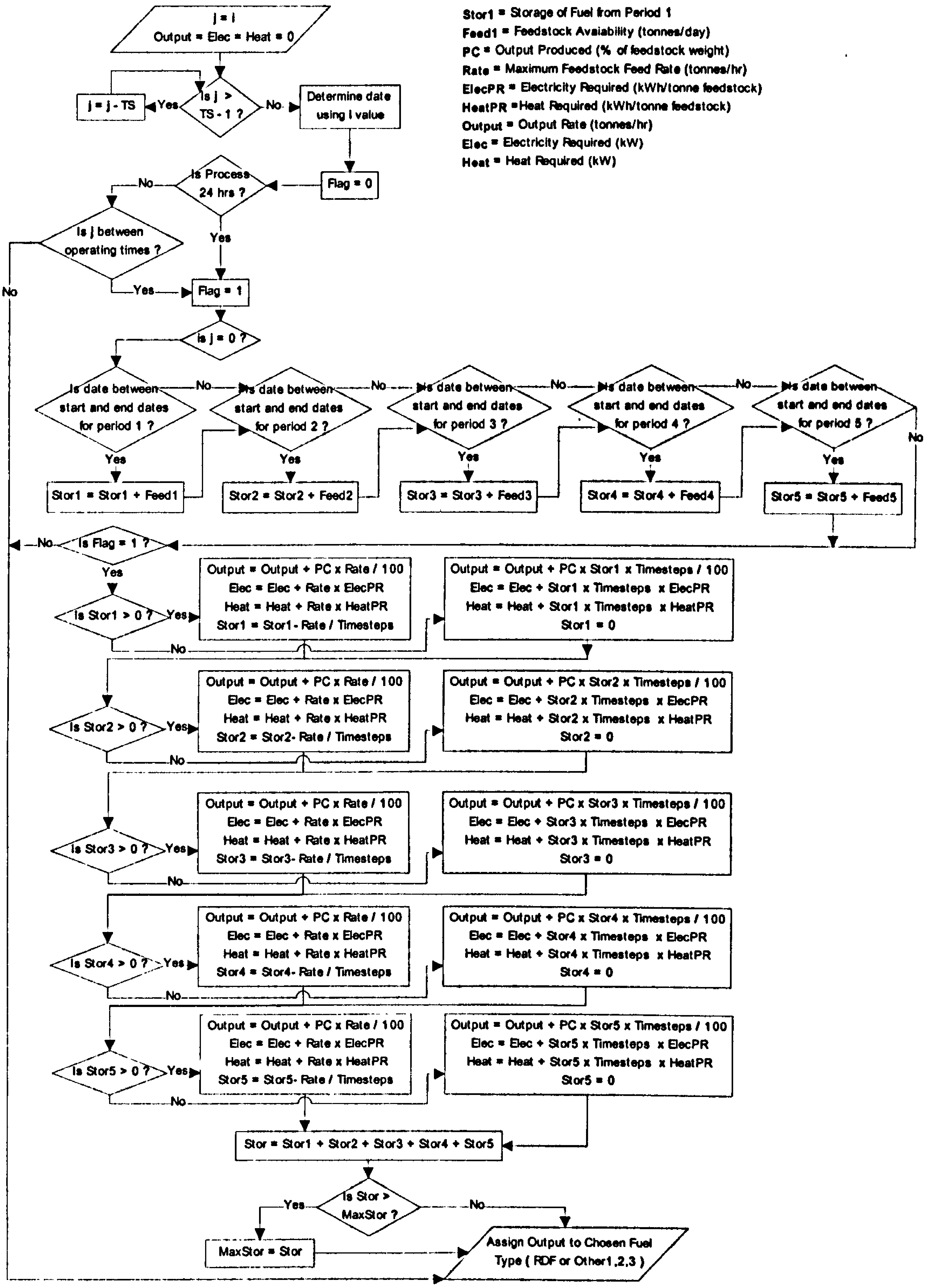
6.5 Electrolysis

As it is sometimes preferable to convert the entire output of a PV or wind farm to hydrogen via electrolysis, rather than just the excess electricity left after some has been used to meet demand, a dedicated supply can be defined. The half-hourly output of a specified PV array or wind turbine set is calculated using the algorithm described by Born [9], and this electricity output, for each timestep, is fed directly into an electrolyser. The electrolyser is defined, and its output is calculated as described in Section 5.7. Information about the amount of electricity used, and the electricity that was wasted due to lack of capacity of the electrolyser is given along with the half-hourly hydrogen production graph. Information is also given about the overall amount of water required and hydrogen made. Examples of the PV and wind electrolysis system definition windows are given in Appendix 1, Figures A1.21 and A1.22. This modelling method, however, is only suitable if a small number of timesteps per hour has been specified, as it does not account for the response time of the electrolyser to high frequency wind power outputs. If the program was to be used with a larger number of timesteps per hour, this model would require further refinement.

6.6 Waste and Biomass Processing Technologies

To allow the modelling of the output and energy use of various waste processing technologies, (e.g. pelletising, shredding, briquetting, chipping, wood or sewage drying), a generic process is defined. The feedstock availability is defined by the amount available (tonnes/day), and the percentage by weight of this feedstock that is output. Different feedstocks may be used at different times of the year, and varying amounts of the same feedstock may be defined. This feedstock is put into a store at each timestep it is available, and is used from that store at a specified feed rate (tonnes/hr). The electricity and heat requirements for the process (kWh/tonne feedstock), and the times over which it is operational are defined, and the output is assigned as RDF or one of the 'other' categories. The temporal fuel production and energy use graphs are then created as described in previous examples, with the process only working between operating times and if sufficient fuel is available. This process is shown in

Figure 6.9. An example of the waste and biomass processing technologies system definition window is given in Appendix 1, Figure A1.23.



Stor1 = Storage of Fuel from Period 1
Feed1 = Feedstock Availability (tonnes/day)
PC = Output Produced (% of feedstock weight)
Rate = Maximum Feedstock Feed Rate (tonnes/hr)
ElecPR = Electricity Required (kWh/tonne feedstock)
HeatPR = Heat Required (kWh/tonne feedstock)
Output = Output Rate (tonnes/hr)
Elec = Electricity Required (kW)
Heat = Heat Required (kW)

Figure 6.9 Waste and Biomass Processing Algorithm

6.7 Landfill Gas Processing

As the biogas from landfill sites is produced constantly, at a steady rate, its production can be defined by the biogas production rate (Nm^3/hr), the percentage of methane in the biogas or its lower heating value (kJ/Nm^3), and the electricity required to extract the biogas (kWh/Nm^3 biogas produced). The biogas may then be used or processed in the same way as biogas derived from anaerobic digestion, as described in Section 6.2.3. An example of the landfill gas system definition window is given in Appendix 1, Figure A1.20.

This chapter described the algorithms used to estimate the rate of fuel production and associated energy demand profiles for chosen derived fuels. Chapter 7 shows how the overall program works from the user's point of view, and also discusses how the changes made to the systems have been verified once incorporated within the existing MERIT program architecture.

6.8 References

[1] C. P. Mitchell, "Development of decision support systems for bioenergy applications", Biomass and Bioenergy, 2000, Vol. 18, pp 265-278

[2] "Pyrolysis & Gasification of Waste: A Worldwide Technology & Business Review. Volume 2 – Technologies and Processes", Juniper Consulting Services, January 2000

[3] The Methanol Institute, www.methanol.org

[4] P. Harris, "An Introduction to BIOGAS", University of Adelaide, July 2001, www.roseworthy.adelaide.edu.au/~pharris/biogas/beginners.html

[5] "Anaerobic Digestion of Farm and Food Processing Residues – Good Practice Guidelines", British Biogen, www.britishbiogen.co.uk

[6] Personal Correspondence, M. Richter, ECB AG

[7] Handmade Projects, Journey To Forever, www.journeytoforever.org

[8] "Biofuels", Energy and Environment Policy Analysis, OECD/IEA, 1994

[9] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001, www.esru.strath.ac.uk

7 Software Development

This chapter describes the MERIT software from a user's perspective. Methods for verifying the developed algorithms within the overall program context are also discussed.

7.1 User View of MERIT

The main program window of MERIT (Appendix 1, Figure A1.1) provides links to each section of the program, as shown in Figure 7.1. From here the different sections described below can be accessed using the appropriate button. Examples of all the MERIT windows are given in Appendix 1.

7.1.1 Climate and Time Scale

To begin a simulation, the analysis conditions are specified. These include the start and end dates for the simulation, a suitable climate file, and the altitude of the site. If the simulation is to include seasonally varying fuel production profiles (e.g. from energy crops), then the study of anything less than a full year will give misleading results.

If the analysis of different seasons is required, without the simulation of an entire year, it is possible to define representative seasonal periods (days, weeks, months). The number of desired seasons and length of the periods are chosen, and representative periods are determined based on the climate data. It is also possible to view the selected climate data.

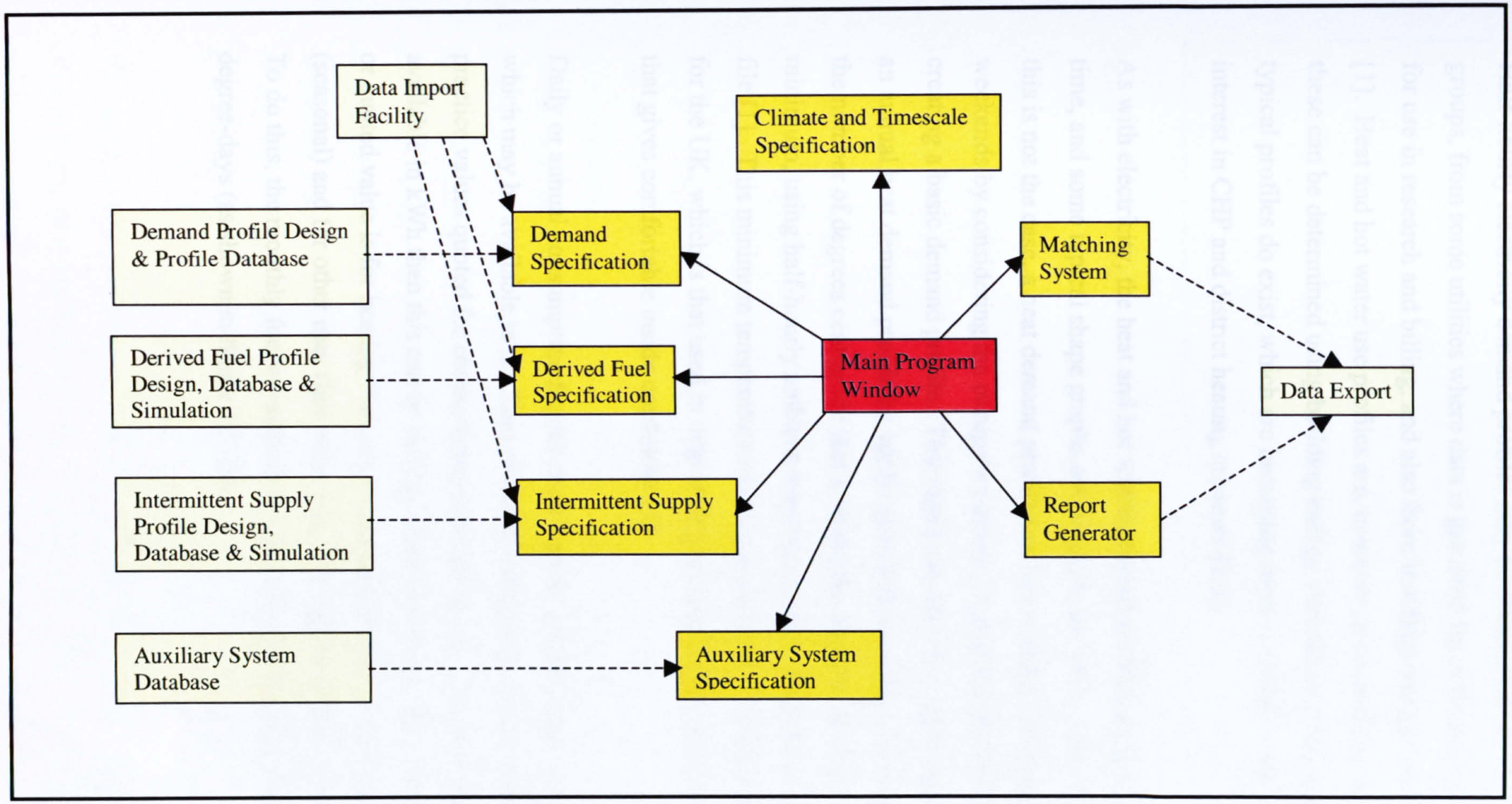


Figure 7.1 The Principal Components of MERIT

7.1.2 Specify Demand

Half-hourly electricity demand profiles may be obtained from load research groups, from some utilities where data is gathered for different types of building for use in research and billing, and also from building energy simulation tools [1]. Heat and hot water use profiles are, however, more difficult to find. Again, these can be determined using building energy simulation tools, and some typical profiles do exist, which are becoming more common with the increased interest in CHP and district heating schemes [2,3].

As with electricity, the heat and hot water demand profiles are given in kW over time, and some typical shape graphs are available for some types of building. If this is not the case, a heat demand profile can be estimated for weekdays and weekends by considering the occupancy hours of certain types of building and creating a basic demand profile. This graph can then be augmented to produce an annual heat demand profile by applying an extra heating load, proportional to the number of degrees centigrade that ambient temperature is below a specified minimum, using half-hourly ambient temperature data from the relevant climate file [1]. This minimum temperature would generally be 15.5 degrees centigrade for the UK, which is that used in degree-day analysis as the outside temperature that gives comfortable inside conditions [4].

Daily or annual consumption figures must then be used to scale this profile, which may be available in the form of meter readings or typical and best practice values quoted for certain types of building [5]. If a total heat demand is available in kWh then this can be directly applied to the profile. If the metered or quoted value is for heating fuel use, the amount of fuel used for space heating (seasonal) and for other uses (hot water and cooking) must first be determined. To do this, the monthly fuel consumption is plotted against the number of degree-days (as shown in figure 7.2) [6].

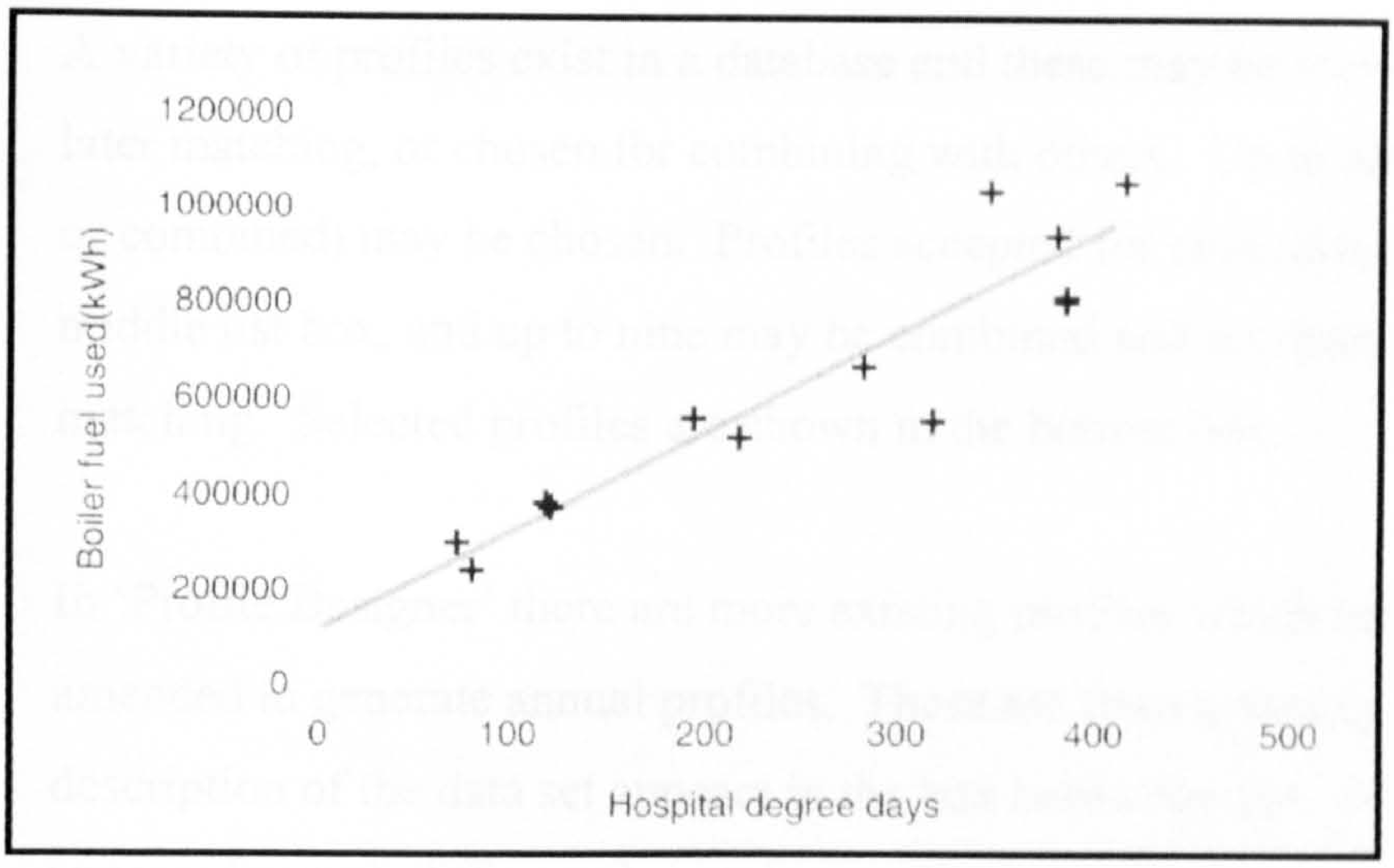


Figure 7.2 Degree-Days Versus Monthly Fuel Use [6]

A best-fit line is then drawn, and the point of intercept of this line with the y-axis gives the monthly fuel use for hot water and cooking. Multiplying this number by twelve gives the annual non-space heating fuel use, and subtracting this value from the total annual fuel use gives the annual fuel use for space heating. To find the total heat demand, an efficiency factor must then be applied, relevant to the type of fuel and plant used to gain the original consumption figures. This figure can then be used to scale the annual profile.

The annual fuel use for water heating (without cooking fuel use) must be determined for each individual case from the annual non-space heating fuel use. As this does not tend to vary greatly throughout the year, daily profiles may be produced for weekdays and weekends based on occupancy and typical behaviour, and these are then used to produce an annual profile. Again an efficiency factor must be applied to the annual fuel use figure, based on the type of fuel and plant used for the original consumption figures, and the overall annual hot water demand can then be used to determine an annual hot water use profile. Parts of these profiles can then be used relevant to the chosen timeframe of the study.

The demand definition window gives the option to load demand data from a database, import a profile from another source, or specifically design a profile.

A variety of profiles exist in a database and these may be viewed, selected for later matching, or chosen for combining with others. Up to nine profiles (single or combined) may be chosen. Profiles accepted for combination appear in the middle list box, and up to nine may be combined and accepted for later matching. Selected profiles are shown in the bottom box.

In 'Profile Designer' there are more existing profiles which may be used or amended to generate annual profiles. These are from a variety of sources and a description of the data set appears in the box below the list. A different list appears for each different demand type. Each data set may include different profiles for different periods of the year, and for weekdays, weekends and holidays, and each profile can be amended manually, or the overall consumption can be changed and applied to the profile shape. The specified time frame or days for which the profile is defined can be altered, and profiles may also be copied and amended.

The profile effects tab allows various effects to be applied to the profile, including the ability to interpolate, or not, between profile defined periods. Temperature effects may also be included, which allows heat profiles to be augmented with reference to the ambient temperature.

An annual profile can be generated, and different overall consumption figures can be applied to the profile shape if desired. The produced annual profile may then be either saved as a template for later use in Profile Designer, or saved to the demand database.

7.1.3 Specify Supply

The creation of supply profiles for sustainable fuels, electricity, heat, hot water and transport, is carried out in three stages.

Stage 1 - Sustainable Fuel Supply Systems

The sustainable fuel system definition window gives the option to simulate fuel supply profiles, import profiles from a database, or design profiles using a profile designer. A variety of sustainable fuel generation methods are available for simulation, and each system type has its own generation type definition window (see Appendix 1), on which the user can input readily available manufacturers' information and process parameters. A variety of existing plant types may be accessed from a database, and augmented as necessary. Information may also be saved to the database. There may be energy demands associated with the manufacture of sustainable fuels, and these are also defined in the definition window.

When a system has been defined, supply profile and energy use graphs are drawn in the sustainable fuel system definition window. If the profile is satisfactory, it may be accepted and combined in the same way as the demand profiles. The associated energy demands are added to the specified demands at the matching stage.

'Fuel Supply Profile Designer' works in a similar way to that for demand. It allows constant or predictable supplies, or supplies which do not require processing, to be represented (e.g. wood or straw availability). Three 'other' categories are available for defining supply profiles of crop or process residues, or other fuels that do not require processing. Profiles saved in the fuel supply profile designer are accessed through the fuel supply database.

Stage 2 - Intermittent Supply Systems

The intermittent supply system definition window gives the option to simulate supply profiles, import profiles from a database, or design profiles using a profile designer. This section functions in the same way as the fuel supply definition section. 'Supply Profile Designer' allows constant or predictable supplies to be represented (e.g. nuclear base load, geothermal generation).

Stage 3 - Auxiliary Systems (dependant on demand and/or fuel availability)

The auxiliary system definition window gives the opportunity to define the plant and control characteristics for a range of auxiliary system types, including electricity storage devices, engines, turbines, fuel cells, heating systems, heat storage systems, electrolysers and vehicles. Again, each technology has its own definition window, which functions in the same way as the supply windows. As the performance of the auxiliary systems cannot be calculated until the demand and supply matching stage, a description of the system appears in the window when each system has been defined. If this is satisfactory, it may be accepted in exactly the same way as for the demand profiles.

7.1.4 Match and Dispatch

The final stage is to match supply and demand. When the matching window opens, the fuel choice window also opens, allowing the choice of which fuels will be available for consideration (see Appendix 1). This choice may be changed at any time during matching. It is important to avoid unnecessary fuel production, as energy demands are often associated with these.

The chosen demand, supply and auxiliary profiles are given as buttons at the top centre of the screen. Different combinations can be tried by clicking once on the different buttons to select them and twice to clear and start again. To see which profile is which, hover over the button for a few seconds and the name will appear below the cursor. Any number of profiles may be chosen for matching, and the auxiliary profiles are applied in the order in which they are chosen.

Three graphs are shown at the bottom:

- Graph 1 - Demand and Supply
- Graph 2 - Residual Power
- Graph 3 - Auxiliary Performance.

The different profile of use graphs for the auxiliary supplies can be toggled between using the arrow button above the third graph. Other useful information about each auxiliary supply is given in the box above this.

The box at the top right hand corner contains information about the match, including a match rating out of ten. This also contains overall fuel consumption information for each of the different fuels available, and an estimated annual consumption if seasonal representative times are being used. Again, the arrow button can be used to toggle between these. Pressing the arrow button above the first graph changes the energy demand and supply shown (e.g. electricity, heat), or shows a fuel storage profile (the amount of fuel requiring to be stored at any given time) for each of the fuel types.

Different demand and supply combinations can be tried, and it is possible, at any time, to go back to the earlier stages and amend demand, supply and auxiliary data to help improve the match. All potential matches between demands and intermittent supplies can be assessed automatically by using the Auto Search function, and specific match and overall data can be exported to a Microsoft Excel file.

7.1.5 General Information

The entire project, including all selected data and profiles may be saved at any time. A report of the project, containing information from all the stages, may also be generated.

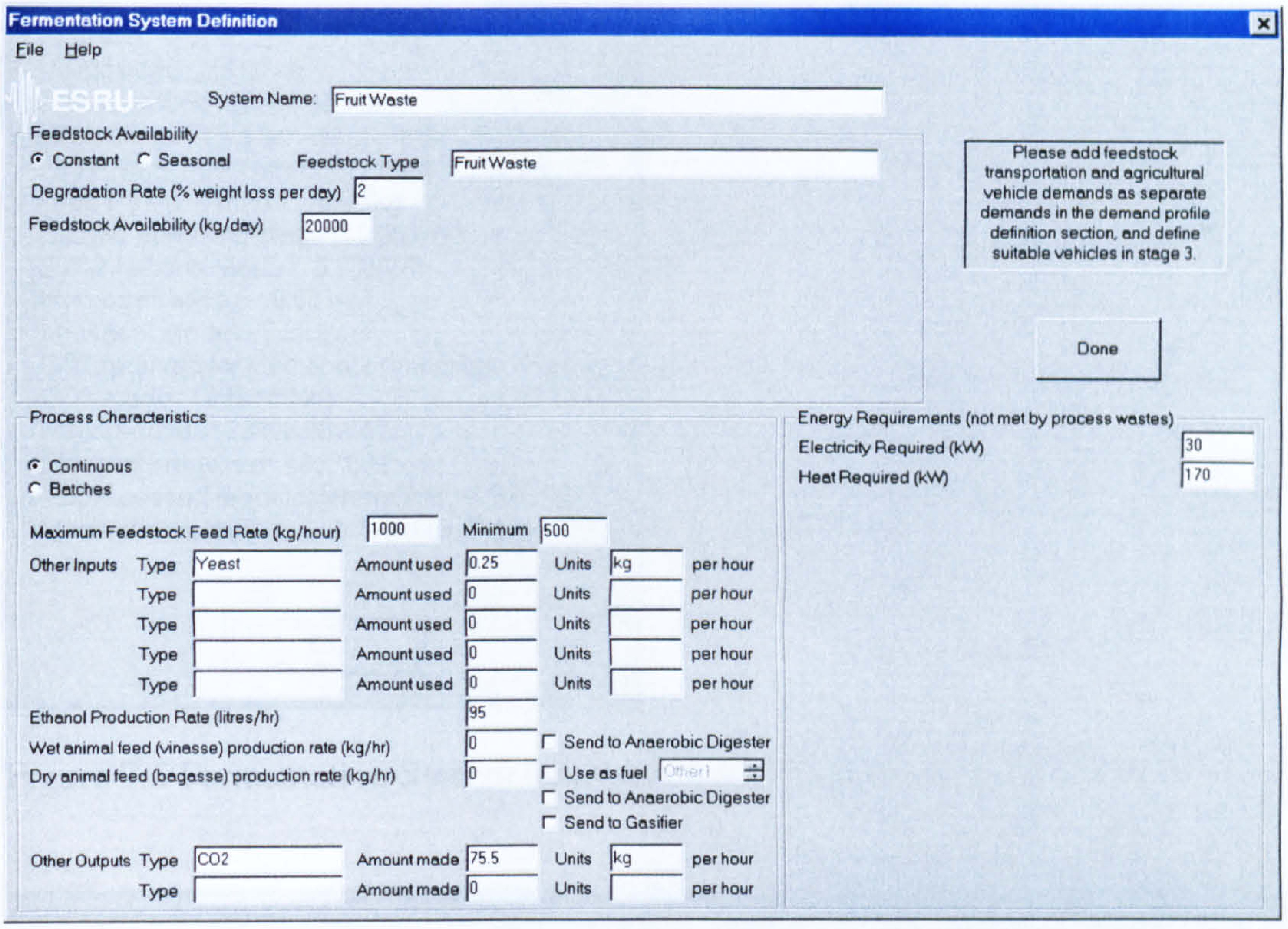
7.2 Verification

As the algorithms used to model the behaviour and output of the various fuel supply and load following plants considered here were designed to emulate the behaviour described by manufacturers and users, and to follow input control strategies, the performance of each of these new models has been verified against these parameters, and the assumptions outlined in Chapters 5 and 6. The verification processes followed are outlined below.

7.2.1 Fuel Supply Specification

For the fuel supply profiles, the accuracy of the timing and magnitude of the fuel supplies and energy requirements were tested against expected results. The provisions for seasonal and continuous supplies, and for batch and continuous production were all analysed in this manner as necessary for each system type. Where multiple energy requirements for the same energy type were specified, these were tested individually, and in combination. The overall required inputs and outputs over the time period were also calculated and compared with the information given in the information box. The mechanism for taking the fuel availability through to the matching procedure and creating a storage profile was tested at the matching stage by comparing the magnitude and shape of the fuel storage profiles created when no fuel is used with expected results. The profiles created when fuel is used were considered when checking the load following supplies, and this is discussed later.

To show how these verifications were carried out, the fermentation system has been taken as an example, as this is the most complicated model. Firstly, the continuous process with a constant supply is analysed to ensure the correct behaviour is being modelled when there is not enough fuel for the fermenter to run continuously. A simulation period of seven days is chosen for clarity. The input parameters are shown in Figure 7.3, and the output graph (Figure 7.4) shows correct fuel production and energy use at the times when enough fuel is available, and no production or energy use when there is insufficient fuel, giving expected production times and magnitudes. The production and energy use rates, and the overall production and consumption figures in the information box (Figure 7.5) are also correct. When the exact amount of feedstock is available, the process runs continually (Figures 7.6). This is also the case when too much feedstock is available, but a residual fuel supply is shown, which correctly accounts for the degradation rate (Figure 7.7). Figure 7.8 shows the fuel storage graph obtained, at the matching stage, from the continuous output, which shows the correct graph shape and magnitude. When the output is not continuous (i.e. as in Figure 7.4) this profile is stepped.



System Name: Fruit Waste

Feedstock Availability

● Constant ○ Seasonal

Feedstock Type: Fruit Waste

Degradation Rate (% weight loss per day): 2

Feedstock Availability (kg/day): 20000

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Process Characteristics

● Continuous

○ Batches

Maximum Feedstock Feed Rate (kg/hour): 1000 Minimum: 500

	Type		Amount used		Units		
Other Inputs	Type	Yeast	Amount used	0.25	Units	kg	per hour
	Type		Amount used	0	Units		per hour
	Type		Amount used	0	Units		per hour
	Type		Amount used	0	Units		per hour
	Type		Amount used	0	Units		per hour

Ethanol Production Rate (litres/hr): 95

Wet animal feed (vinasse) production rate (kg/hr): 0 ☐ Send to Anaerobic Digester

Dry animal feed (bagasse) production rate (kg/hr): 0 ☐ Use as fuel Other1 ☐ Send to Anaerobic Digester ☐ Send to Gasifier

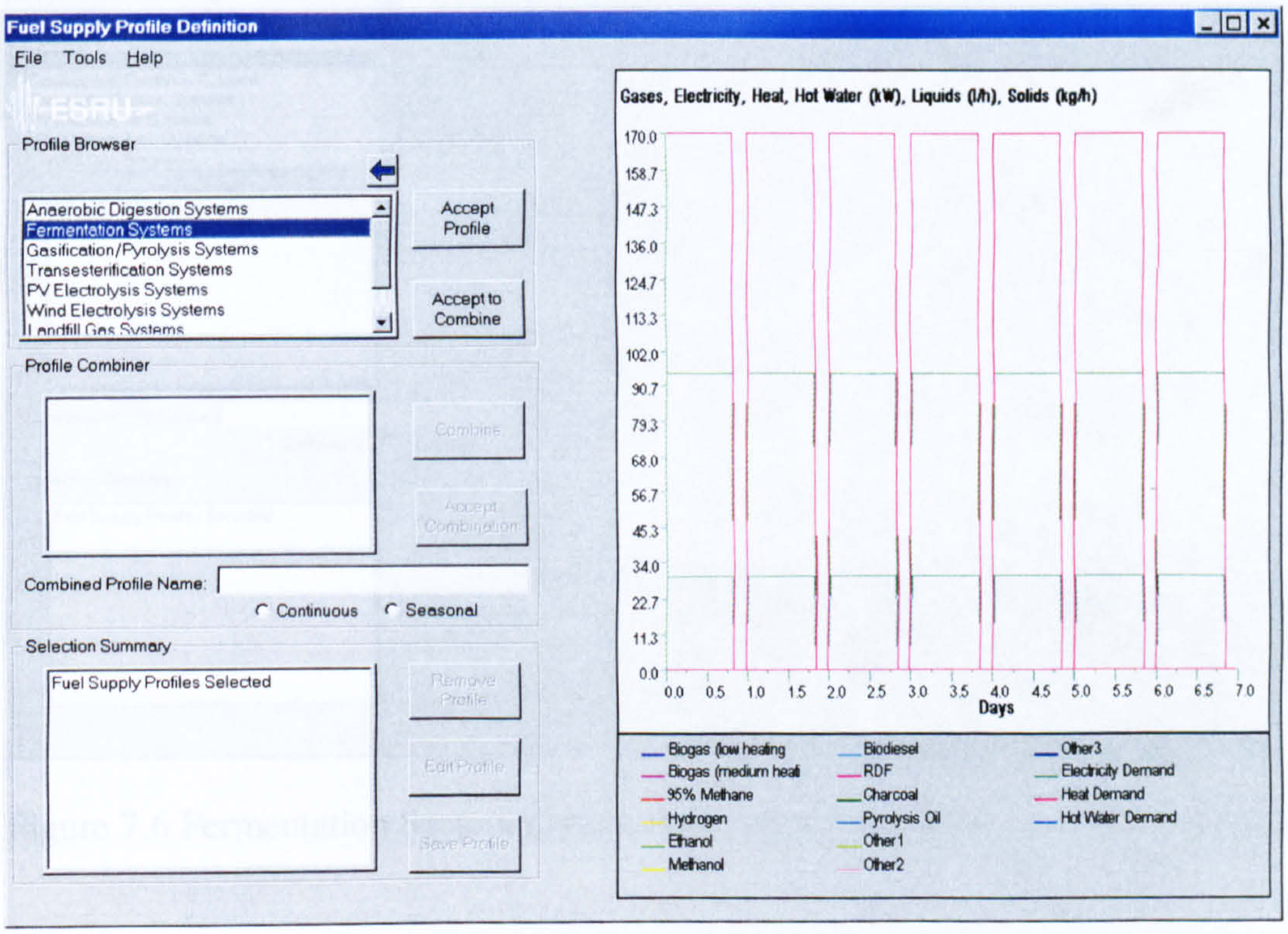
	Type		Amount made		Units		
Other Outputs	Type	CO2	Amount made	75.5	Units	kg	per hour
	Type		Amount made	0	Units		per hour

Energy Requirements (not met by process wastes)

Electricity Required (kW): 30

Heat Required (kW): 170

Figure 7.3 Fermentation System Input Parameters



Profile Browser

- Anaerobic Digestion Systems
- Fermentation Systems
- Gasification/Pyrolysis Systems
- Transesterification Systems
- PV Electrolysis Systems
- Wind Electrolysis Systems
- Landfill Gas Systems

Profile Combiner

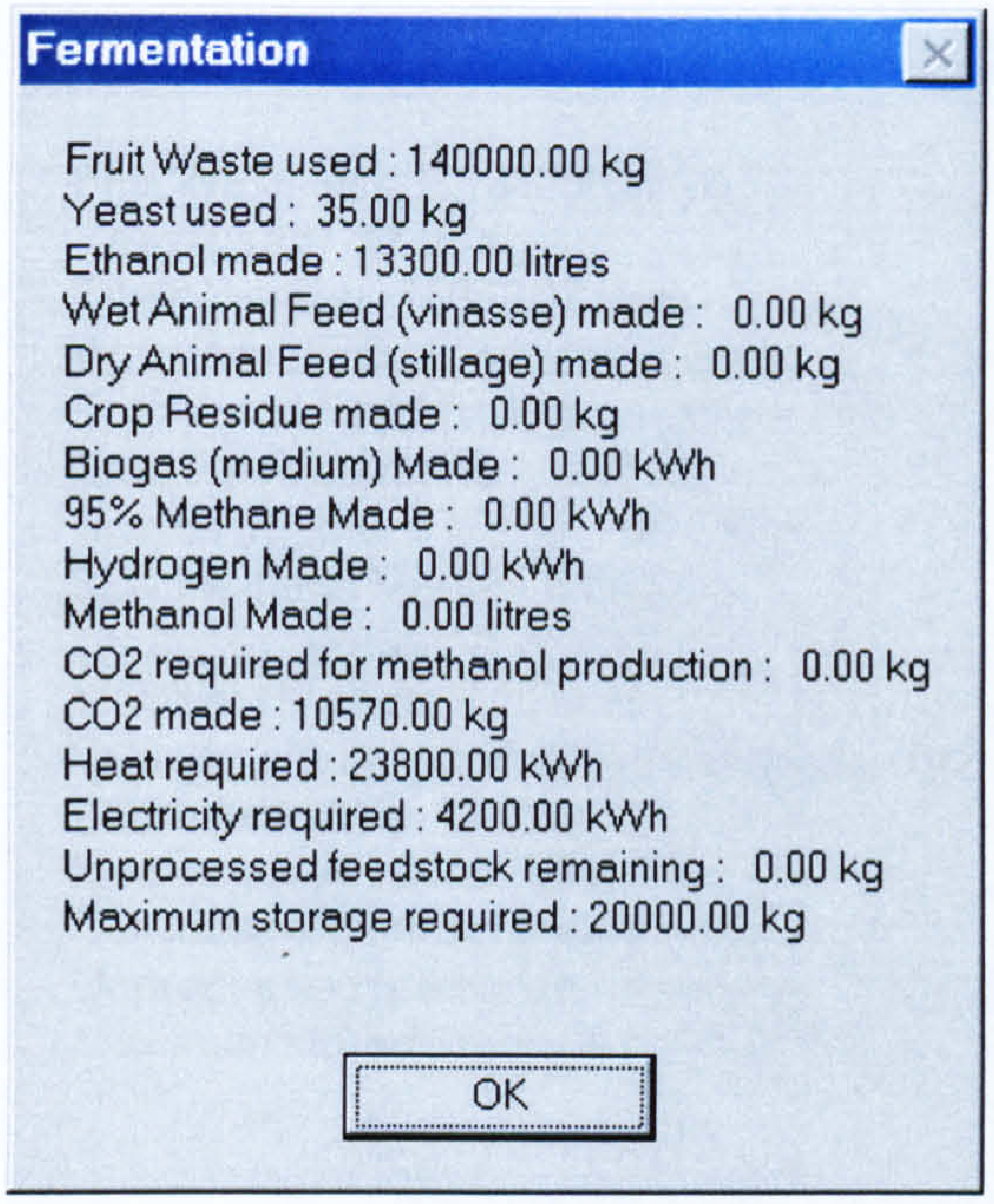
Combined Profile Name:

○ Continuous ○ Seasonal

Selection Summary

Fuel Supply Profiles Selected

Figure 7.4 Fermentation System Output (Insufficient Feedstock)



Fermentation

Fruit Waste used : 140000.00 kg
Yeast used : 35.00 kg
Ethanol made : 13300.00 litres
Wet Animal Feed (vinasse) made : 0.00 kg
Dry Animal Feed (stillage) made : 0.00 kg
Crop Residue made : 0.00 kg
Biogas (medium) Made : 0.00 kWh
95% Methane Made : 0.00 kWh
Hydrogen Made : 0.00 kWh
Methanol Made : 0.00 litres
CO2 required for methanol production : 0.00 kg
CO2 made : 10570.00 kg
Heat required : 23800.00 kWh
Electricity required : 4200.00 kWh
Unprocessed feedstock remaining : 0.00 kg
Maximum storage required : 20000.00 kg

Figure 7.5 Fermentation System Information Box (Insufficient Feedstock)

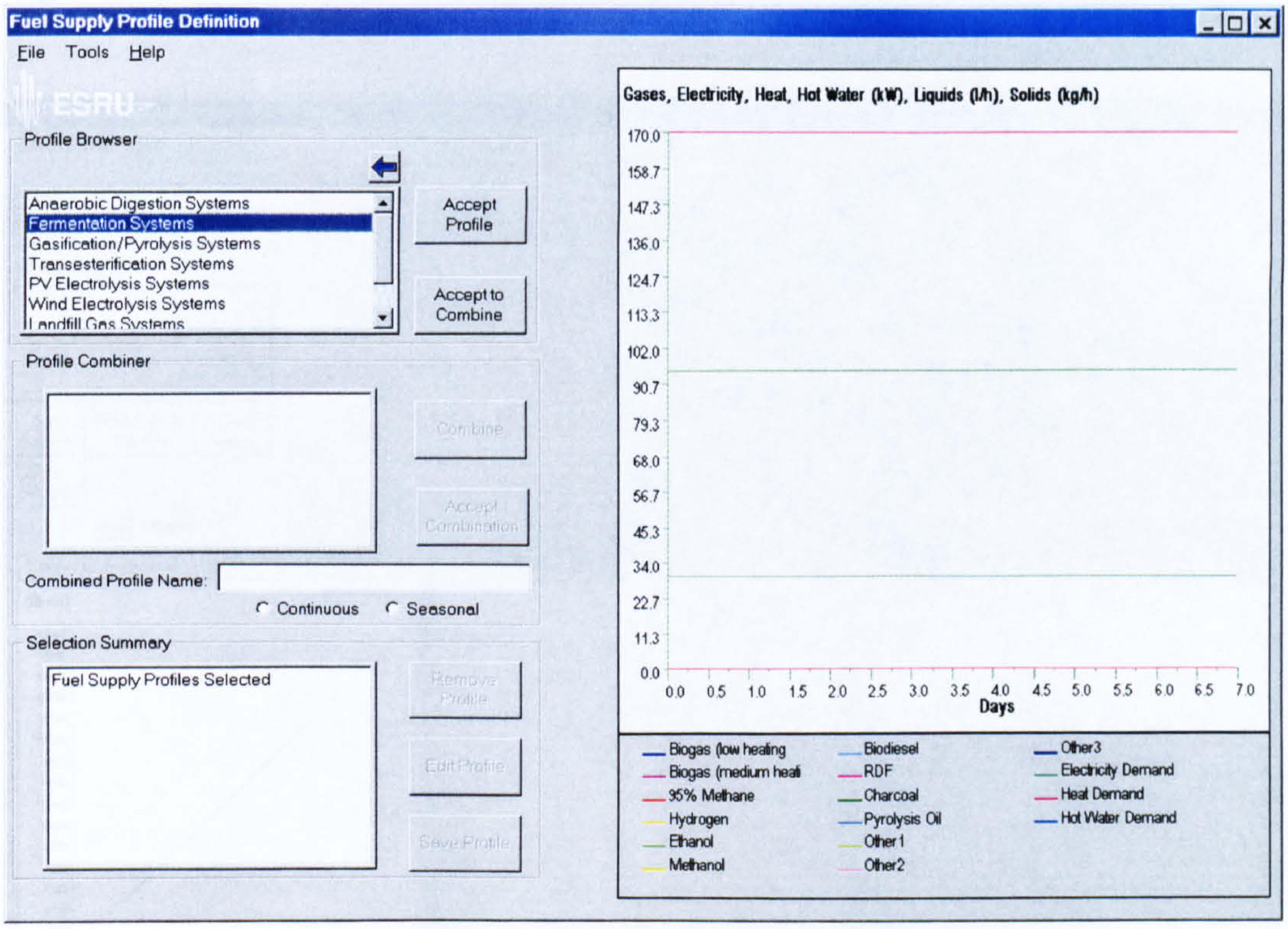
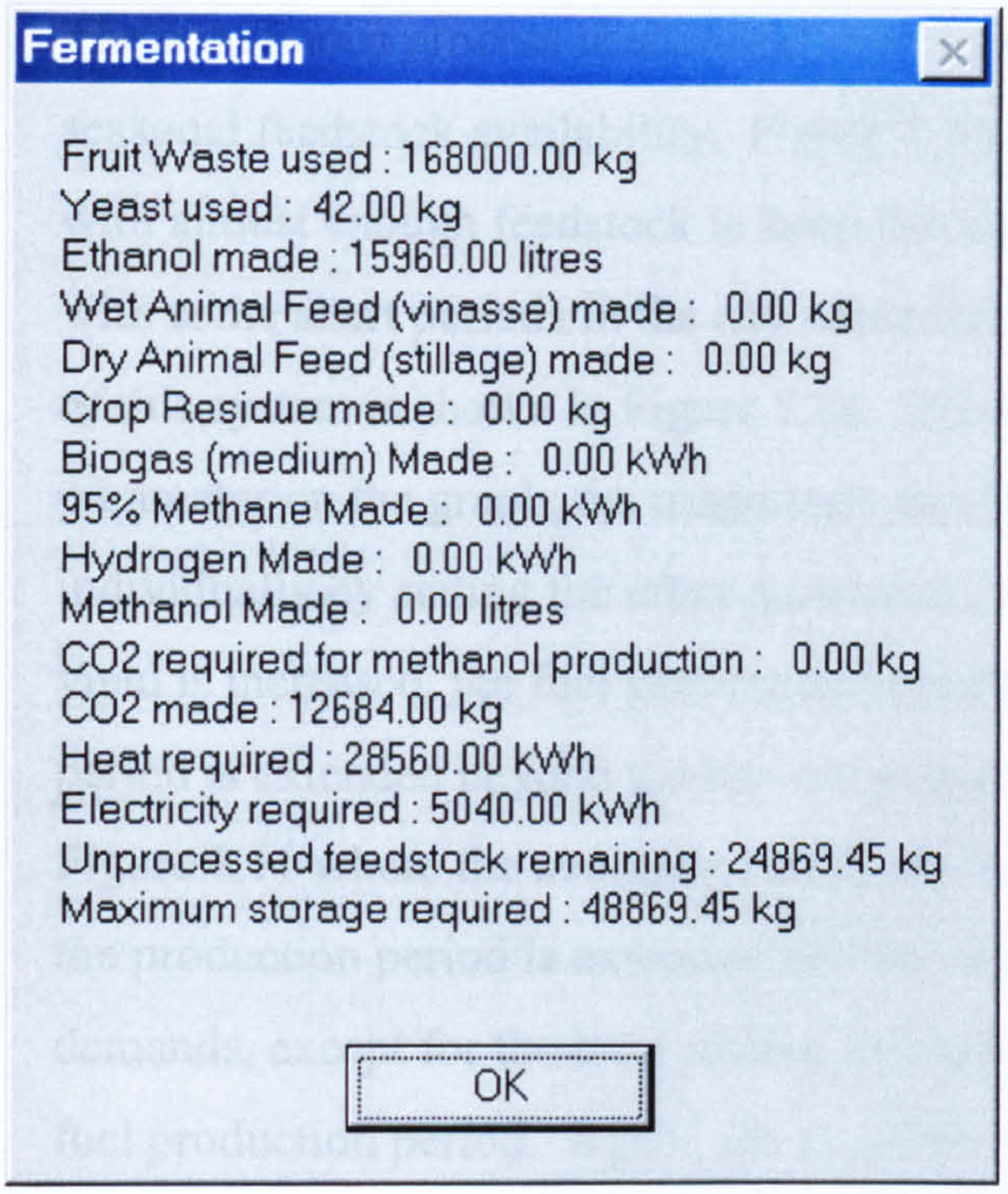
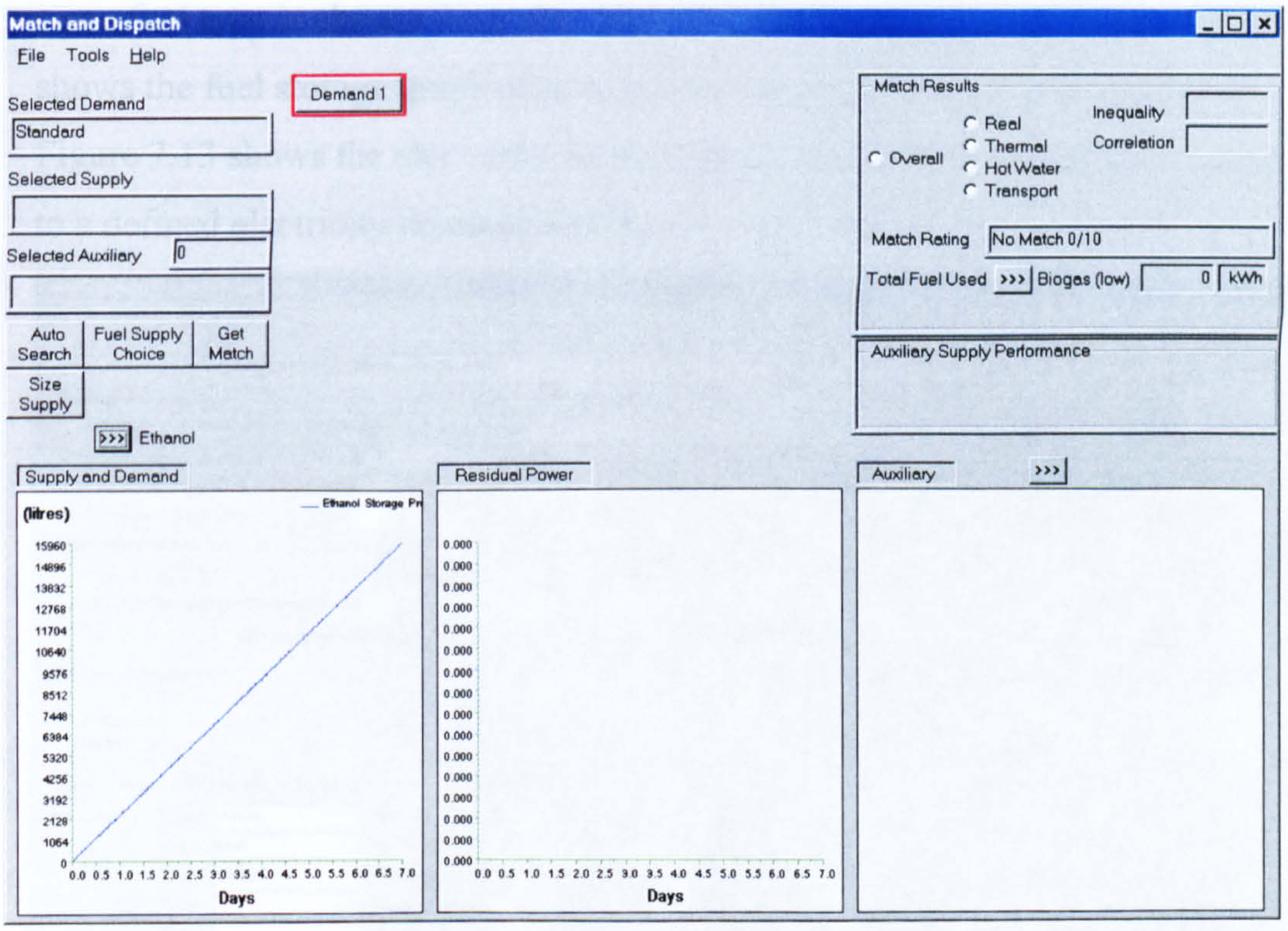


Figure 7.6 Fermentation System Output (Sufficient Feedstock)



Fruit Waste used : 168000.00 kg
Yeast used : 42.00 kg
Ethanol made : 15960.00 litres
Wet Animal Feed (vinasse) made : 0.00 kg
Dry Animal Feed (stillage) made : 0.00 kg
Crop Residue made : 0.00 kg
Biogas (medium) Made : 0.00 kWh
95% Methane Made : 0.00 kWh
Hydrogen Made : 0.00 kWh
Methanol Made : 0.00 litres
CO2 required for methanol production : 0.00 kg
CO2 made : 12684.00 kg
Heat required : 28560.00 kWh
Electricity required : 5040.00 kWh
Unprocessed feedstock remaining : 24869.45 kg
Maximum storage required : 48869.45 kg

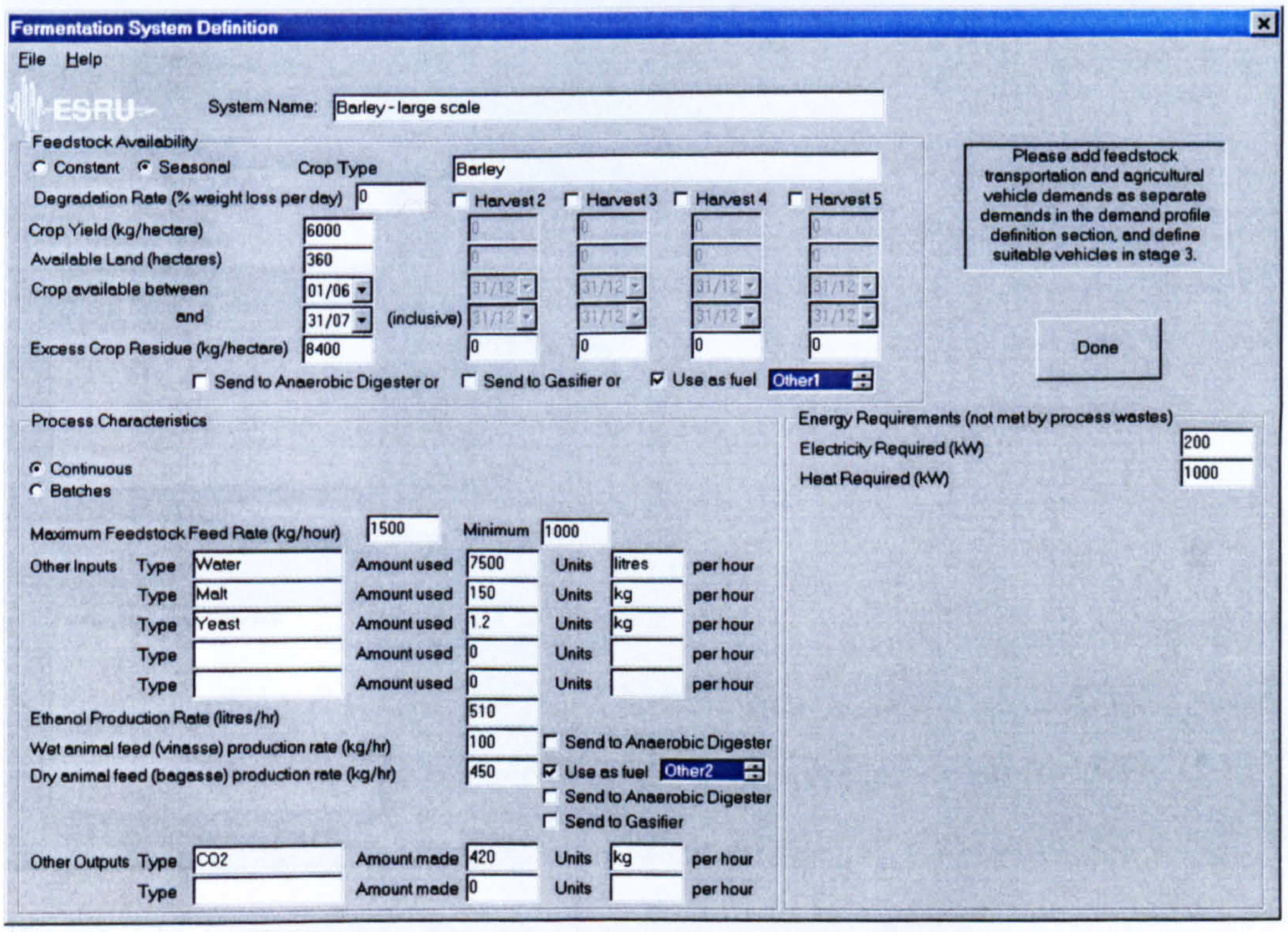
Figure 7.7 Fermentation System Information Box (Insufficient Feedstock)



Selected Demand: Standard
Selected Auxiliary: 0
Match Rating: No Match 0/10
Total Fuel Used >>> Biogas (low) 0 kWh

Figure 7.8 Fuel Storage Graph at the Matching Stage

The continuous process is analysed over a year to verify the handling of seasonal feedstock availability. Figure 7.9 shows the specification for a system with almost enough feedstock to keep the fermenter running continuously, but with some short periods in the day when feedstock is not available. The output of this system is shown in Figure 7.10. If it is difficult to see the output for each parameter on the graph, the magnitude and timing of these are tested individually by setting the other parameters to zero. If the available land or crop yield is increased, the fuel generation becomes continuous, and the production period is extended beyond the harvest period, as expected. This can be seen in Figure 7.11 where the available land is set to 1500 hectares and, subsequently, the production period is extended into the next year. All fuel production and demands, except for the crop residue availability, are continuous throughout the fuel production period. Again, the magnitude and timing of all the outputs are analysed against calculated results, as is the overall data in the information box. The correct allocation of the residues to Other1 and Other2 is checked, and if the same fuel type is chosen for both, these are correctly combined. Figure 7.12 shows the fuel storage graph obtained from the output shown in Figure 7.10. Figure 7.13 shows the electricity demand associated with this production added to a defined electricity demand profile.



System Name: Barley - large scale

Feedstock Availability

○ Constant ● Seasonal

Crop Type: Barley

Degradation Rate (% weight loss per day): 0

Crop Yield (kg/hectare): 6000

Available Land (hectares): 360

Crop available between 01/06 and 31/07 (inclusive)

Excess Crop Residue (kg/hectare): 8400

☐ Harvest 2 ☐ Harvest 3 ☐ Harvest 4 ☐ Harvest 5

☐ Send to Anaerobic Digester or ☐ Send to Gasifier or ☑ Use as fuel Other1

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Process Characteristics

● Continuous
○ Batches

Maximum Feedstock Feed Rate (kg/hour): 1500 Minimum: 1000

Other Inputs	Type	Water	Amount used	7500	Units	litres	per hour
	Type	Malt	Amount used	150	Units	kg	per hour
	Type	Yeast	Amount used	1.2	Units	kg	per hour
	Type		Amount used	0	Units		per hour
	Type		Amount used	0	Units		per hour

Ethanol Production Rate (litres/hr): 510

Wet animal feed (vinasse) production rate (kg/hr): 100 ☐ Send to Anaerobic Digester

Dry animal feed (bagasse) production rate (kg/hr): 450 ☑ Use as fuel Other2 ☐ Send to Anaerobic Digester ☐ Send to Gasifier

Other Outputs	Type	CO2	Amount made	420	Units	kg	per hour
	Type		Amount made	0	Units		per hour

Energy Requirements (not met by process wastes)

Electricity Required (kW): 200

Heat Required (kW): 1000

Figure 7.9 Fermentation System Input Parameters

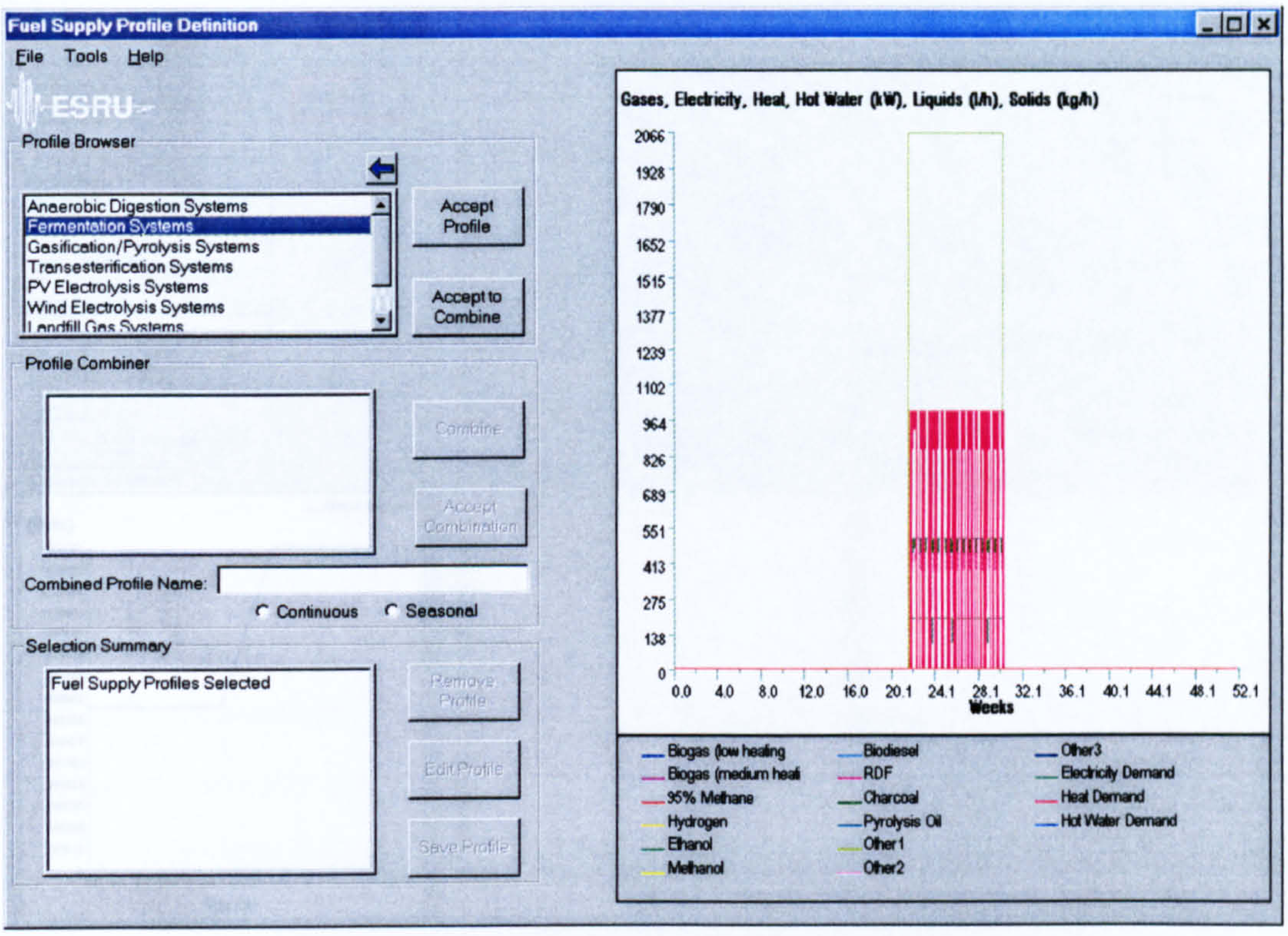


Figure 7.10 Fermentation System Output (Insufficient Feedstock)

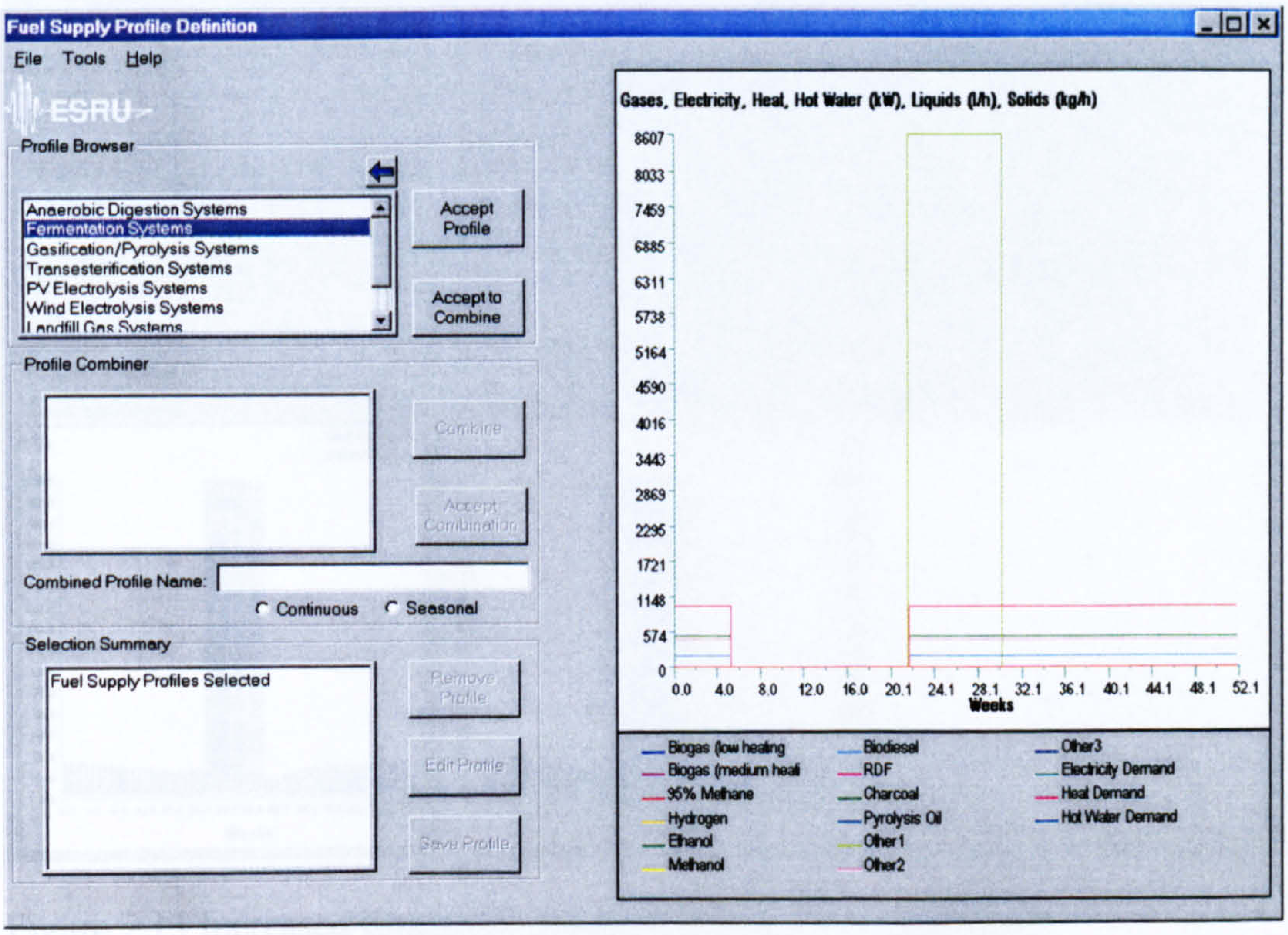
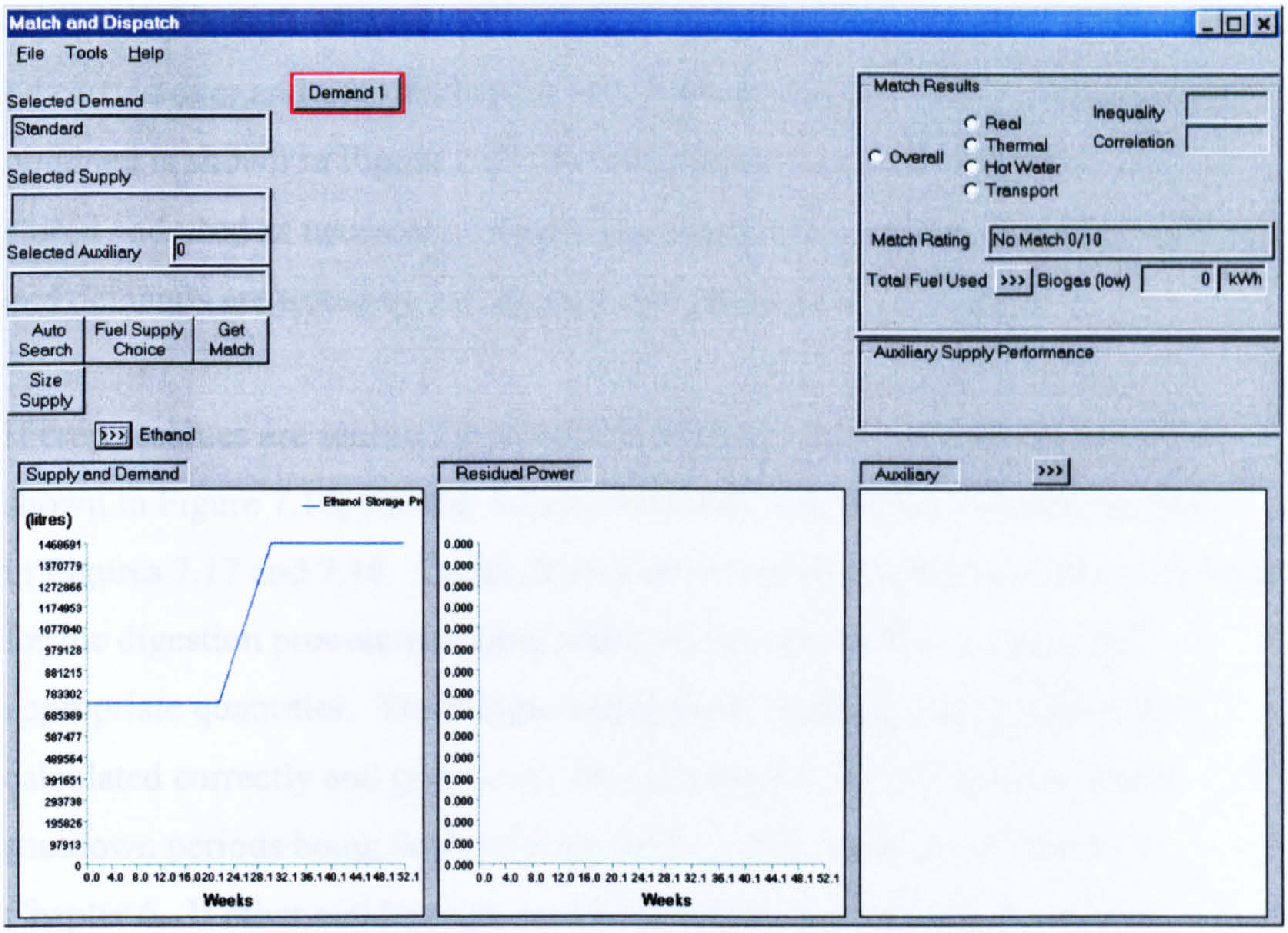


Figure 7.11 Fermentation System Output (Excess Feedstock)



Selected Demand: Standard

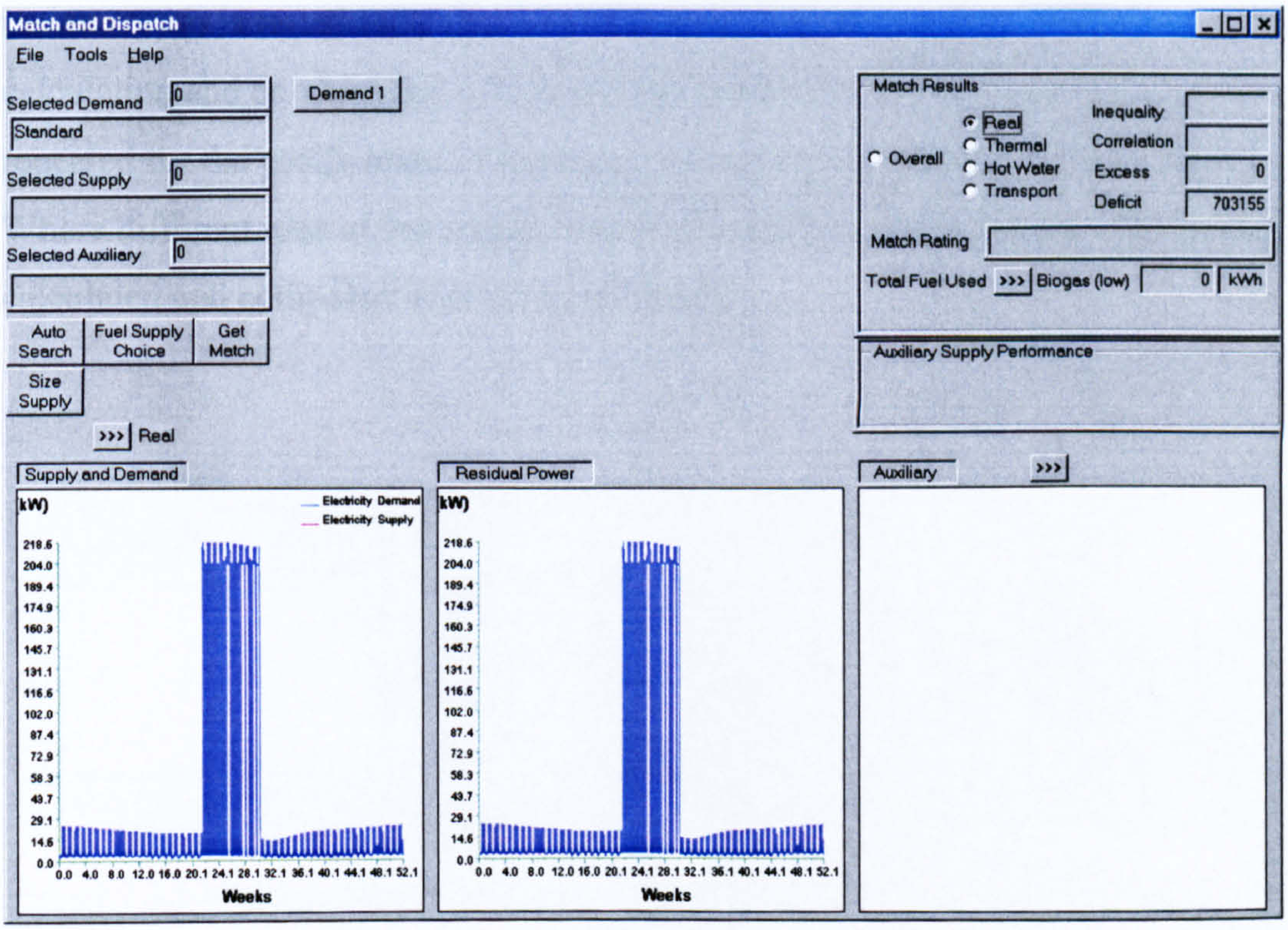
Selected Auxiliary: 0

>>> Ethanol

Match Rating: No Match 0/10

Total Fuel Used >>> Biogas (low) 0 kWh

Figure 7.12 Fuel Storage Graph at the Matching Stage



Selected Demand: 0 Standard

Selected Supply: 0

Selected Auxiliary: 0

>>> Real

Excess: 0

Deficit: 703155

Total Fuel Used >>> Biogas (low) 0 kWh

Figure 7.13 Increased Electricity Demand Due to Fuel Production

The output obtained when a second harvest period with larger feedstock availability is defined is shown in figure 7.14. If this allows some feedstock to be carried over and used during the next harvest period, the production graph obtained is shown in Figure 7.15, showing that the feedstock is being correctly stored and used as necessary. Again, the magnitudes and timing of the supplies and demands are tested by calculation, and against the input times.

If crop residues are sent to the anaerobic digester, these parameters are set as shown in Figure 7.16, and the outputs produced and energy required are shown in Figures 7.17 and 7.18. These show that the extra heat and electricity required for the digestion process are being added at the correct times, and in the appropriate quantities. The biogas output from the digestion process is also calculated correctly and given over the appropriate time, with start-up and shutdown periods being dealt with according to the assumptions made in Chapter 6. If other residues are sent to the anaerobic digester, the process parameters are defined separately, and the model is tested to ensure that outputs of the same type are combined correctly. The anaerobic digestion of all three residue types is tested individually and in combination to ensure proper calculation and combination of outputs and demands. This process is also repeated for the gasification of residues, both individually and in combination. Where different uses of the output biogas are specified, the expected outputs are calculated and compared with the given results.

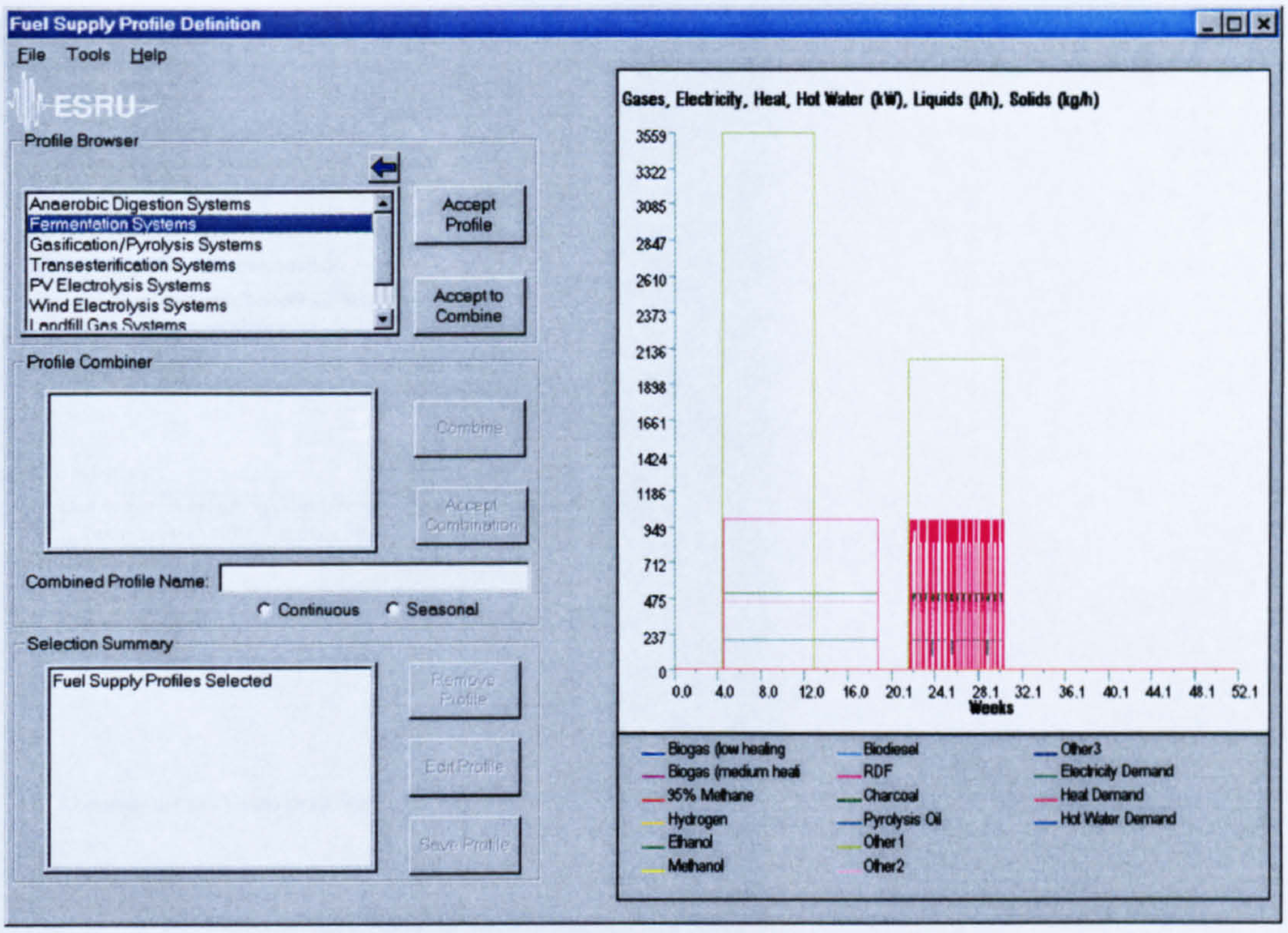


Figure 7.14 Multiple Harvest Period Output (1)

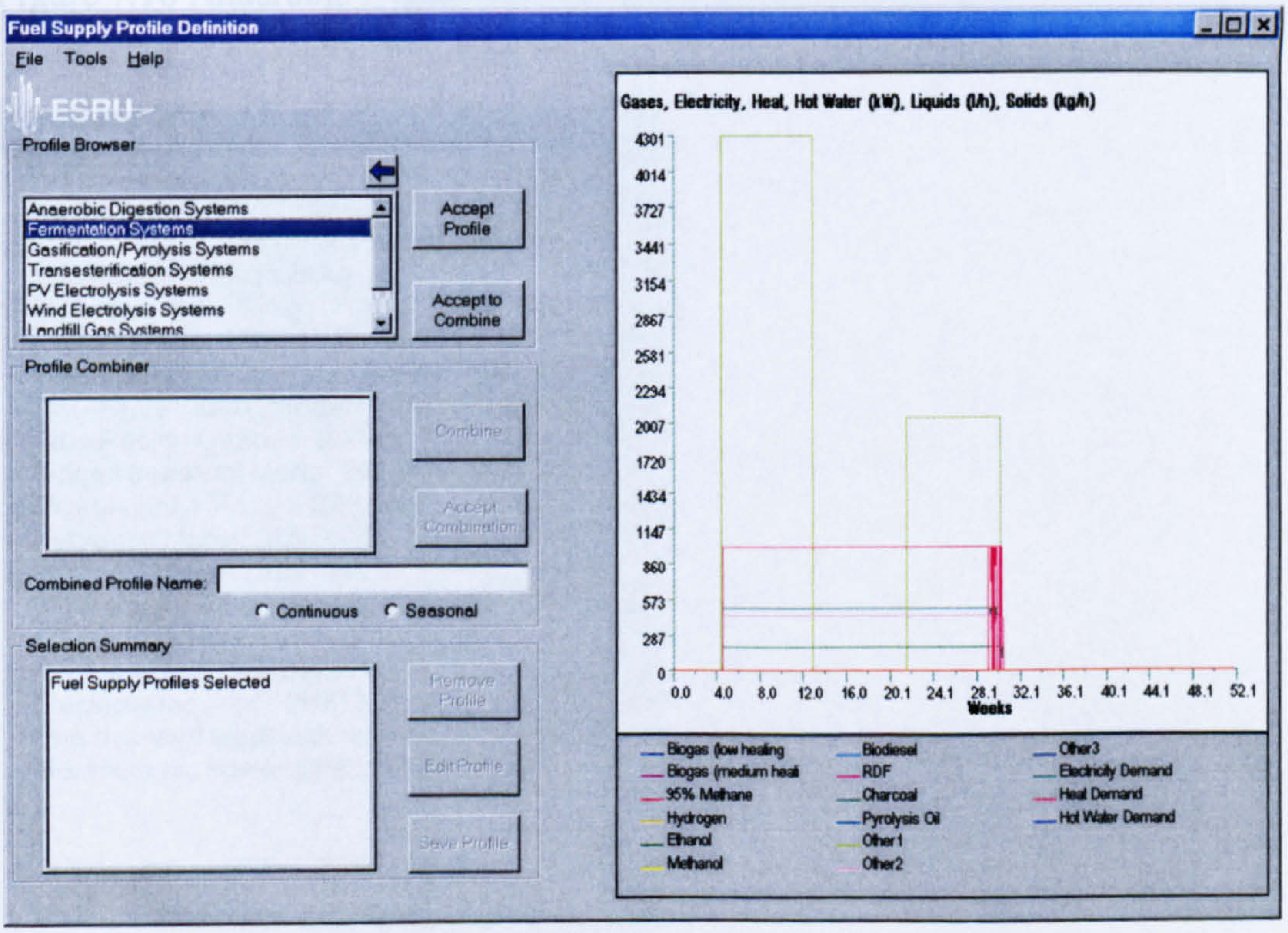
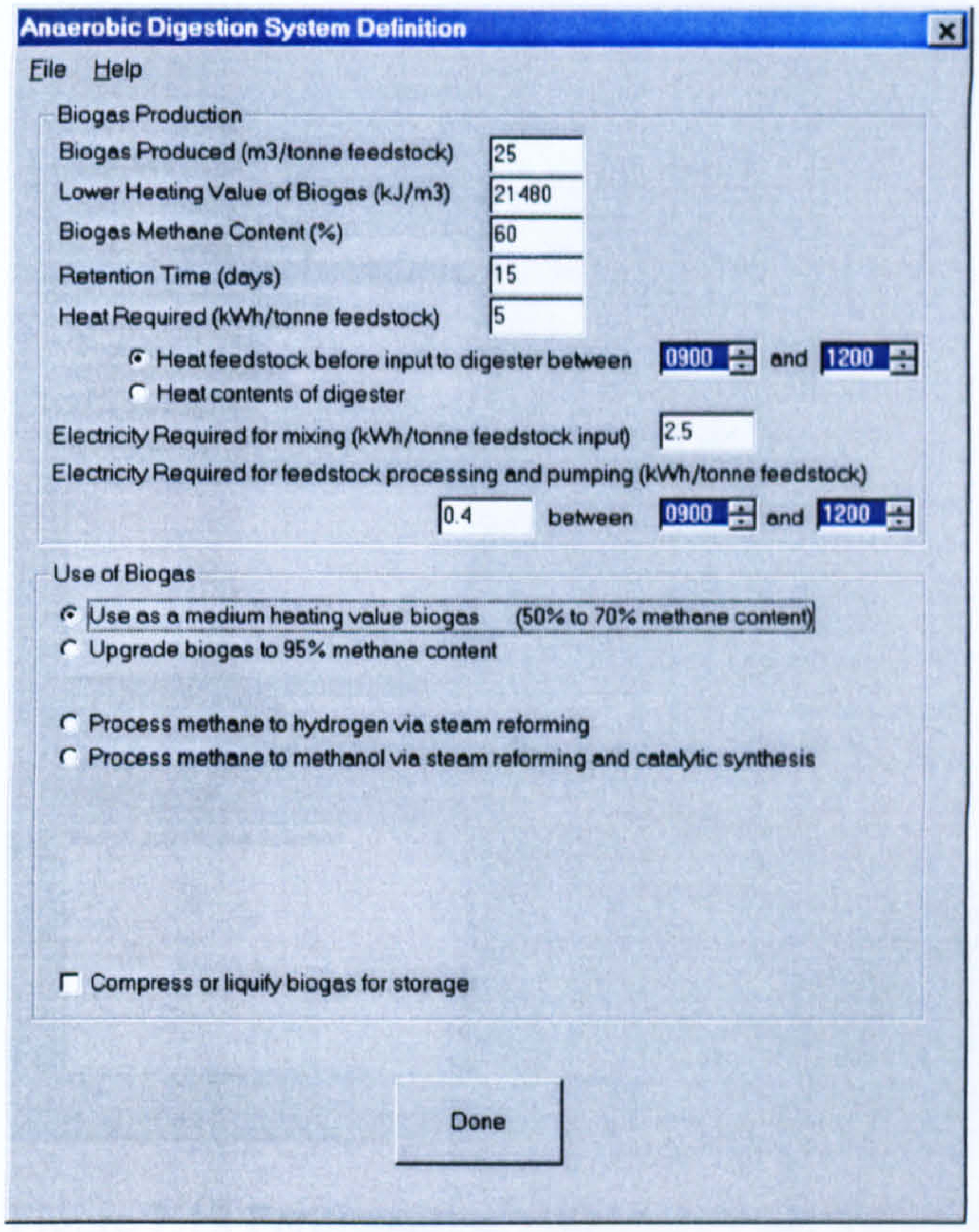


Figure 7.15 Multiple Harvest Period Output (2)



Biogas Production

Biogas Produced (m3/tonne feedstock) 25

Lower Heating Value of Biogas (kJ/m3) 21480

Biogas Methane Content (%) 60

Retention Time (days) 15

Heat Required (kWh/tonne feedstock) 5

● Heat feedstock before input to digester between 0900 and 1200

○ Heat contents of digester

Electricity Required for mixing (kWh/tonne feedstock input) 2.5

Electricity Required for feedstock processing and pumping (kWh/tonne feedstock) 0.4 between 0900 and 1200

Use of Biogas

● Use as a medium heating value biogas (50% to 70% methane content)

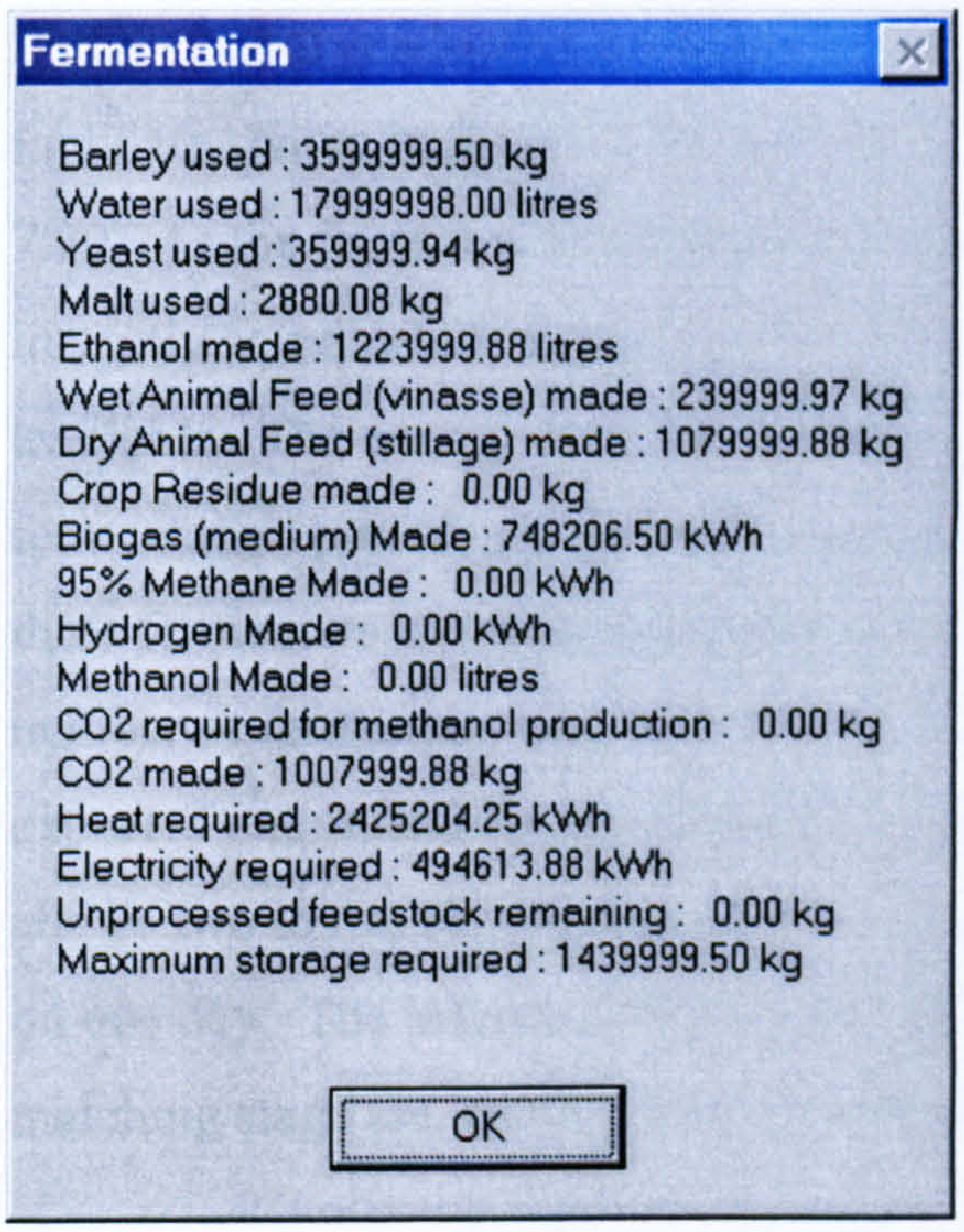
○ Upgrade biogas to 95% methane content

○ Process methane to hydrogen via steam reforming

○ Process methane to methanol via steam reforming and catalytic synthesis

☐ Compress or liquify biogas for storage

Figure 7.16 Anaerobic Digestion Parameters for the Crop Residues



```
Barley used : 3599999.50 kg
Water used : 17999998.00 litres
Yeast used : 359999.94 kg
Malt used : 2880.08 kg
Ethanol made : 1223999.88 litres
Wet Animal Feed (vinasse) made : 239999.97 kg
Dry Animal Feed (stillage) made : 1079999.88 kg
Crop Residue made :  0.00 kg
Biogas (medium) Made : 748206.50 kWh
95% Methane Made :  0.00 kWh
Hydrogen Made :  0.00 kWh
Methanol Made :  0.00 litres
CO2 required for methanol production :  0.00 kg
CO2 made : 1007999.88 kg
Heat required : 2425204.25 kWh
Electricity required : 494613.88 kWh
Unprocessed feedstock remaining :  0.00 kg
Maximum storage required : 1439999.50 kg
```

Figure 7.17 Information Box

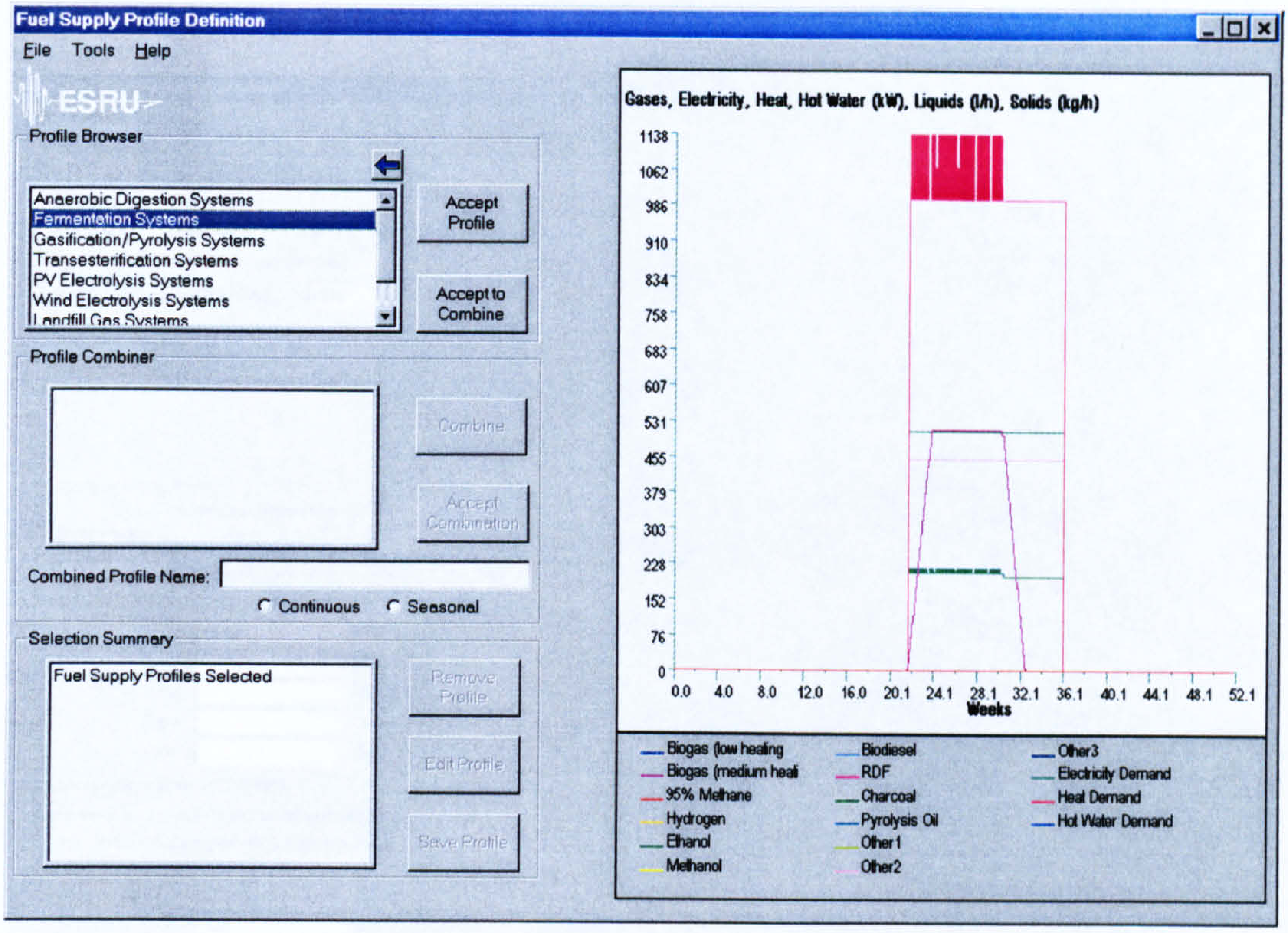
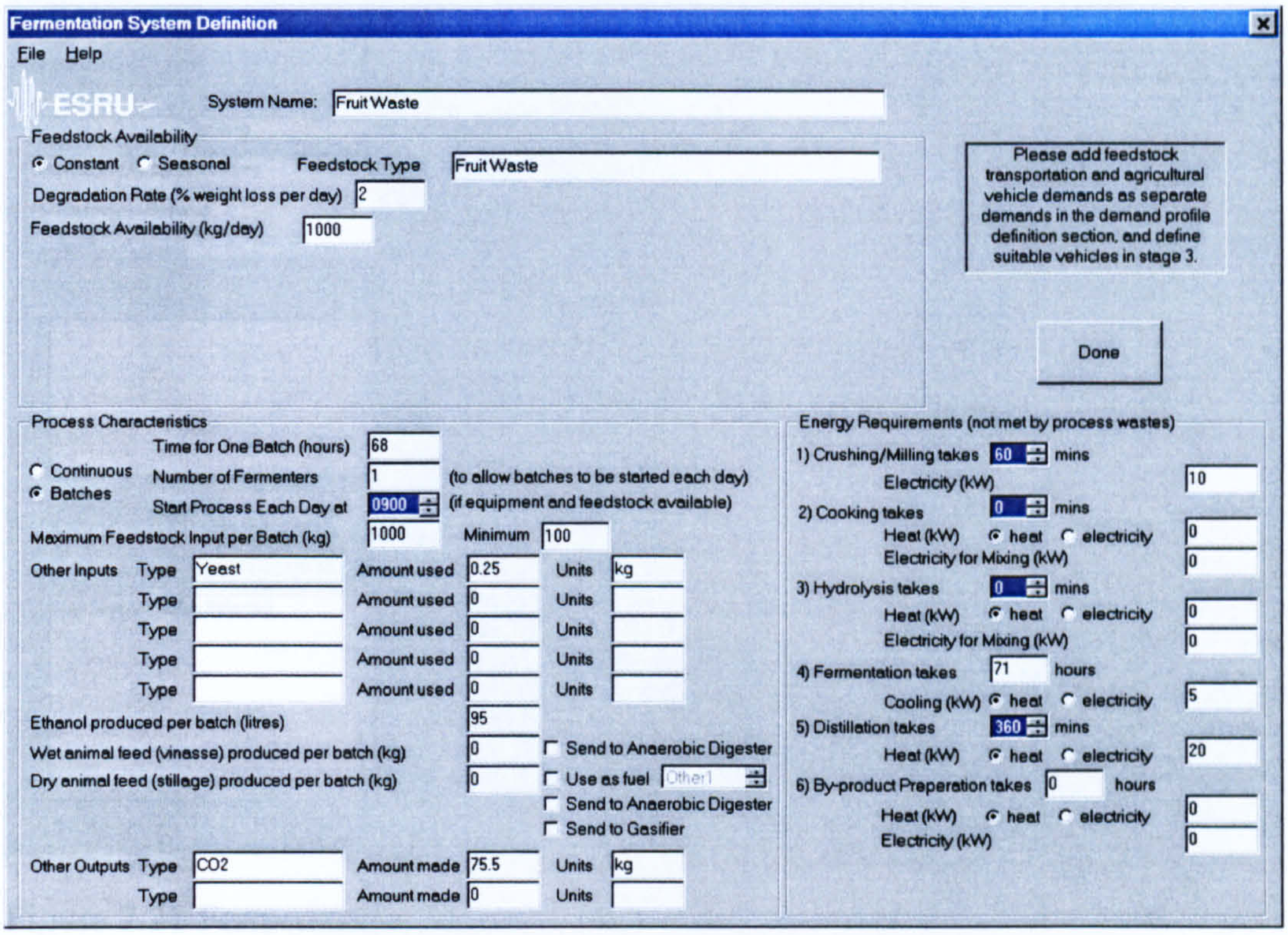


Figure 7.18 Fermentation Output Including Anaerobic Digestion

Batch ethanol production is tested first for one fermenter only. The parameters input are shown in Figure 7.19, and the output graph obtained is given in Figure 7.20. As the feedstock availability is constant, the ethanol production starts instantly as expected, and is once every three days as there is only one fermenter available. The energy demands, some of which occur after the 68-hour main fermentation period, are properly calculated and summed at the correct times. If three fermenters are used, the graph shown in Figure 7.21 is given, and the number of fermenters may be increased further, if desired, still giving the expected output and energy demands. For example, using four fermenters allows two to run simultaneously for one day in three, giving a doubled output on one day. The information box data and the storage graph generated at the matching stage are, again, tested for temporal and quantitative accuracy.

Similar testing was carried out for seasonal batch production, and for the gasification or anaerobic digestion of residues produced by batch production, and expected results were obtained. Similar comprehensive tests were also carried out, as necessary, for all the other fuel supply production models.



Fermentation System Definition

System Name: Fruit Waste

Feedstock Availability

● Constant ○ Seasonal

Feedstock Type: Fruit Waste

Degradation Rate (% weight loss per day): 2

Feedstock Availability (kg/day): 1000

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Process Characteristics

○ Continuous

● Batches

Time for One Batch (hours): 68

Number of Fermenters: 1 (to allow batches to be started each day)

Start Process Each Day at: 0900 (if equipment and feedstock available)

Maximum Feedstock Input per Batch (kg): 1000 Minimum: 100

Other Inputs	Type	Yeast	Amount used	0.25	Units	kg
	Type		Amount used	0	Units	
	Type		Amount used	0	Units	
	Type		Amount used	0	Units	
	Type		Amount used	0	Units	

Ethanol produced per batch (litres): 95

Wet animal feed (vinasse) produced per batch (kg): 0 ☐ Send to Anaerobic Digester

Dry animal feed (stillage) produced per batch (kg): 0 ☐ Use as fuel Other1 ☐ Send to Anaerobic Digester ☐ Send to Gasifier

Other Outputs	Type	CO2	Amount made	75.5	Units	kg
	Type		Amount made	0	Units	

Energy Requirements (not met by process wastes)

1) Crushing/Milling takes 60 mins
Electricity (kW): 10

2) Cooking takes 0 mins
Heat (kW) ● heat ○ electricity: 0
Electricity for Mixing (kW): 0

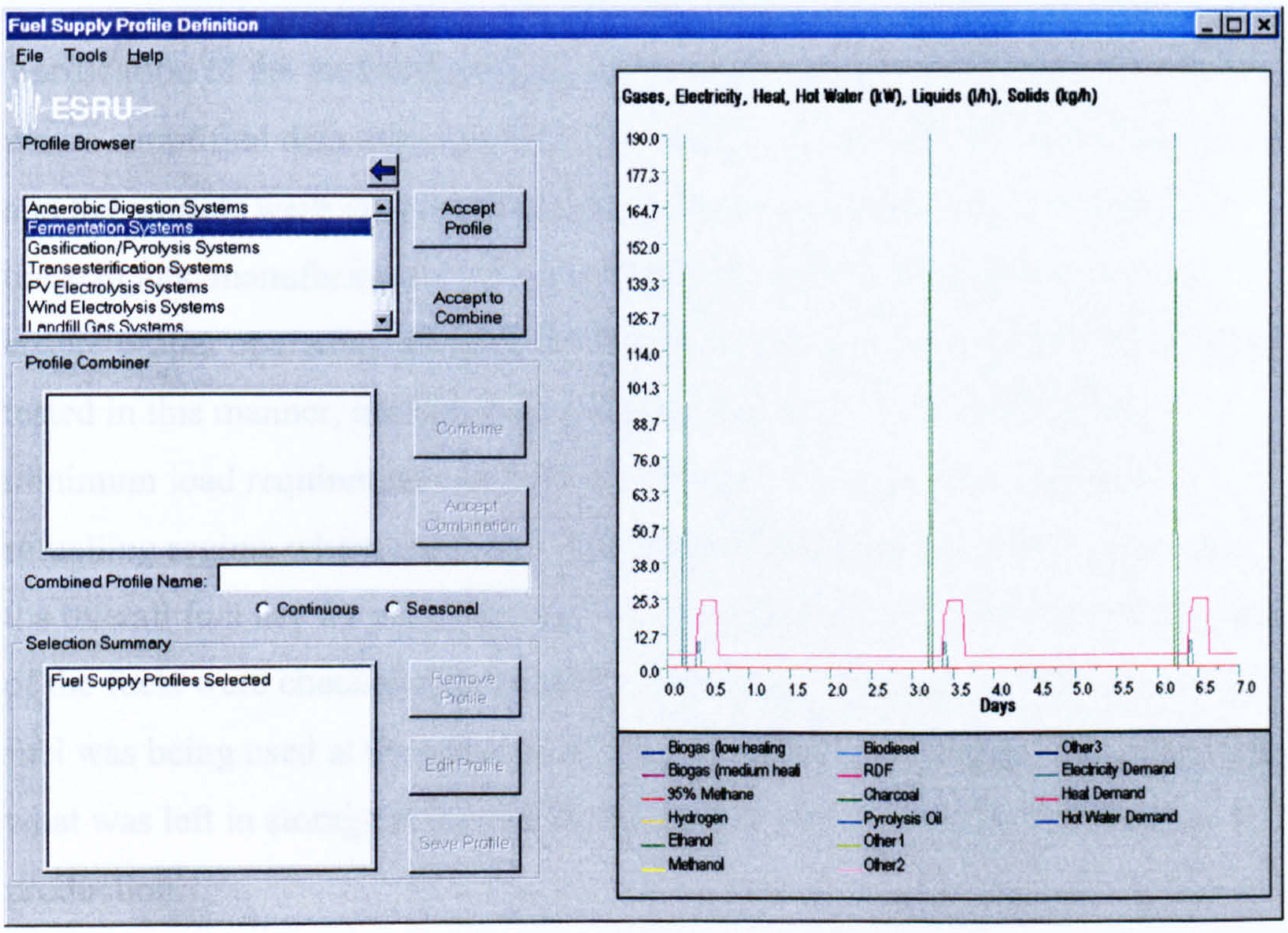
3) Hydrolysis takes 0 mins
Heat (kW) ● heat ○ electricity: 0
Electricity for Mixing (kW): 0

4) Fermentation takes 71 hours
Cooling (kW) ● heat ○ electricity: 5

5) Distillation takes 360 mins
Heat (kW) ● heat ○ electricity: 20

6) By-product Preperation takes 0 hours
Heat (kW) ● heat ○ electricity: 0
Electricity (kW): 0

Figure 7.19 Fermentation System Input Parameters



Fuel Supply Profile Definition

Profile Browser

- Anaerobic Digestion Systems
- Fermentation Systems
- Gasification/Pyrolysis Systems
- Transesterification Systems
- PV Electrolysis Systems
- Wind Electrolysis Systems
- Landfill Gas Systems

Profile Combiner

Combined Profile Name:

○ Continuous ○ Seasonal

Selection Summary

Fuel Supply Profiles Selected

Figure 7.20 Fermentation System Output (Batch Production)

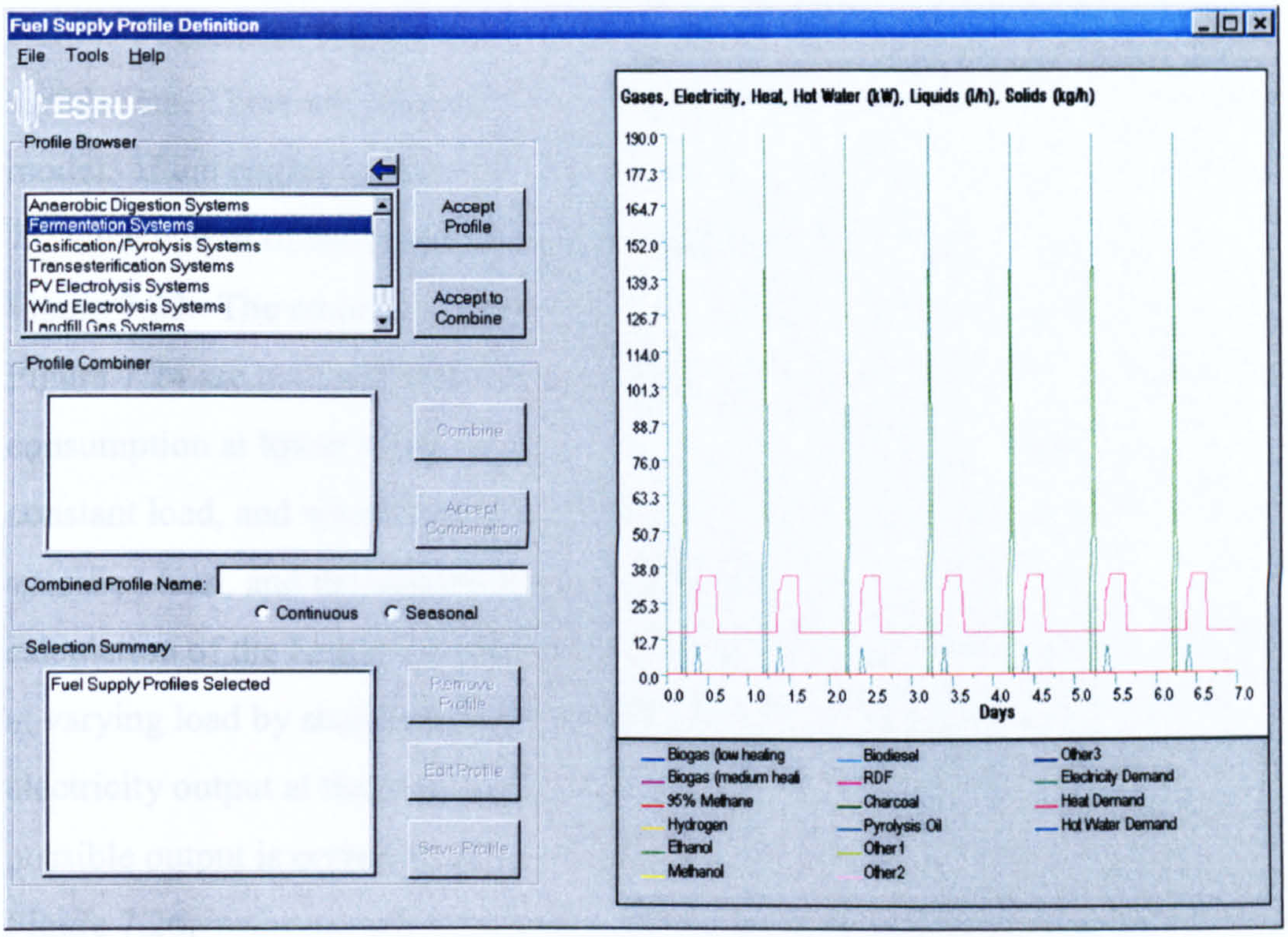
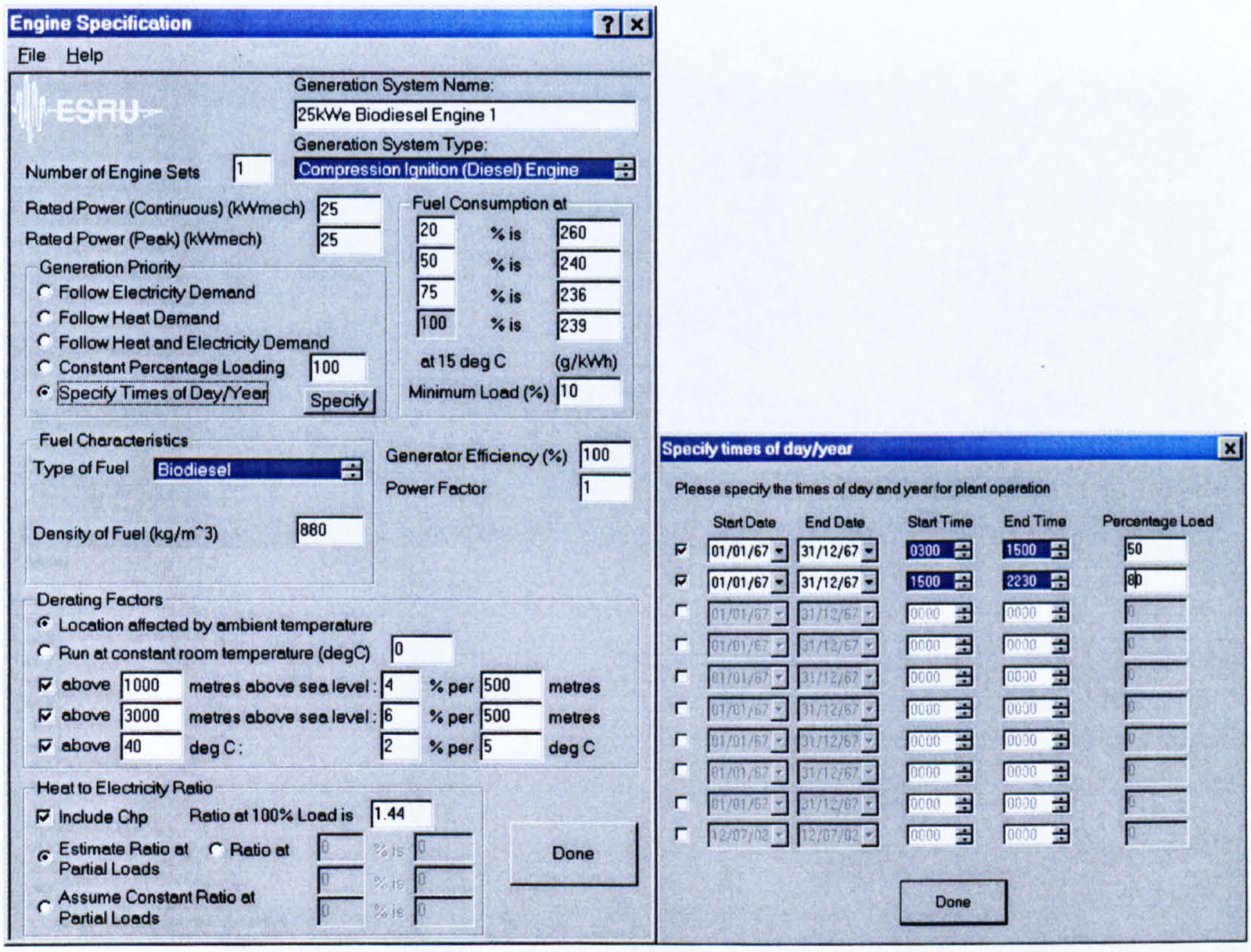


Figure 7.21 Fermentation System Output (Batch Production)

7.2.2 *Auxiliary Supply Specification*

Verification of the load following supplies was carried out at the matching stage, where simplified demands, and fuel and energy inputs were fed into the systems, and the outputs were analysed against expected calculated behaviour based on these inputs, manufacturers' data and specified control strategies. In order to ensure proper operation, all aspects of the different models' performances were tested in this manner, including increased fuel demand at lower loading, minimum load requirement, and the following of the appropriate demand or refuelling regime where required. The fuel used by each individual plant, and the overall fuel use for each fuel type was verified. The storage profiles for each of the fuels were checked against the profile of use graphs in order to ensure that fuel was being used at the appropriate times, and that the overall fuel used, plus what was left in storage at the end of the period, matched the overall fuel production.

To describe the verification process for auxiliary supplies, the example of a biodiesel engine is used, and a simulation period of one day has been chosen for clarity. A constant supply rate of 100 litres/hr of biodiesel is specified for this simulation. There are various control strategies that can be used with the engine model. If the engine is set to run at specific times of the day, as shown in Figure 7.22, the output of the engine, provided enough fuel is available, is shown in Figure 7.23. The amount of fuel used and the fuel storage profile, shown in Figure 7.24 are both calculated correctly, taking into account the increased fuel consumption at lower loads. This is also the case for an engine running at a constant load, and where multiple engines are defined, all engines run at the specified load, and the calculated fuel consumption is as expected. The calculation of the heat to electricity ratio is also verified against expected results at varying load by studying the heat output (Figure 7.25) compared with the electricity output at these set loads. If there is not enough fuel available the possible output is correctly calculated using the available fuel, as shown in Figure 7.26.



Generation System Name: 25kWe Biodiesel Engine 1
Generation System Type: Compression Ignition (Diesel) Engine
Number of Engine Sets: 1
Rated Power (Continuous) (kWmech): 25
Rated Power (Peak) (kWmech): 25

Generation Priority
○ Follow Electricity Demand
○ Follow Heat Demand
○ Follow Heat and Electricity Demand
○ Constant Percentage Loading: 100
● Specify Times of Day/Year (Specify)

Fuel Consumption at
20 % is 260
50 % is 240
75 % is 236
100 % is 239
at 15 deg C (g/kWh)
Minimum Load (%): 10

Fuel Characteristics
Type of Fuel: Biodiesel
Density of Fuel (kg/m^3): 880

Generator Efficiency (%): 100
Power Factor: 1

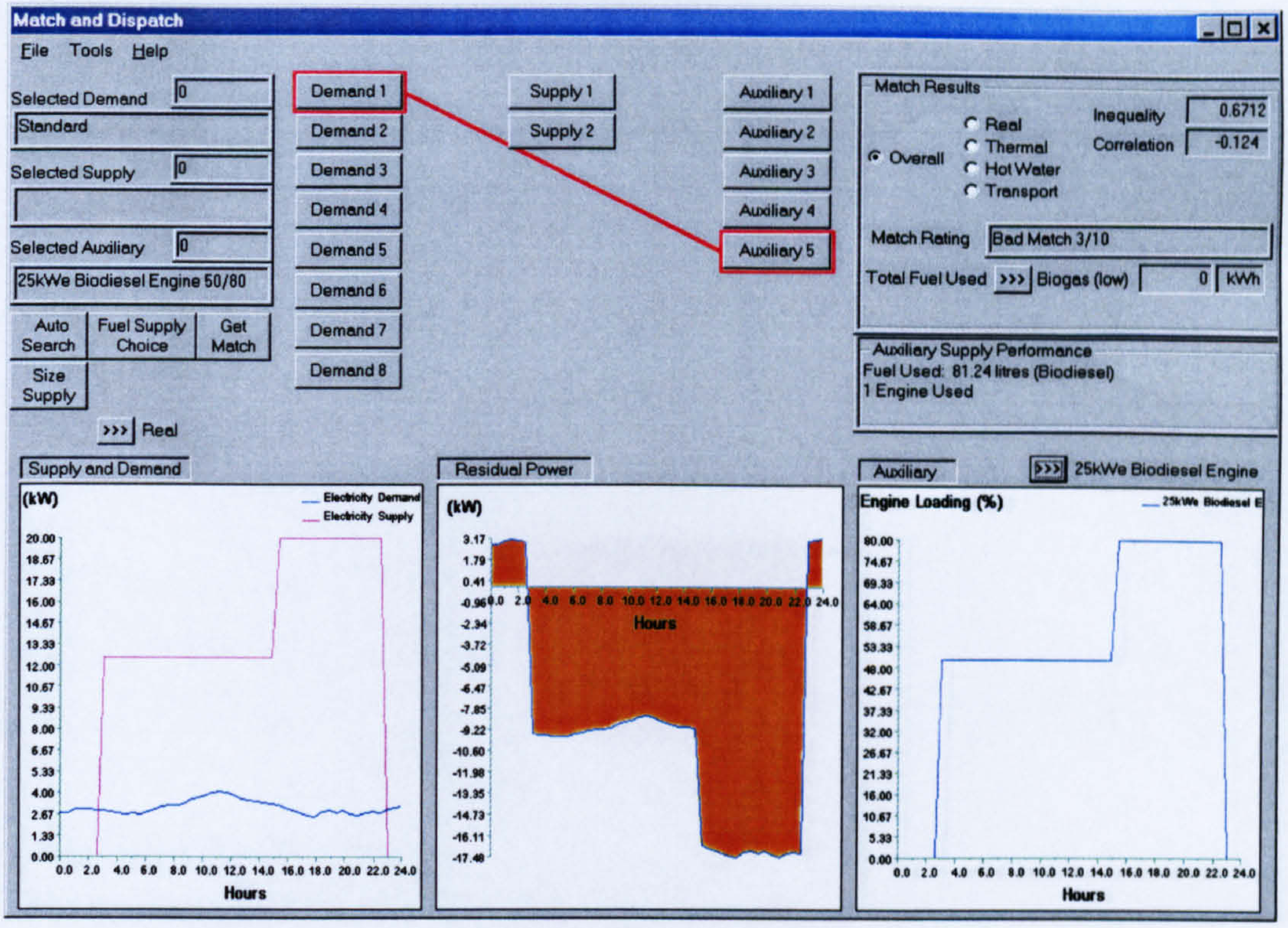
Derating Factors
● Location affected by ambient temperature
○ Run at constant room temperature (degC): 0
☑ above 1000 metres above sea level : 4 % per 500 metres
☑ above 3000 metres above sea level : 6 % per 500 metres
☑ above 40 deg C : 2 % per 5 deg C

Heat to Electricity Ratio
☑ Include Chp
Ratio at 100% Load is 1.44
● Estimate Ratio at Partial Loads
○ Ratio at 0 % is 0
0 % is 0
0 % is 0
○ Assume Constant Ratio at Partial Loads

Please specify the times of day and year for plant operation

	Start Date	End Date	Start Time	End Time	Percentage Load
☑	01/01/67	31/12/67	0300	1500	50
☑	01/01/67	31/12/67	1500	2230	80
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	12/07/02	12/07/02	0000	0000	0

Figure 7.22 Engine Specification



Selected Demand 0
Standard

Selected Supply 0

Selected Auxiliary 0
25kWe Biodiesel Engine 50/80

>>> Real

○ Real
○ Thermal
● Overall
○ Hot Water
○ Transport

Inequality 0.6712
Correlation -0.124

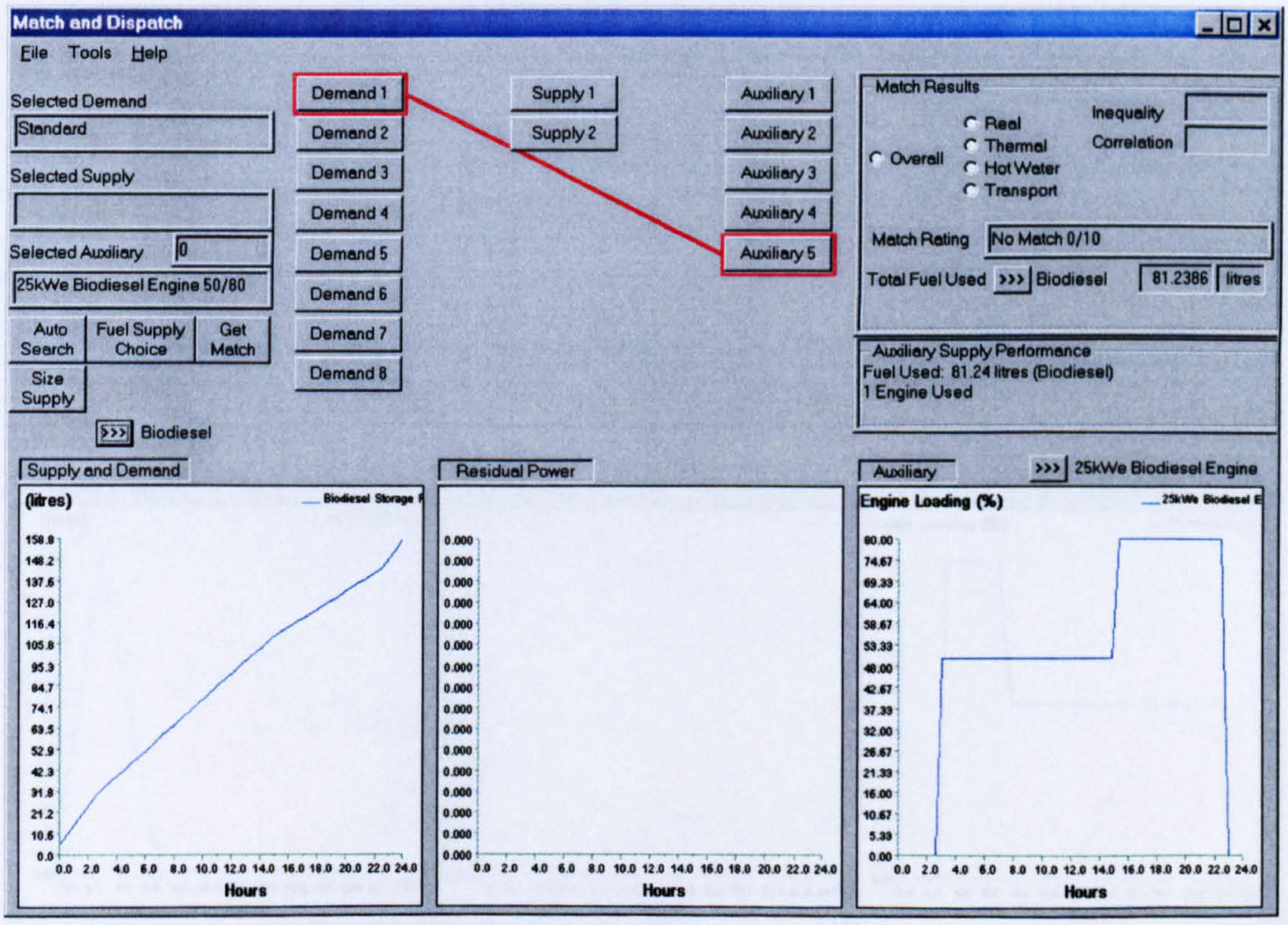
Match Rating Bad Match 3/10

Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance
Fuel Used: 81.24 litres (Biodiesel)
1 Engine Used

>>> 25kWe Biodiesel Engine

Figure 7.23 Engine Output (Run at Specific Times)



Selected Demand
Standard

Selected Supply

Selected Auxiliary 0
25kWe Biodiesel Engine 50/80

>>> Biodiesel

○ Real
○ Thermal
○ Overall
○ Hot Water
○ Transport

Inequality
Correlation

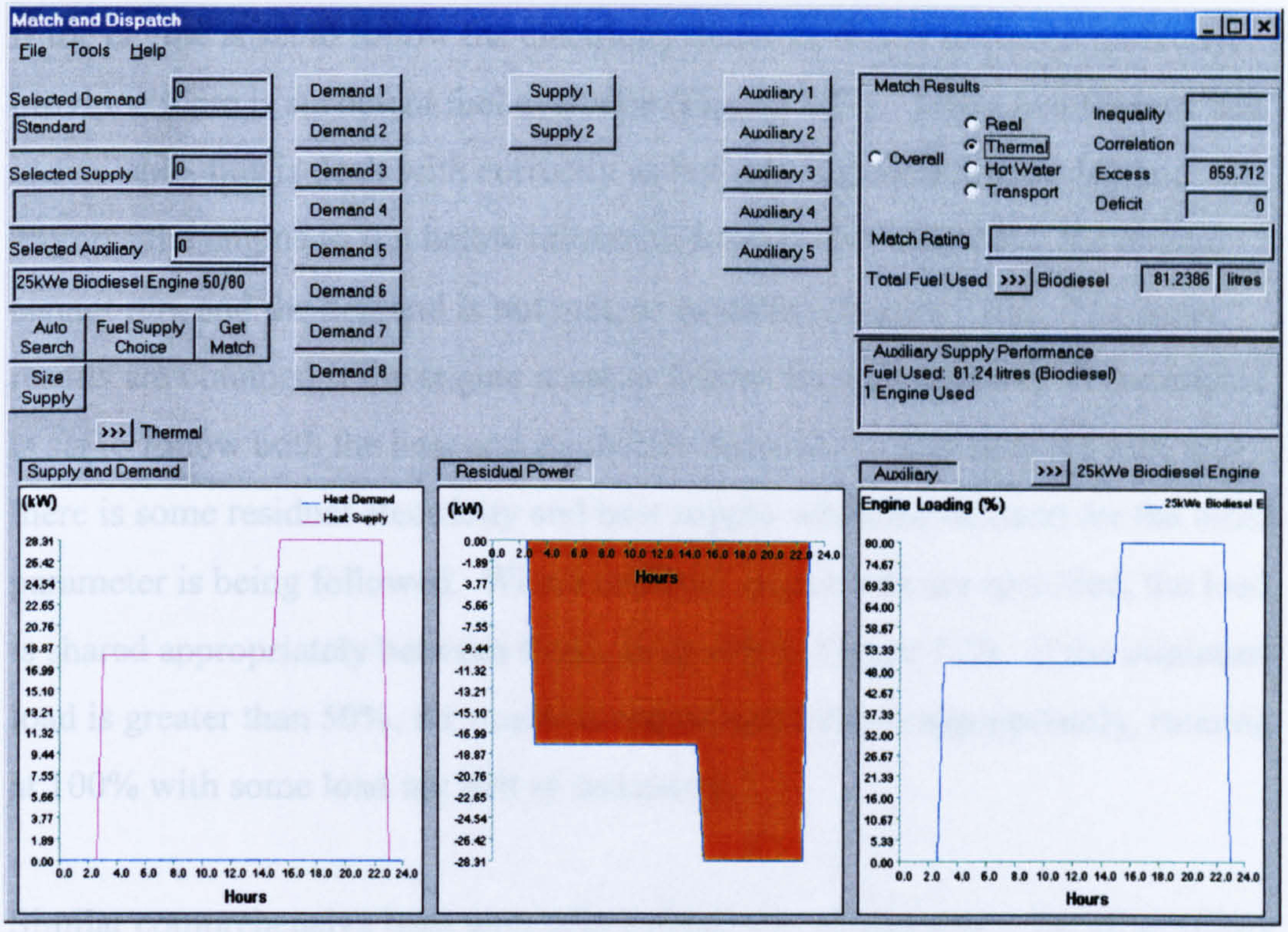
Match Rating No Match 0/10

Total Fuel Used >>> Biodiesel 81.2386 litres

Auxiliary Supply Performance
Fuel Used: 81.24 litres (Biodiesel)
1 Engine Used

>>> 25kWe Biodiesel Engine

Figure 7.24 Fuel Storage Profile



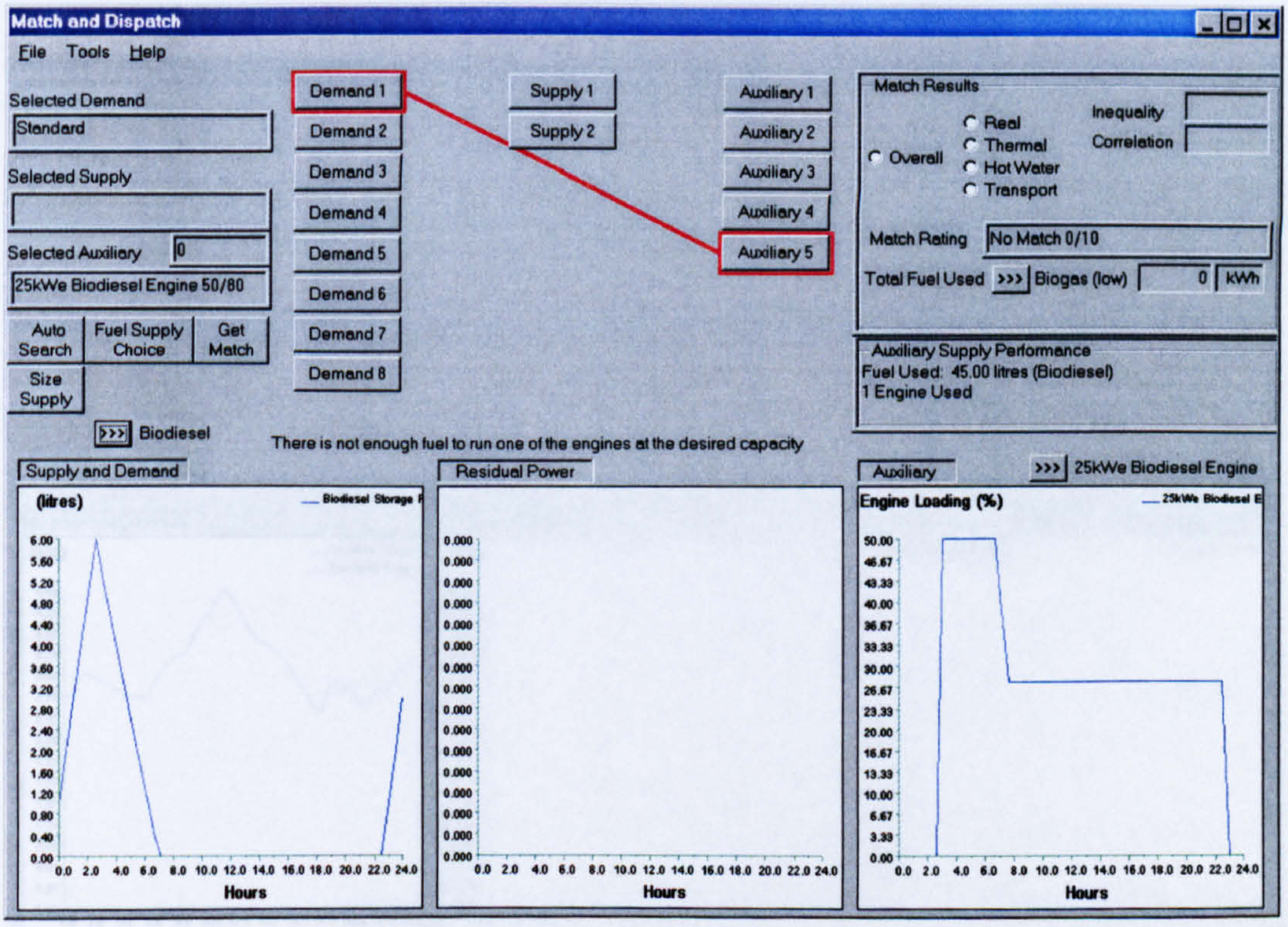
Selected Demand 0
Standard
Selected Supply 0
Selected Auxiliary 0
25kWe Biodiesel Engine 50/80
>>> Thermal

Match Results
○ Overall ○ Real ● Thermal ○ Hot Water ○ Transport
Inequality
Correlation
Excess 859.712
Deficit 0
Match Rating
Total Fuel Used >>> Biodiesel 81.2386 litres

Auxiliary Supply Performance
Fuel Used: 81.24 litres (Biodiesel)
1 Engine Used

Auxiliary >>> 25kWe Biodiesel Engine

Figure 7.25 Heat Demand Profile



Selected Demand
Standard
Selected Supply
Selected Auxiliary 0
25kWe Biodiesel Engine 50/80
>>> Biodiesel

Match Results
○ Overall ○ Real ○ Thermal ○ Hot Water ○ Transport
Inequality
Correlation
Match Rating No Match 0/10
Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance
Fuel Used: 45.00 litres (Biodiesel)
1 Engine Used

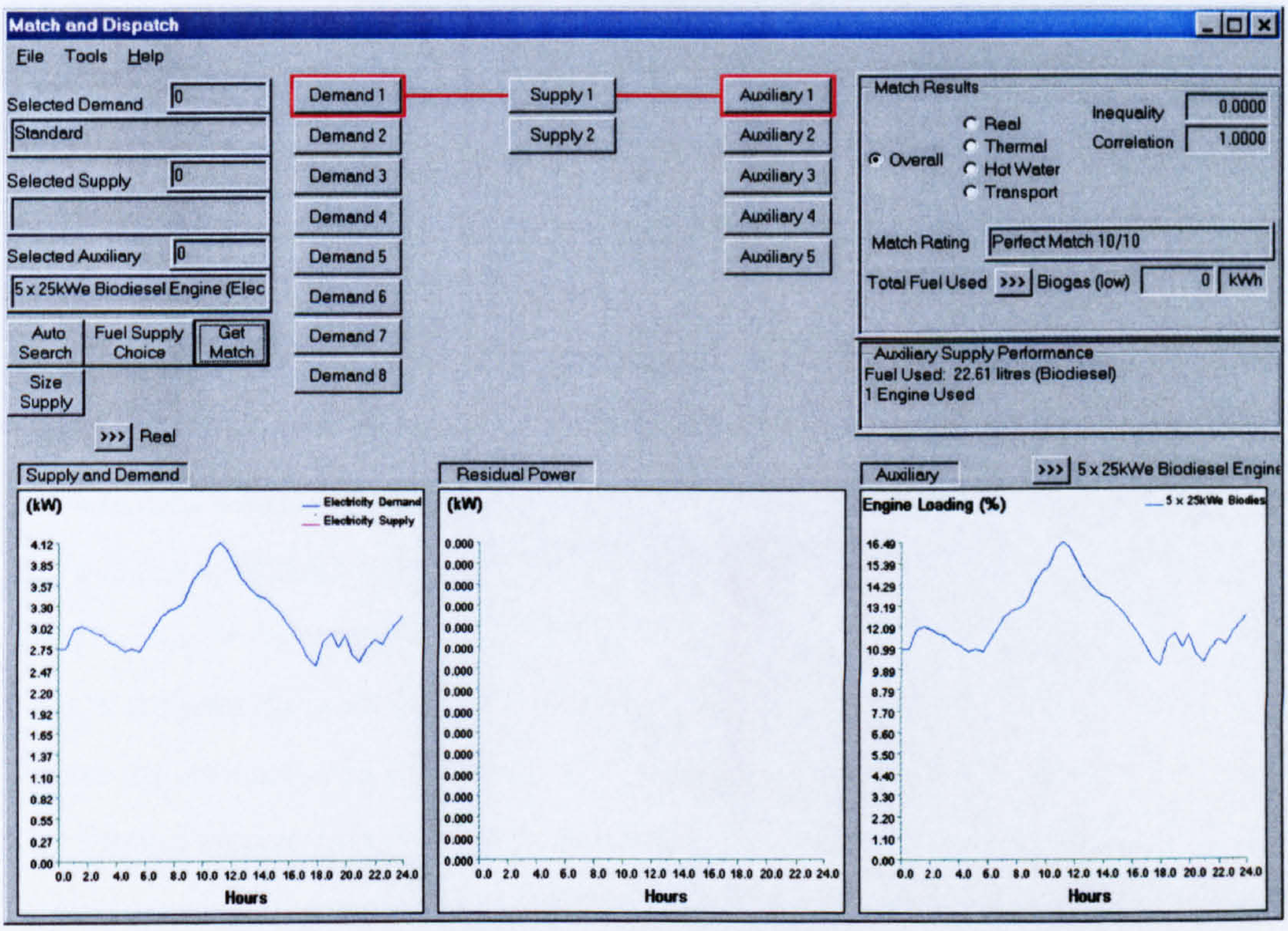
There is not enough fuel to run one of the engines at the desired capacity

Auxiliary >>> 25kWe Biodiesel Engine

Figure 7.26 Insufficient Fuel

If the engine is set to follow the electricity demand, this is followed perfectly, provided there is sufficient fuel available (Figure 7.27). When insufficient fuel is available, this is dealt with correctly as before. If the electricity demand requires the engine to run below minimum load, in this case 20%, the engine cannot run, and the demand is not met, as expected (Figure 7.28). The same results are obtained if the engine is set to follow the heat demand. If the engine is set to follow both the heat and electricity demand, all demands are met, and there is some residual electricity and heat supply when the demand for the other parameter is being followed. Where multiple engine sets are specified, the load is shared appropriately between them, as shown in Figure 7.29. If the minimum load is greater than 50%, the multiple engine sets behave appropriately, running at 100% with some load not met as necessary.

Similar comprehensive tests were also carried out, as necessary, for all auxiliary supply models, in order to test their behaviour against the input data and control or refuelling strategies as appropriate.

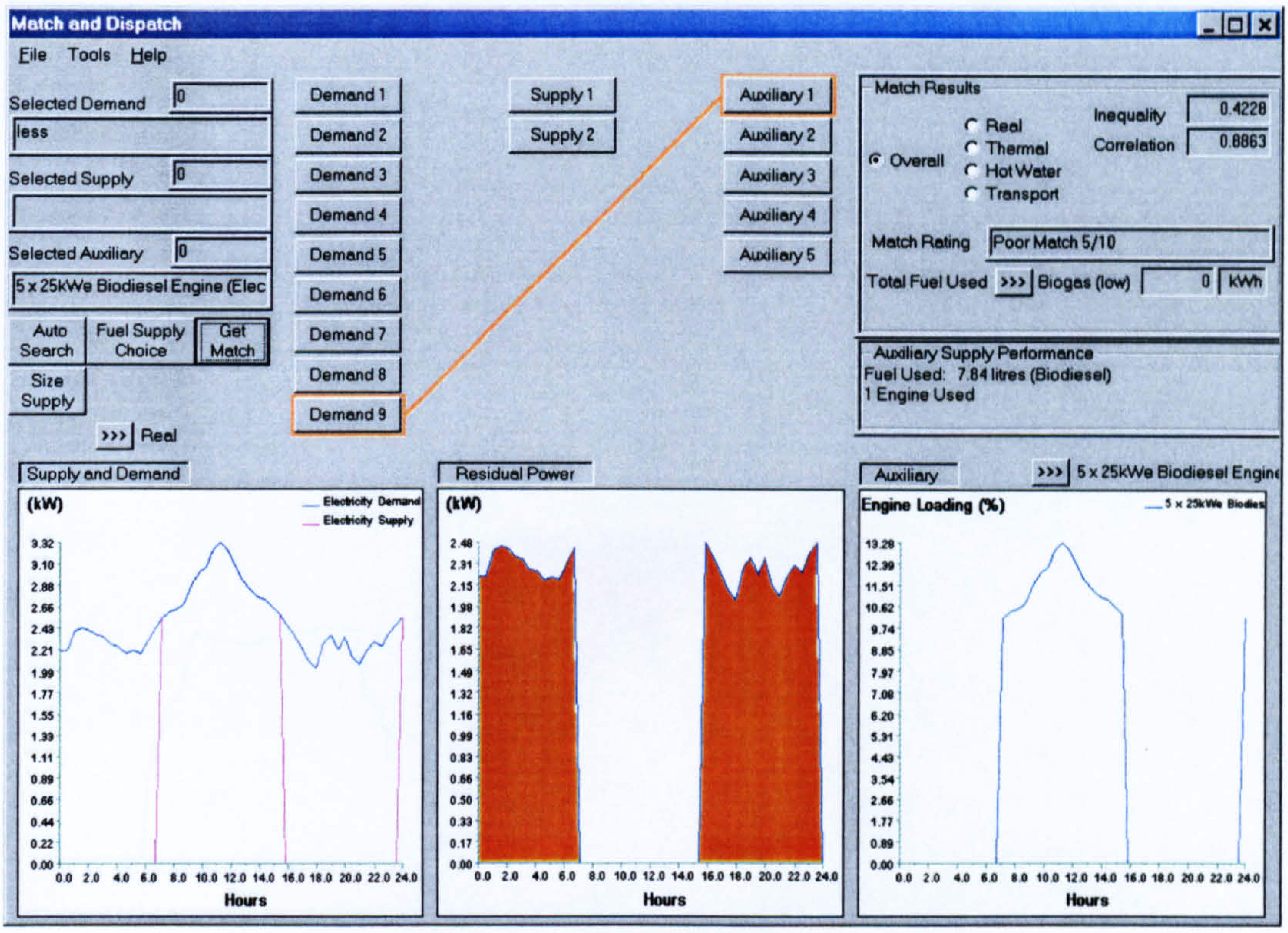


Selected Demand 0
Standard
Selected Supply 0
Selected Auxiliary 0
5 x 25kWe Biodiesel Engine (Elec

Match Results
● Overall
○ Real
○ Thermal
○ Hot Water
○ Transport
Inequality 0.0000
Correlation 1.0000
Match Rating Perfect Match 10/10
Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance
Fuel Used: 22.61 litres (Biodiesel)
1 Engine Used

Figure 7.27 Following Electricity Demand



Selected Demand: 0
less

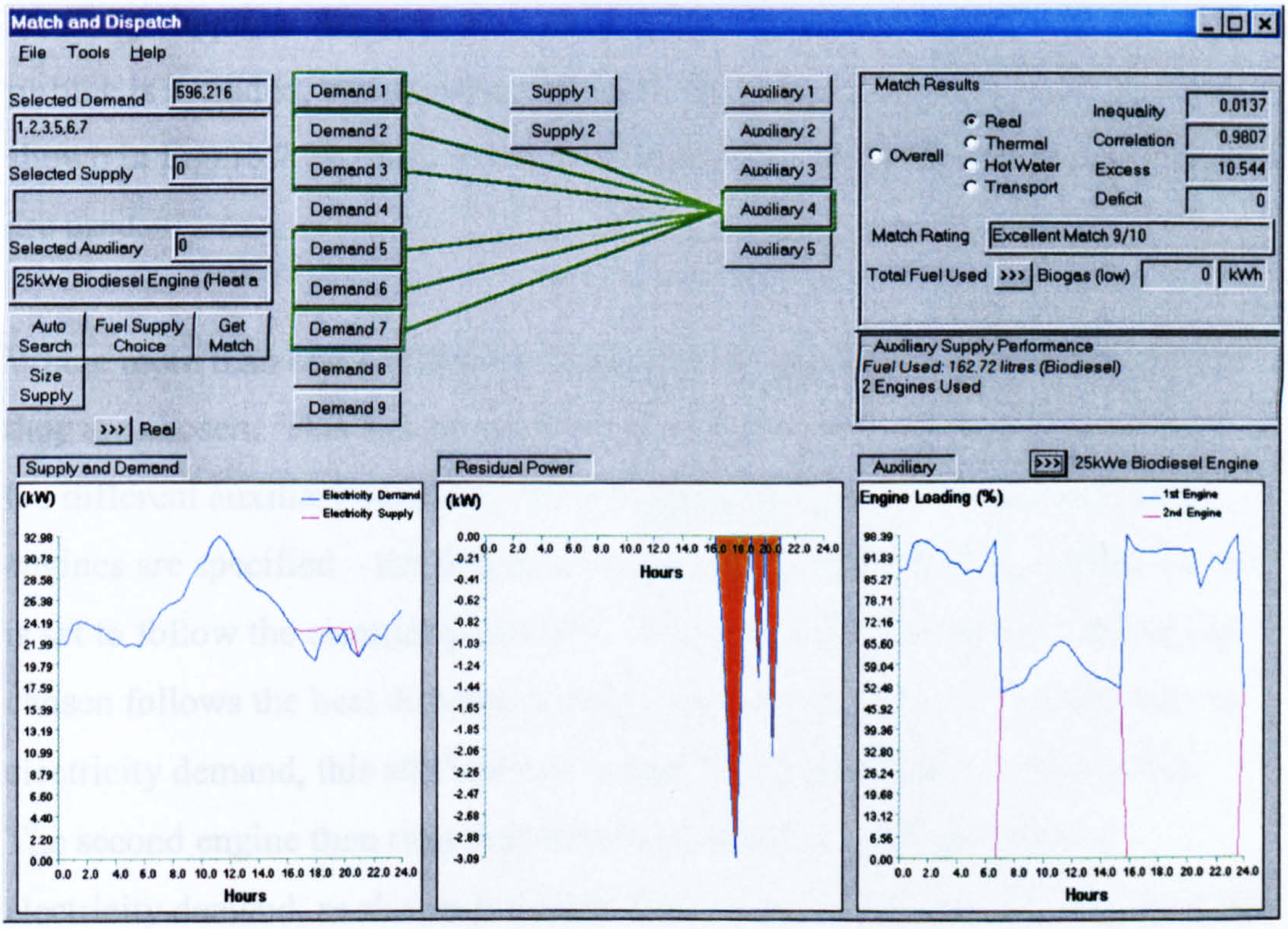
Selected Supply: 0

Selected Auxiliary: 0
5 x 25kWe Biodiesel Engine (Elec

Match Results
● Overall ○ Real ○ Thermal ○ Hot Water ○ Transport
Inequality: 0.4228
Correlation: 0.8863
Match Rating: Poor Match 5/10
Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance
Fuel Used: 7.84 litres (Biodiesel)
1 Engine Used

Figure 7.28 Effect of Minimum Load



Selected Demand: 596.216
1,2,3,5,6,7

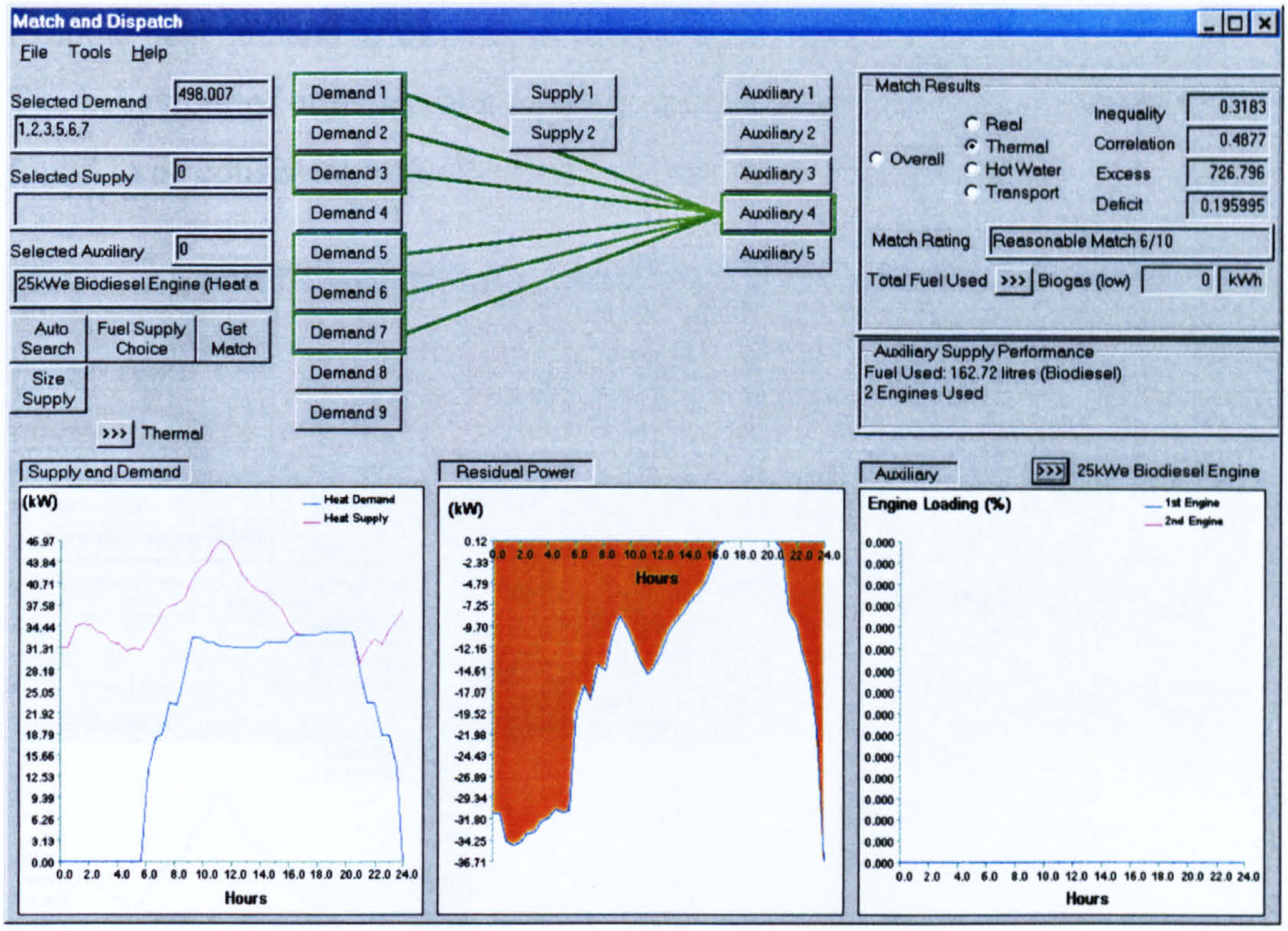
Selected Supply: 0

Selected Auxiliary: 0
25kWe Biodiesel Engine (Heat a

Match Results
○ Overall ● Real ○ Thermal ○ Hot Water ○ Transport
Inequality: 0.0137
Correlation: 0.9807
Excess: 10.544
Deficit: 0
Match Rating: Excellent Match 9/10
Total Fuel Used >>> Biogas (low) 0 kWh

Auxiliary Supply Performance
Fuel Used: 162.72 litres (Biodiesel)
2 Engines Used

Figure 7.29 Following Electricity and Heat Demand (1)



Selected Demand 498.007
1,2,3,5,6,7

Selected Supply 0

Selected Auxiliary 0
25kWe Biodiesel Engine (Heat a

Thermal

Match Results
○ Overall
○ Real
● Thermal
○ Hot Water
○ Transport

Inequality	0.3183
Correlation	0.4877
Excess	726.796
Deficit	0.195995

Match Rating Reasonable Match 6/10

Total Fuel Used >>> Biogas (low) 0 kWh

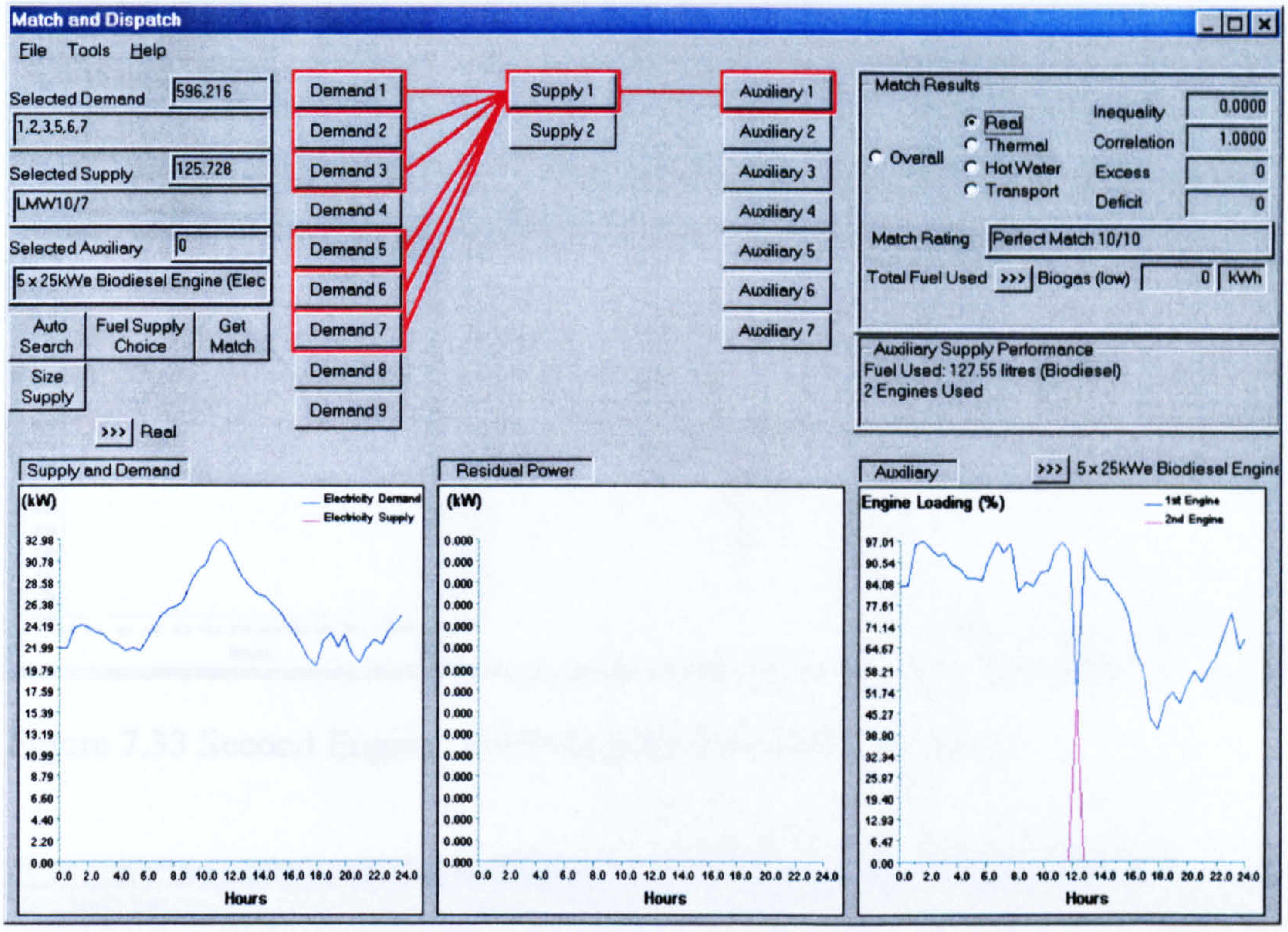
Auxiliary Supply Performance
Fuel Used: 162.72 litres (Biodiesel)
2 Engines Used

25kWe Biodiesel Engine

Figure 7.30 Following Electricity and Heat Demand (2)

When intermittent supplies are also used, these are considered before the auxiliary supplies. This is seen in Figure 7.31 where the output from a wind turbine is included, which reduces the required load on the engine from that shown in Figure 7.29. This is the case no matter how many intermittent supplies are used.

Where more than one auxiliary is used, they are applied in the order in which they are chosen. This can be checked by analysing the load characteristics of the different auxiliary supplies. For example, in Figures 7.32 and 7.33, two engines are specified – the first is set to follow the heat demand, and the second is set to follow the electricity demand. Figure 7.32 shows that the first engine chosen follows the heat demand exactly. As the heat demand is lower than the electricity demand, this still leaves a substantial residual electricity demand. The second engine then runs only when necessary to meet the residual electricity demand, as shown in Figure 7.33. If the engine order is reversed, the first engine that is following the electricity demand also provides most of the heat required due to the higher electricity demand. The second engine, therefore, does not require to run to any great extent, and cannot supply all the residual heat demand as this would require running below the minimum load. The behaviour of other auxiliary supply combinations was also tested and was found to be consistent with the correct supply order being followed.


Match and Dispatch

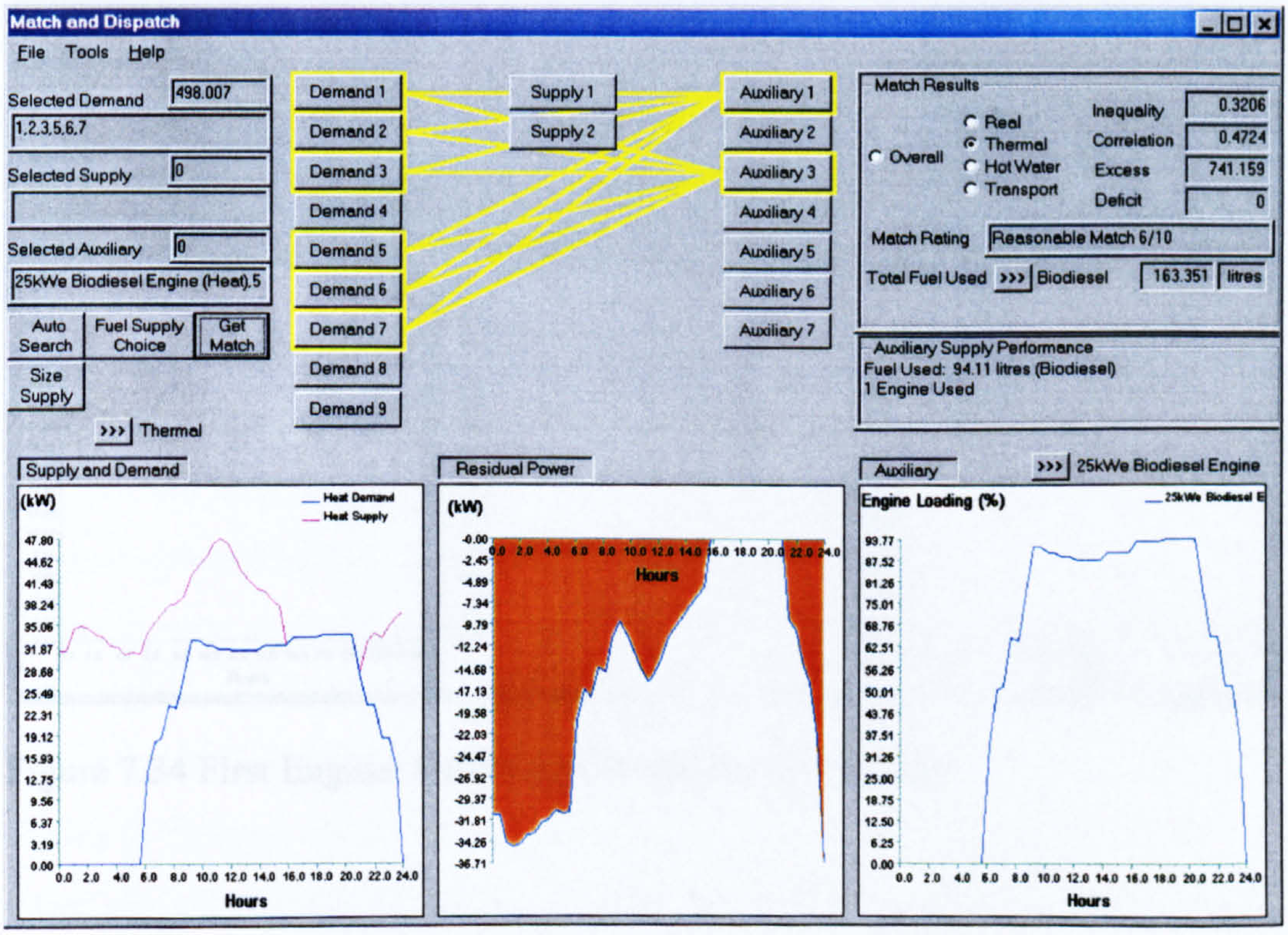
Selected Demand: 596.216
1,2,3,5,6,7
Selected Supply: 125.728
LMW10/7
Selected Auxiliary: 0
5 x 25kWe Biodiesel Engine (Elec
>>> Real

Match Results: ● Real
Inequality: 0.0000
Correlation: 1.0000
Excess: 0
Deficit: 0
Match Rating: Perfect Match 10/10
Total Fuel Used >>> Biogas (low): 0 kWh

Auxiliary Supply Performance
Fuel Used: 127.55 litres (Biodiesel)
2 Engines Used

Auxiliary >>> 5 x 25kWe Biodiesel Engine

Figure 7.31 Including Intermittent Supplies


Match and Dispatch

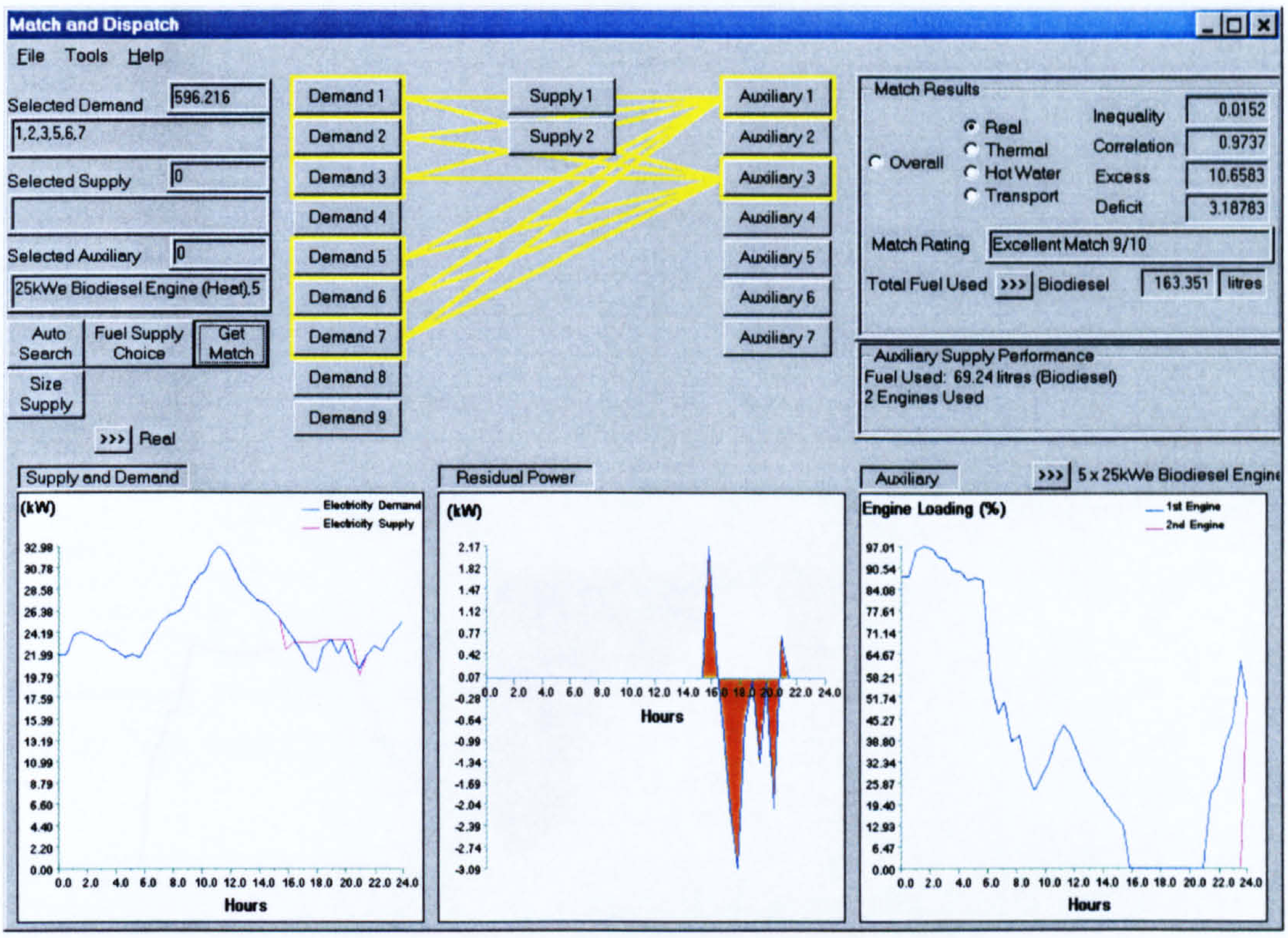
Selected Demand: 498.007
1,2,3,5,6,7
Selected Supply: 0
Selected Auxiliary: 0
25kWe Biodiesel Engine (Heat).5
>>> Thermal

Match Results: ● Thermal
Inequality: 0.3206
Correlation: 0.4724
Excess: 741.159
Deficit: 0
Match Rating: Reasonable Match 6/10
Total Fuel Used >>> Biodiesel: 163.351 litres

Auxiliary Supply Performance
Fuel Used: 94.11 litres (Biodiesel)
1 Engine Used

Auxiliary >>> 25kWe Biodiesel Engine

Figure 7.32 First Engine: Following the Heat Demand



Selected Demand: 596.216
1,2,3,5,6,7

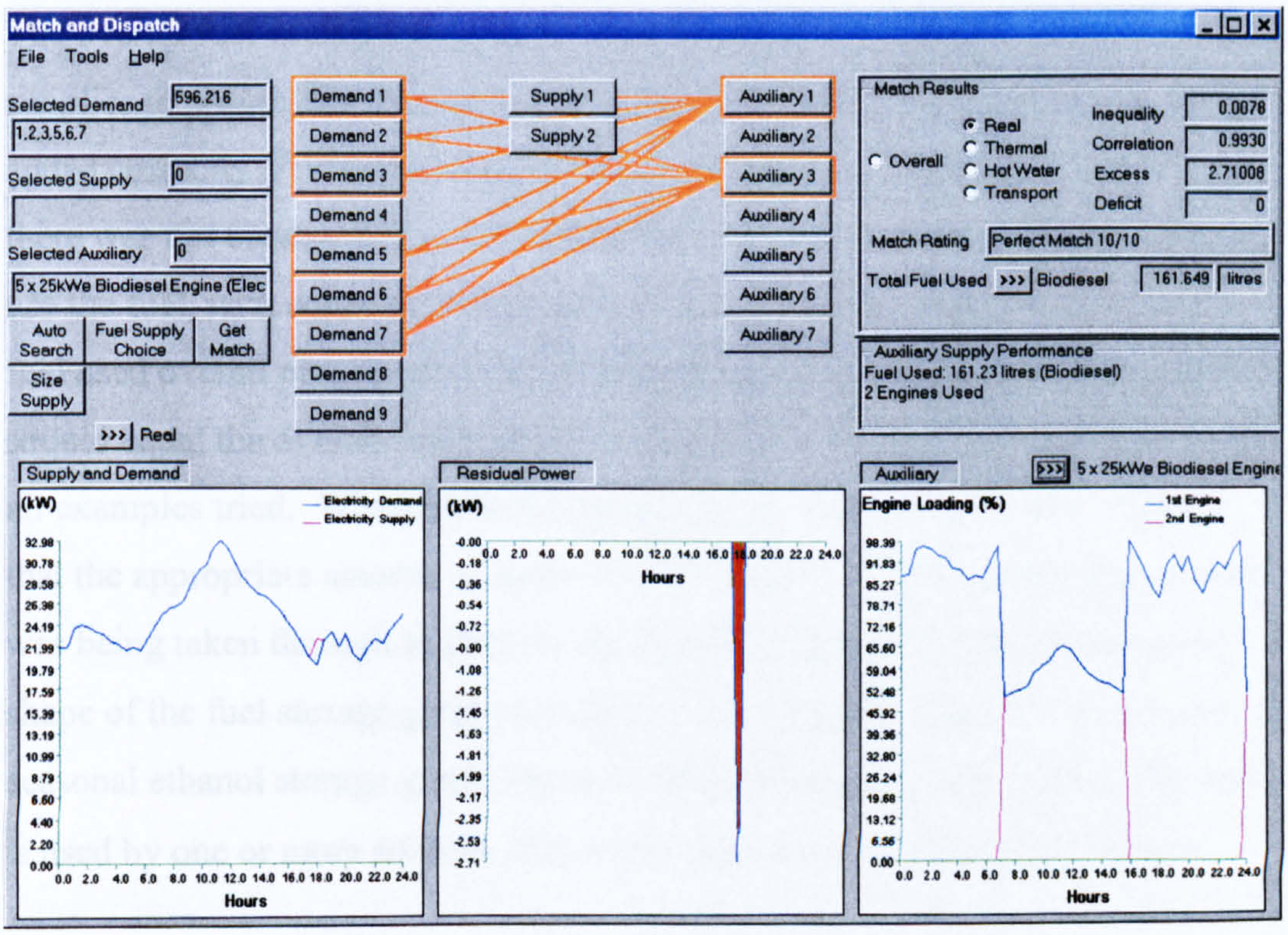
Selected Supply: 0

Selected Auxiliary: 0
25kWe Biodiesel Engine (Heat),5

Match Results
○ Overall ● Real ○ Thermal ○ Hot Water ○ Transport
Inequality: 0.0152
Correlation: 0.9737
Excess: 10.6583
Deficit: 3.18783
Match Rating: Excellent Match 9/10
Total Fuel Used >>> Biodiesel 163.351 litres

Auxiliary Supply Performance
Fuel Used: 69.24 litres (Biodiesel)
2 Engines Used

Figure 7.33 Second Engine: Following the Electricity Demand



Selected Demand: 596.216
1,2,3,5,6,7

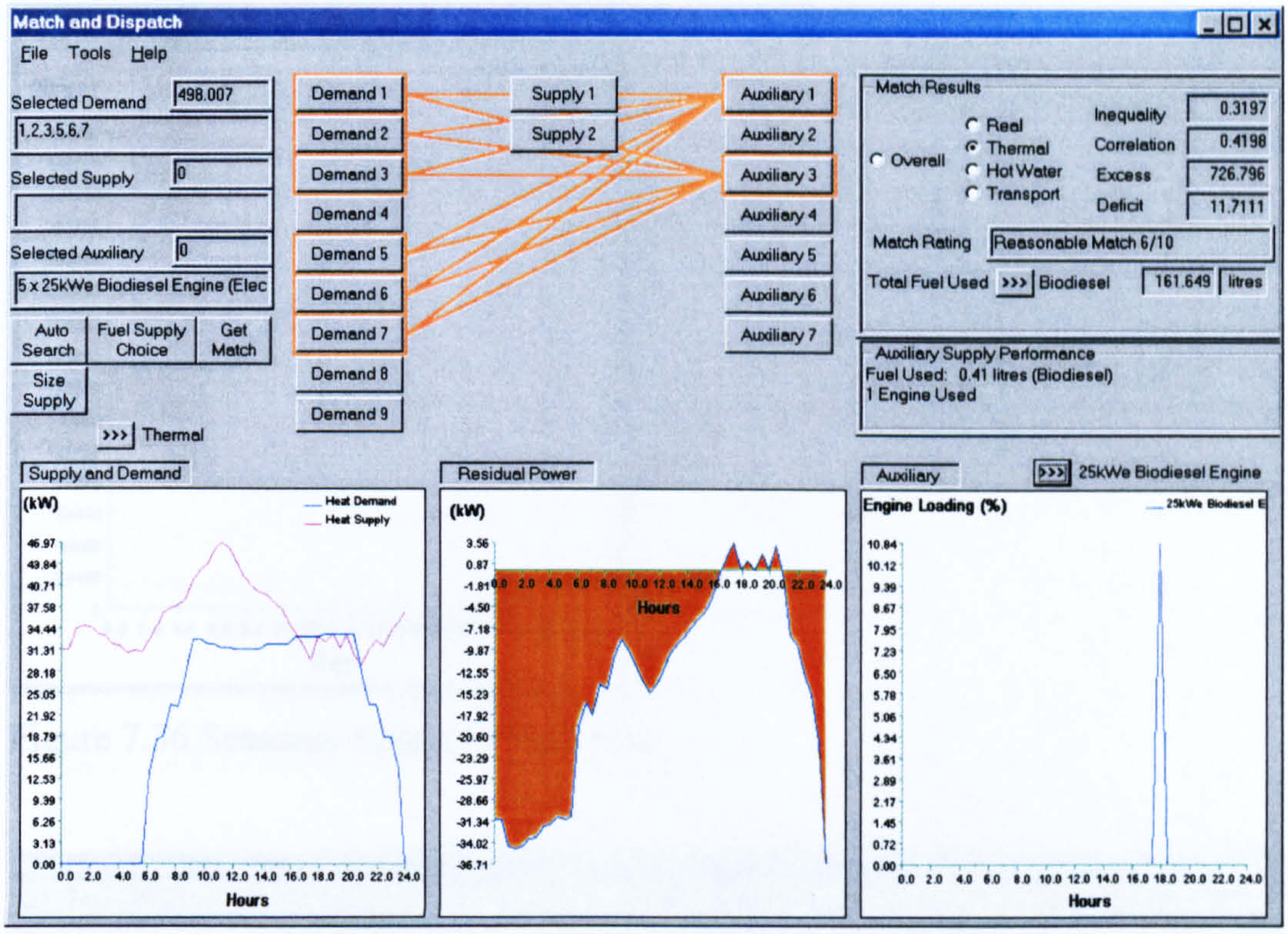
Selected Supply: 0

Selected Auxiliary: 0
5 x 25kWe Biodiesel Engine (Elec

Match Results
○ Overall ● Real ○ Thermal ○ Hot Water ○ Transport
Inequality: 0.0078
Correlation: 0.9930
Excess: 2.71008
Deficit: 0
Match Rating: Perfect Match 10/10
Total Fuel Used >>> Biodiesel 161.649 litres

Auxiliary Supply Performance
Fuel Used: 161.23 litres (Biodiesel)
2 Engines Used

Figure 7.34 First Engine: Following the Electricity Demand



Selected Demand 498.007

1,2,3,5,6,7

Selected Supply 0

Selected Auxiliary 0

5 x 25kWe Biodiesel Engine (Elec

>>> Thermal

Match Results

○ Overall

○ Real

● Thermal

○ Hot Water

○ Transport

Inequality 0.3197

Correlation 0.4198

Excess 726.796

Deficit 11.7111

Match Rating Reasonable Match 6/10

Total Fuel Used >>> Biodiesel 161.649 litres

Auxiliary Supply Performance

Fuel Used: 0.41 litres (Biodiesel)

1 Engine Used

>>> 25kWe Biodiesel Engine

Figure 7.35 Second Engine: Following the Heat Demand

The overall fuel use data was checked for various combinations of auxiliary supplies to ensure that the amount of fuel used by the individual supplies was added correctly if different supplies were using the same fuel. In the case where there was not enough fuel, the supply chosen first gets the initial opportunity to use the fuel, with subsequent supplies using any residual fuel. The amount of fuel used overall plus the amount remaining in storage at the end of the period should equal the overall fuel production for that period, and this was the case in all examples tried. Where seasonal supplies were considered, it was verified that the appropriate amount of each fuel left at the end of the simulation period was being taken through to start the second simulation period by studying the shape of the fuel storage graphs produced. For example, Figure 7.36 shows a seasonal ethanol storage graph where no ethanol has been used. When the fuel is used by one or more sources, this is still dealt with in the correct manner.

Where an electrolyser was used to create hydrogen using excess electricity, as shown in Figure 7.37, this was done in the correct manner, and in the correct order, allowing hydrogen to be available to supplies chosen after the electrolyser, and added to the supply profile if not used.

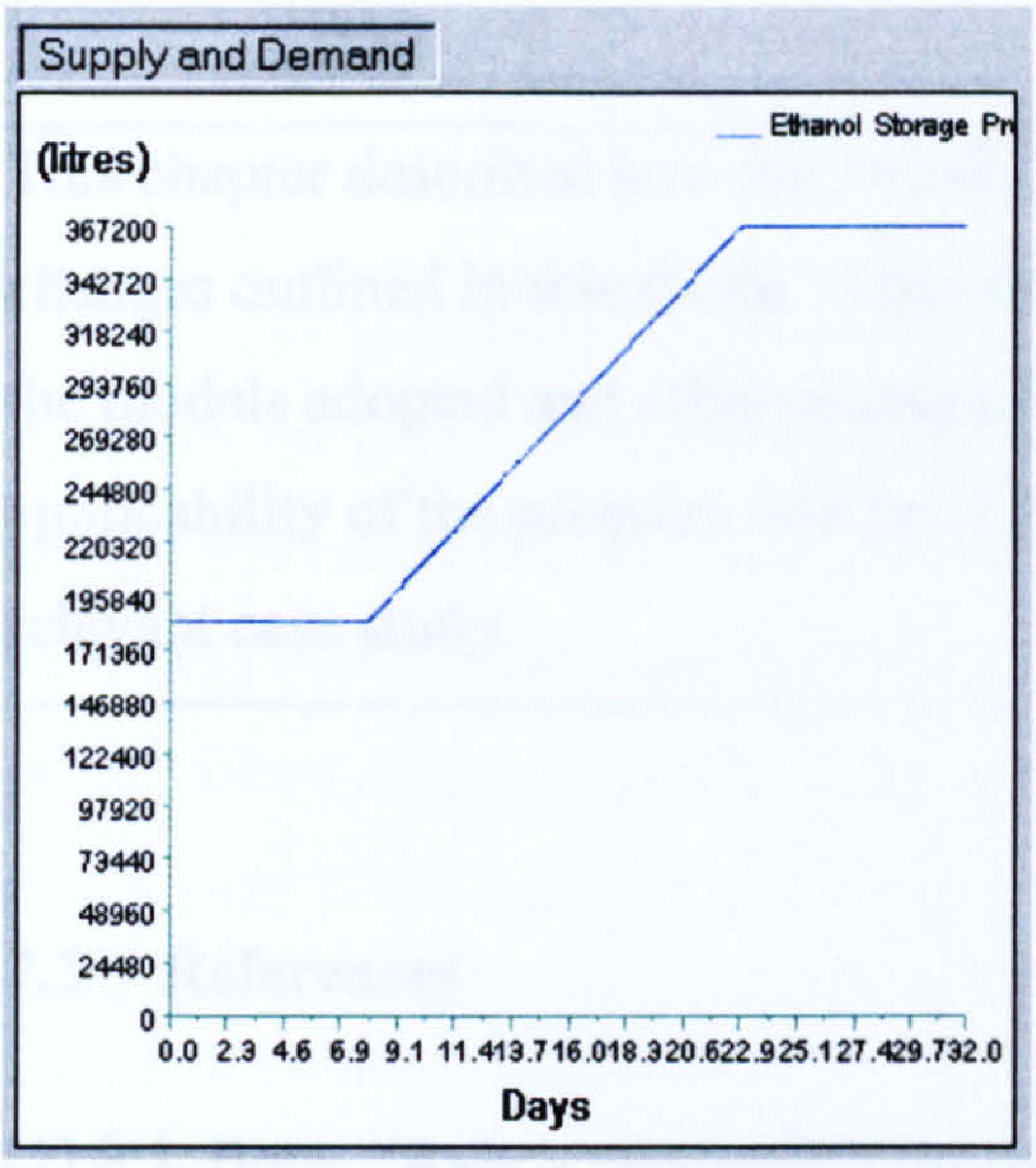
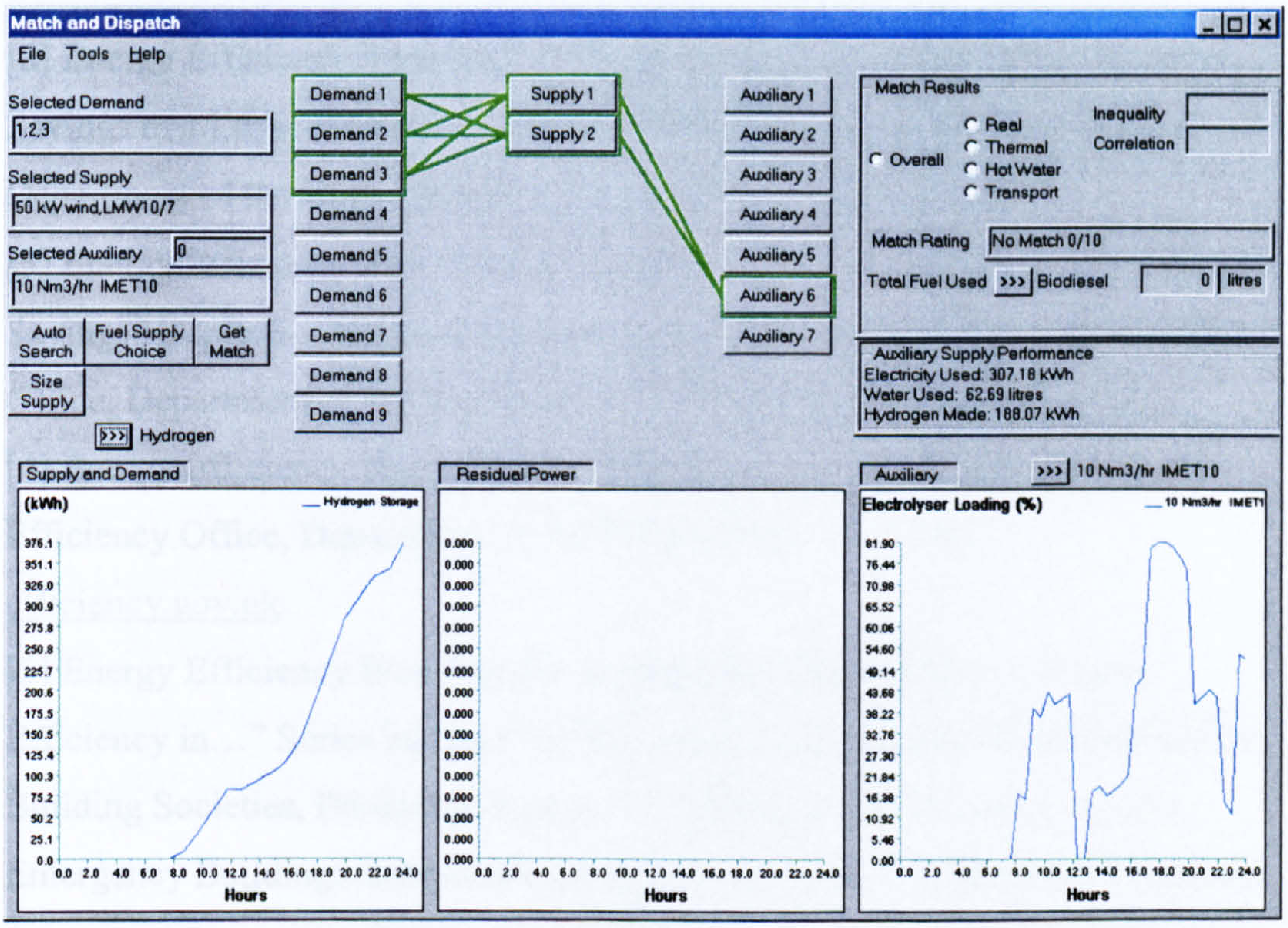


Figure 7.36 Seasonal Ethanol Production



Selected Demand: 1,2,3

Selected Supply: 50 kW wind,LMW10/7

Selected Auxiliary: 0

10 Nm3/hr IMET10

Match Rating: No Match 0/10

Total Fuel Used >>> Biodiesel 0 litres

Auxiliary Supply Performance
Electricity Used: 307.18 kWh
Water Used: 62.69 litres
Hydrogen Made: 188.07 kWh

Figure 7.37 Producing Hydrogen from Excess Electricity

All the checks described in this section were carried out comprehensively to ensure that the functionality described in Chapter 4 has been successfully implemented. All auxiliary supplies were also studied in a methodical manner to ensure that the algorithms outlined in Chapter 5 are being correctly followed.

This chapter described how the overall MERIT system works, incorporating the changes outlined in this thesis. The techniques used to verify the behaviour of the models adopted and other changes made were also discussed. The applicability of the program will be shown in Chapter 8, through the use of a relevant case study.

7.3 References

[1] F.J. Born, "Aiding renewable energy integration through complementary demand-supply matching", PhD Thesis, University of Strathclyde, 2001, www.esru.strath.ac.uk

[2] Energy Efficiency Best Practice Programme, "Case Study 196 - Electricity Savings in a Large Acute Hospital", April 1994, Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk

[3] Energy Efficiency Best Practice Programme, "Case Study 197 - Electricity Savings Hospitals – Airedale General Hospital", June 1994, Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk

[4] Energy Efficiency Best Practice Programme, "Degree Days", Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk

[5] Energy Efficiency Best Practice Programme, "Introduction to Energy Efficiency in…" Series includes Offices, Hotels, Shops and Stores, Post Offices, Building Societies, Banks and Agencies, Catering Establishments, Prisons, Emergency Buildings and Courts, Museums, Galleries, Libraries and Churches, Sports and Recreation Centres, Healthcare Buildings, Entertainment Buildings, and Schools, Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk

[6] Energy Efficiency Best Practice Programme, "Combined Heat and Power for Community Heating", January 1996, Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk

8 Applicability

To show the applicability and usefulness of the changes made to the MERIT software, the program has been used to analyse the options for creating an energy-autonomous community on a typical small Scottish island. Results are presented showing the feasibility of accomplishing 100% renewable provision on this island using available local resources. A hypothetical community, based on the population, building use and industry of the island of Muck, off the west coast of Scotland, has been conceived for the purposes of this case study [1].

An island community has been chosen for this study as islands represent an interesting challenge in terms of energy supply. There are many small islands and remote communities around Scotland that are grid-isolated and have no other energy supplies brought in by pipeline. These communities rely on expensive and difficult imports of fuel (often diesel or compressed natural gas) to meet their energy needs. If local resources could be used to meet local energy needs, this may provide significant benefits, such as the possible decrease in the cost of living, increase in the reliability of supply, and creation of local employment. These factors may boost the local economy and may help stem the de-population of these areas. Also, the use of renewable and sustainable methods of energy conversion benefits the local environment and helps preserve natural resources. Such communities, therefore, currently have more incentive than mainland communities (where electricity and fuel supplies are cheaper and more easily available) to become self-sufficient in energy terms.

8.1 Demand Profile Definition

A hypothetical small island, based on the island of Muck, has been conceived for the purposes of this case study. Forty people live on the island, supported mainly by a 400-hectare farm, and tourism. There are fifteen, three-bedroom houses, a school for six pupils, two workshops and a craft and grocery store all of which require heat and electricity all year round. There are also two, three-bedroom holiday cottages, a ten-bedroom hotel and a teashop, which require heat and electricity during the tourist season (April to October). Vehicles on the island include two tractors and one combine harvester with 170hp engines, and three general-purpose 4x4 vehicles, which all run on diesel fuel. Heat is also required for drying grain during the harvest period.

Annual consumption figures were estimated for the different building types using the standard practice figures detailed in the relevant Good Practice Guides, published by the Energy Efficiency Office [2]. This electrical consumption was then applied to annual, half-hourly demand profiles that have been defined for various relevant building types with non-electrical heating [3,4]. Thermal demand profiles for each building type were derived by estimating occupancy hours, assigning appropriate heating loads, correlating these with ambient temperatures given by local climate statistics, and applying annual consumption figures. These figures were derived using the figures for fossil fuel use given in the Good Practice Guides [2], estimating heating use and applying a fuel to heat conversion efficiency of 70%. Table 8.1 provides information about the annual consumption figures used for the different buildings.

Building Type	Number of Units	Thermal Demand per Unit (kWh/year)	Electrical Demand per Unit (kWh/year)
3 Bedroom House*	15	14000	2000
School **	1	3500	1000
Workshop (50m2) *	2	2500	3000
Store *	1	2500	10000
3 Bedroom Holiday Cottage ***	2	2000	900
Hotel ***	1	15000	22000
Teashop***	1	2500	10000

* All year
** Except School Holidays
*** Tourist Season (1st April – 20th October)

Table 8.1: Annual Consumption Figures

It is assumed that the three farm vehicles operate for 8 hours per day from February to mid July, and 15 hours per day from mid July to mid October [5], and the 4x4 vehicles are assumed to travel 40 km per day, mostly between 9am and 5pm, all year round. The energy required for grain drying is assumed to be 72500 kWh each year, required throughout each day during the harvest period (mid July to mid October) [6].

Figure 8.1 represents the estimated yearly electricity demand profile for this island, showing a large increase in consumption during the tourist season (1st April – 20th October). Figure 8.2 shows the yearly heat demand profile. Increased heat demand during the tourist season, and the requirement for crop drying during the harvest period make this profile more level than would otherwise be the case. As the heat demand is substantial throughout most of the year, the use of combined heat and power (CHP) should be considered. There is a reasonable base load that can be met by CHP, but the lack of correlation between the electricity and heat demand profiles means that the use of CHP on its own will lead to large losses if suitable storage and/or other electricity and heat supplies are not used.

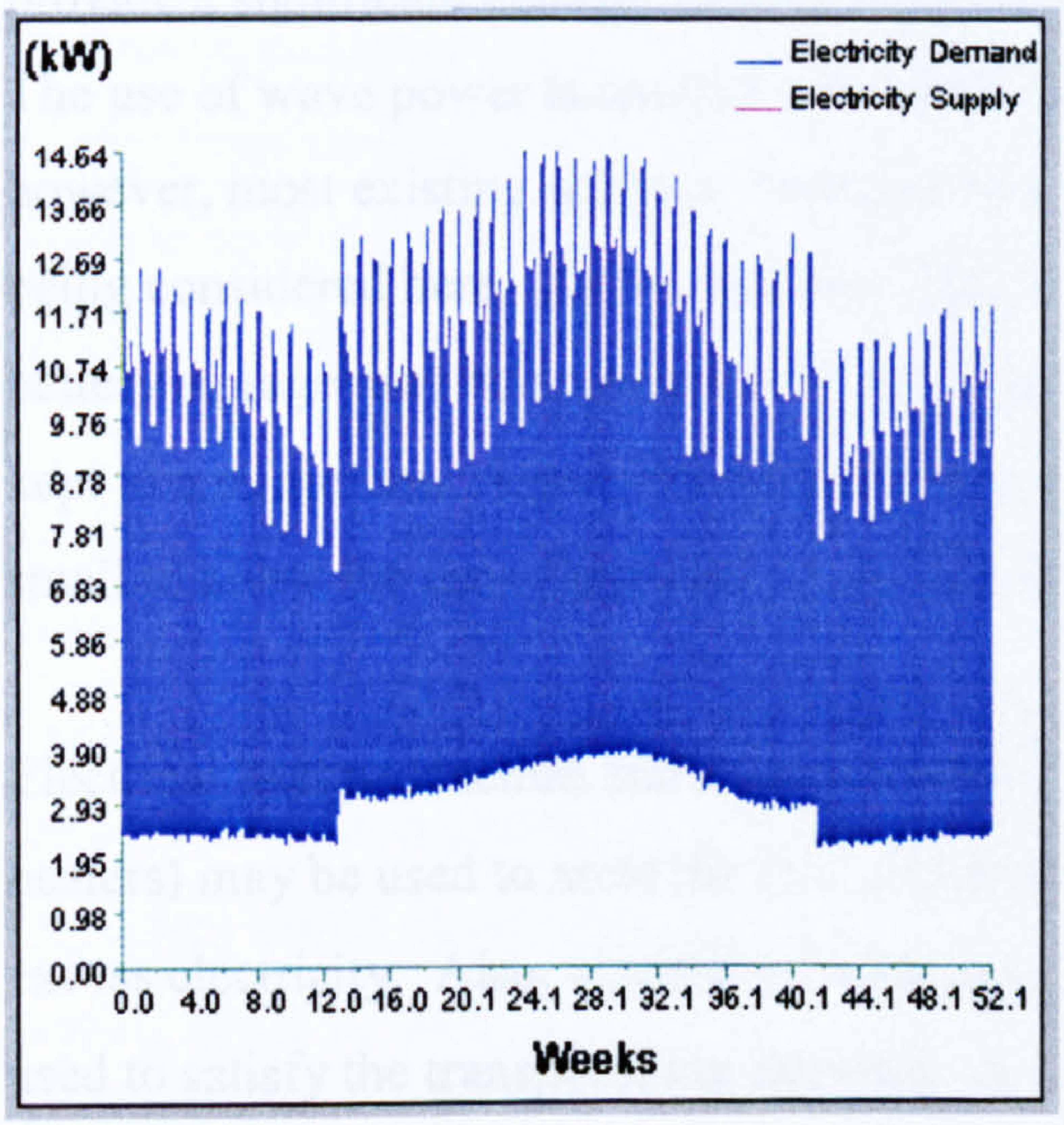


Figure 8.1: Overall Yearly Electricity Demand Profile

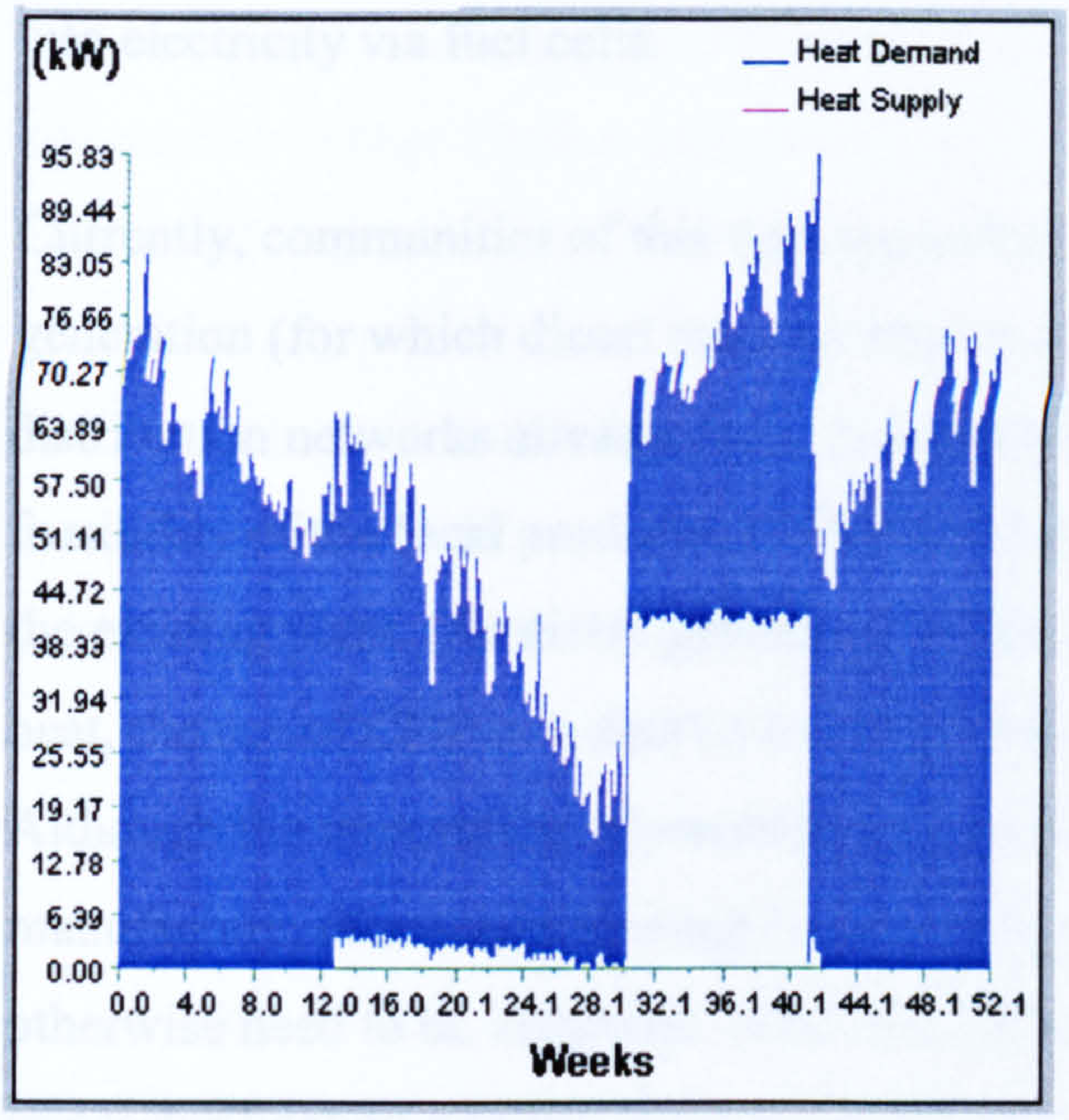


Figure 8.2: Overall Yearly Heat Demand Profile

8.2 Supply Options

There is a large available wind power resource in Scotland, particularly on islands and in coastal areas. The available solar power resource is limited by the space and insolation available, and the conversion efficiency of currently available photovoltaic panels. Therefore solar technologies are unlikely to provide a significant enough electrical contribution to justify the costs involved. The use of wave power is another important consideration on an island; however, most existing schemes would be too large for the size of community being considered here. As the islands' demands are relatively small, the use of battery storage may be appropriate if excesses and deficits of electricity can be kept to a minimum. Again, the demands being considered are likely to be too small to allow the use of pumped storage as a form of electricity storage.

Electrical heat production and storage (in hot water tanks or electric storage heaters) may be used to meet the heat demand and provide a useful outlet for excess electricity. Also, electric vehicles, charged at off-peak hours, may be used to satisfy the transportation demand. Another use for excess electricity may be the production of hydrogen via electrolysis of water, which may then be used in vehicles, for the production of heat, and, when necessary, turned back into electricity via fuel cells.

Currently, communities of this type typically use diesel generators for electricity generation (for which diesel must be imported) and many small local electricity distribution networks already exist. It would, therefore, be prudent to assess the feasibility of the local production of biodiesel from dedicated crops for use in the existing plant. As diesel generators produce a substantial amount of waste heat, the use of CHP in a district-heating scheme should also be considered. Although the importation of methanol would still be required to allow biodiesel manufacture, this would be roughly one tenth of the amount of diesel that would otherwise need to be imported. Also, the glycerine produced by the transesterification process is a valuable by-product, which may be exported or used on the island to produce toiletries and cosmetics that may be exported or sold alongside the local craftwork. As biodiesel and diesel can be mixed in an engine with no ill effects, diesel may still be imported and used in the same plant if a shortage should occur.

Another option for the production of a multi-purpose fuel from an energy crop would be the fermentation of an extension to the currently grown grain crops to produce ethanol. A by-product of this process would be a nutrient rich animal feed that could be used on the farm, reducing the need to import feed. Such energy crops could be grown on the 10% to 15% of the farmer's land that is required to be set-aside under European Union legislation, but can be used for non-food production.

To reduce the amount of biodiesel or ethanol required, and therefore the amount of land required, electricity and heat production from either of these fuels could be supplemented by electricity from the intermittent sources outlined earlier. As the heat demand is substantially larger than the electricity demand, some electricity would be required to produce heat, and this supplementary electrical heating could be used, in conjunction with heat storage, to help achieve a desirable heat to electricity ratio, and allow the CHP plant to operate as efficiently as possible. The use of multiple engine sets may also be appropriate to allow for efficient operation during different seasons and times of the day. The use of biodiesel, electric and hydrogen-powered vehicles should also be considered, along with the other supplementary supply and storage methods mentioned earlier.

The amount of waste available on the island should also be considered as a potential source of fuel for heat, electricity and transportation. Unfortunately, due to the small population, the amount of household waste produced would not be enough to make burning it for heat and/or electricity production a viable option both practically and ecomonically. However, household organic, garden and agricultural wastes could be put into an anaerobic digester, along with the main feedstock (the manure produced by 100 dairy cows on the farm), in order to produce biogas. The small amount of human sewage produced on the island could also be treated in this way in order to solve a disposal problem. The biogas produced could be used in gas engines for CHP production, and as a transportation fuel, and the fertiliser produced could be used on the farm, reducing the need for import. The potential amount of biogas available throughout the year is shown in Figure 8.3, with less being available during the summer as the animals go out to pasture for some of the time, making collection more difficult. The anaerobic digestion process requires heat and electricity inputs, but these have been removed from this graph for clarity.

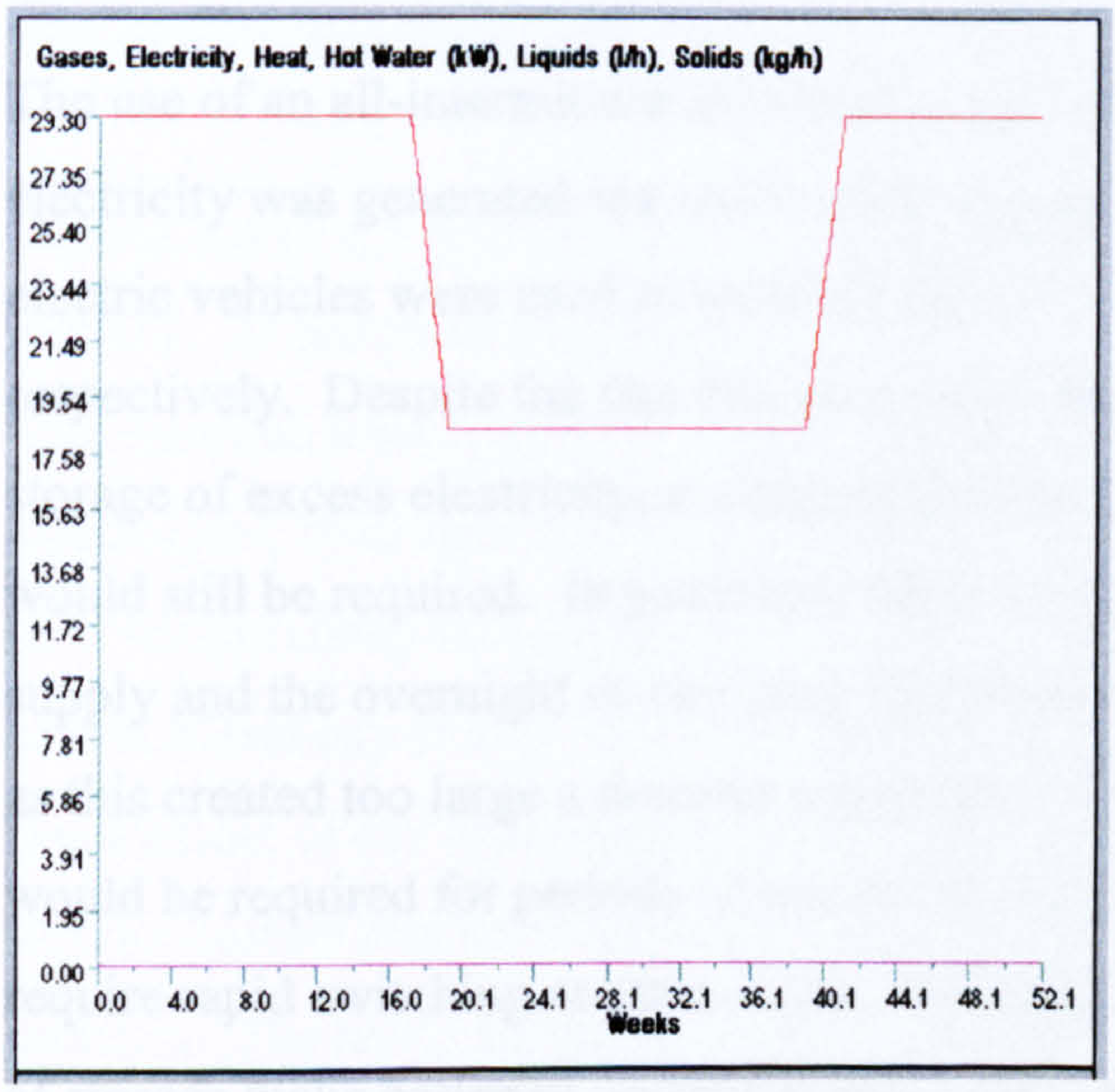


Figure 8.3: Potential Biogas Supply

All of these different possible fuel, intermittent electricity and auxiliary supplies and storage technologies could be used in a variety of combinations to fully satisfy the total energy demands for this island, but a technically attractive range of potential mixes of technologies and processes emerge from the analysis carried out using MERIT, and are discussed in Section 8.3. The final, most suitable solution, however, would depend on a variety of other factors, which might include available land, local geography, positioning of buildings, existing plant, cost of equipment, available subsidies, and projected future demand.

8.3 Analysis Results

MERIT has been used to study a variety of different demand scenarios, to ascertain the most technically attractive use of the available local supplies. When considering seasonal fuel supplies such as biodiesel or ethanol from energy crops, it is necessary to consider the half-hourly demand and supply profiles over a whole year. The required plant types and sizes, and the amount of fuel production and storage necessary to allow all the energy requirements (for electricity, heat and transportation) to be met are ascertained for these different possible supply mixes, and the results are discussed below.

8.3.1 Intermittent Electricity Supply

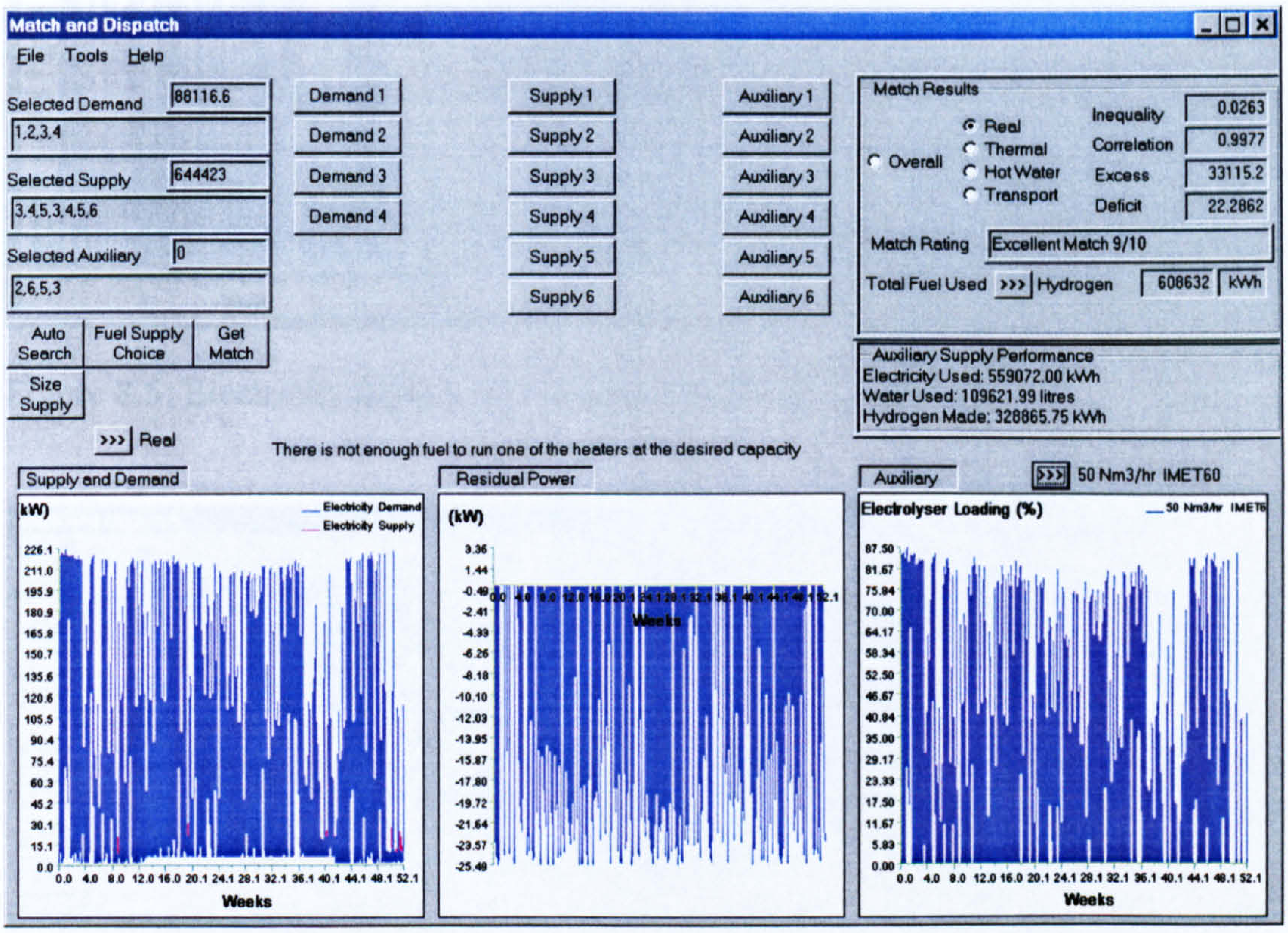
The use of an all-intermittent electrical supply was considered, where all the electricity was generated via wind turbines, and electrical storage heaters and electric vehicles were used to meet the heat and transportation demands respectively. Despite the fact that the storage heaters and vehicles provide some storage of excess electricity, a substantial amount of other electrical storage would still be required. In particular, the co-relation between the electricity supply and the overnight re-charging requirements of the vehicles was not good, as this created too large a demand overnight. The electrical storage necessary would be required for periods of one or two months at some times, and would require rapid switching at other times. This pattern of use and the required scale of storage make batteries unsuitable due to the equipment costs and losses which would be incurred, and the scale of the demands being considered are too small for pumped storage to be a viable option.

The required installed wind turbine capacity would vary with the inclusion of suitable storage, but would be in the order of 300 to 400 kW to allow all demands to be satisfactorily met within the limitations of currently available storage devices. The introduction of a small amount of photovoltaic generated electricity made little difference to the overall supply pattern due to limited available insolation and areas to site panels.

8.3.2 Intermittent Electricity Supply with Hydrogen Storage

Hydrogen has the advantage that it can be used for both long and short term storage as necessary, without significant loss of the energy potential of the stored fuel, and has been considered here, not only as a form of electrical storage, but also for direct use as a fuel for transportation and heating. Any excess electricity is converted into hydrogen via the electrolysis of water (subject to a minimum electrolyser load of 10% of its rated capacity), and can then be used directly in vehicles, in fuel cells for CHP production, and in catalytic hydrogen heaters. For this example, the production of electricity and heat would be carried out centrally, and transmitted to households via an electricity network and district-heating scheme.

Figures 8.4 to 8.7 present the results given by the matching procedure in MERIT. These show that all the energy requirements for this area can be met, with minimal losses, by 210 kW of installed wind capacity, a 50Nm^3 (150kW) electrolyser, hydrogen fuelled vehicles, two 20kW proton exchange membrane (low temperature) fuel cells, and a 100kW catalytic hydrogen heater. The excess electricity shown on the residual graph is due to the minimum load requirement of the electrolyser, but the use of this excess electricity in electric storage heaters makes no difference to the required rated capacity of wind turbines. The small amount of excess heat generated is due to excess heat production by the fuel cell CHP plant that is following the electricity demand. The use of the fuel cell CHP plant is considered before the use of the heaters to keep this excess production to a minimum. The hydrogen storage requirement profile shown in Figure 8.7 gives the maximum amount of hydrogen storage that needs to be provided during the year, and also shows the necessity for interseasonal storage (which is partly due to the large heat requirement for crop drying during the harvest period). To find this optimum solution, different scenarios were tried in order to reduce the required plant sizes, and minimise excess electricity, heat and hydrogen production, while still meeting all the required energy demands.



Selected Demand 88116.6
1,2,3,4

Selected Supply 644423
3,4,5,3,4,5,6

Selected Auxiliary 0
2,6,5,3

Match Results

○ Overall
● Real
○ Thermal
○ Hot Water
○ Transport

Inequality 0.0263
Correlation 0.9977
Excess 33115.2
Deficit 22.2862

Match Rating Excellent Match 9/10

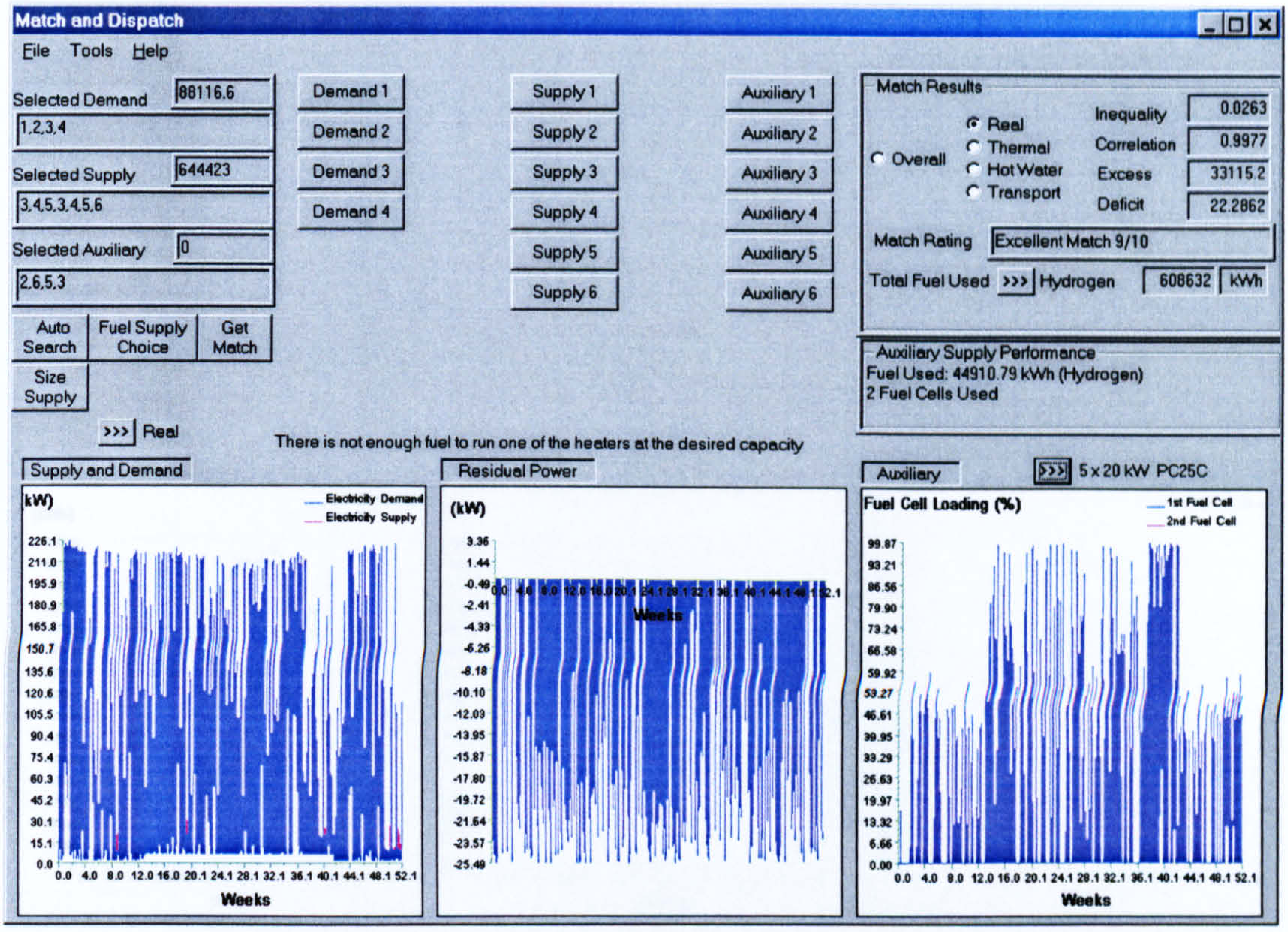
Total Fuel Used >>> Hydrogen 608632 kWh

Auxiliary Supply Performance
Electricity Used: 559072.00 kWh
Water Used: 109621.99 litres
Hydrogen Made: 328865.75 kWh

There is not enough fuel to run one of the heaters at the desired capacity

>>> 50 Nm3/hr IMET60

Figure 8.4: Electricity Supply and Demand and Electrolyser Loading



Selected Demand 88116.6
1,2,3,4
Selected Supply 644423
3,4,5,3,4,5,6
Selected Auxiliary 0
2,6,5,3

Real

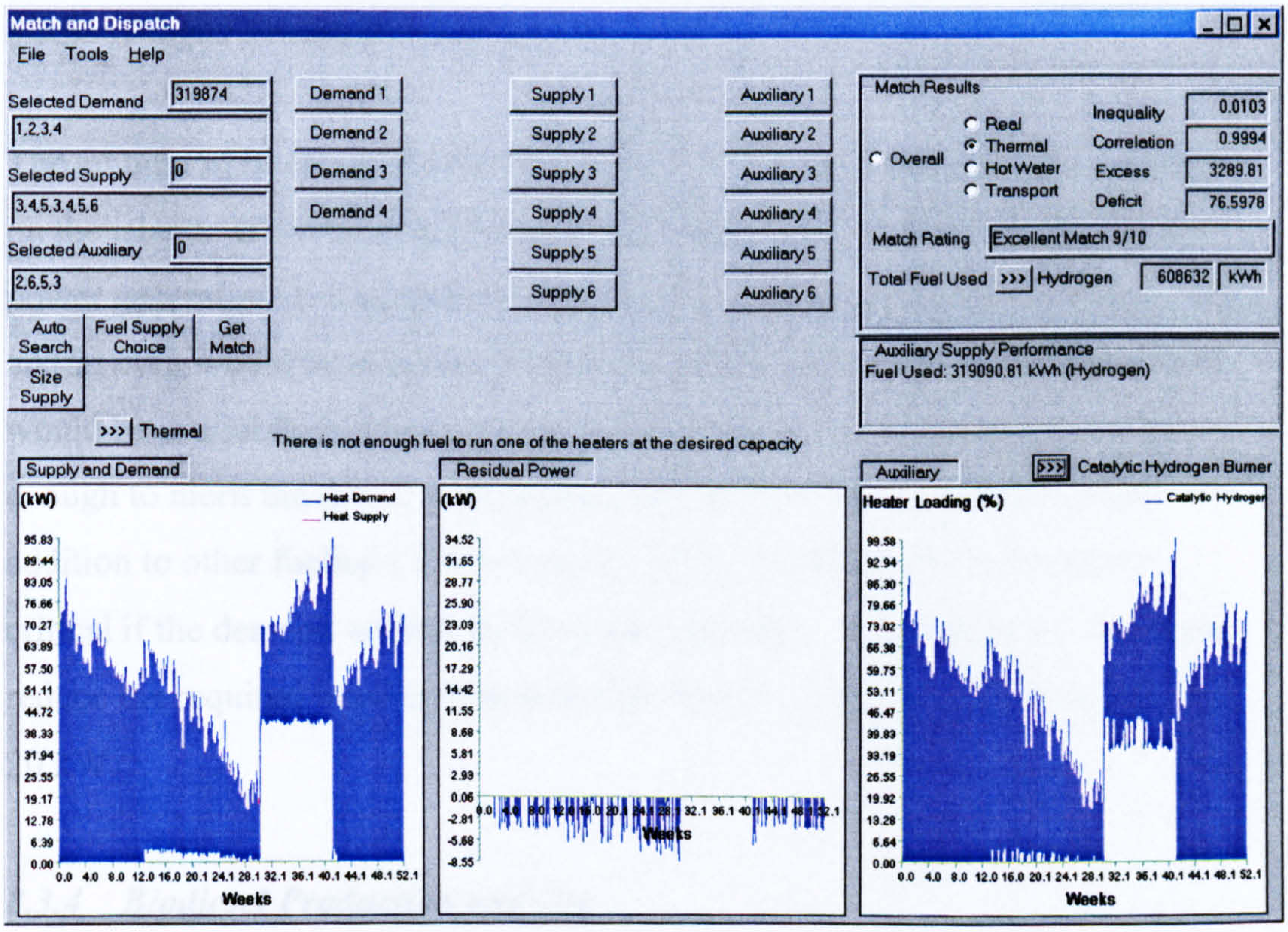
There is not enough fuel to run one of the heaters at the desired capacity

Match Results
○ Overall
● Real
○ Thermal
○ Hot Water
○ Transport
Inequality 0.0263
Correlation 0.9977
Excess 33115.2
Deficit 22.2862
Match Rating Excellent Match 9/10
Total Fuel Used >>> Hydrogen 608632 kWh

Auxiliary Supply Performance
Fuel Used: 44910.79 kWh (Hydrogen)
2 Fuel Cells Used

5 x 20 kW PC25C

Figure 8.5: Electricity Supply and Demand and Fuel Cell Loading



Selected Demand 319874
1,2,3,4
Selected Supply 0
3,4,5,3,4,5,6
Selected Auxiliary 0
2,6,5,3

Thermal

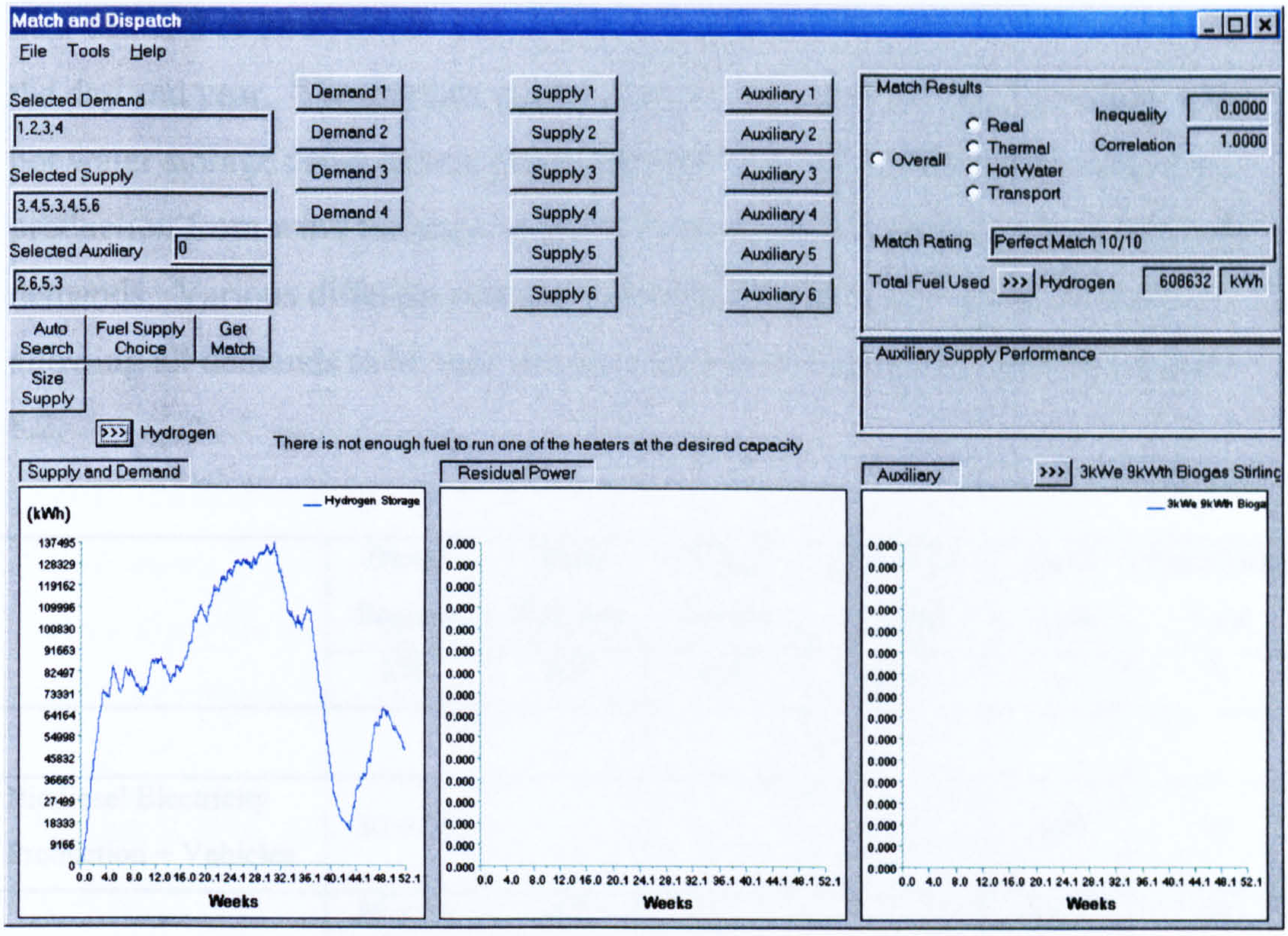
There is not enough fuel to run one of the heaters at the desired capacity

Match Results
○ Overall
○ Real
● Thermal
○ Hot Water
○ Transport
Inequality 0.0103
Correlation 0.9994
Excess 3289.81
Deficit 76.5978
Match Rating Excellent Match 9/10
Total Fuel Used >>> Hydrogen 608632 kWh

Auxiliary Supply Performance
Fuel Used: 319090.81 kWh (Hydrogen)

Catalytic Hydrogen Burner

Figure 8.6: Heat Supply and Demand and Catalytic Hydrogen Heater Loading



Selected Demand: 1,2,3,4

Selected Supply: 3,4,5,3,4,5,6

Selected Auxiliary: 0

2,6,5,3

>>> Hydrogen

There is not enough fuel to run one of the heaters at the desired capacity

Match Results

Inequality: 0.0000

Correlation: 1.0000

Match Rating: Perfect Match 10/10

Total Fuel Used: >>> Hydrogen 608632 kWh

Auxiliary: >>> 3kWe 9kWh Biogas Stirling

Figure 8.7: Hydrogen Storage Requirement Profile

8.3.3 *Biogas Production and Use*

The amount of biogas available would not be enough to run all of the vehicles on the island. If the available biogas is, instead, used for combined heat and power generation in a suitable Stirling engine, a constant supply of around 7kW$_e$ and 21kW$_{th}$ would be available during the winter, and around 4kW$_e$ and 12kW$_{th}$ would be available during the summer. This amount on its own may not be enough to merit the use of a district-heating scheme, but would be a useful addition to other fuelled CHP production plant, where it would also not be critical if the demand were to increase unexpectedly. This would, for example, reduce the required wind turbine installed capacity in the previous example by 20 kW.

8.3.4 *Biodiesel Production and Use*

Biodiesel can be used to fuel both vehicles and diesel engines for CHP production. The diesel engines can be used to follow the electricity demand, heat demand or both, or run at constant percentage loadings at different times of the day and year. The engines can be used on there own, or supplemented with hot water storage using excess electricity and heat, and intermittent electricity production from wind turbines, in order to meet the required electricity and heat demands. Various different scenarios were simulated, and a range of results, allowing all demands to be met, are discussed below and summarised in Table 8.2.

	Diesel Engines	Wind Turbines	Water Heater	Hot Water Storage	Land Used	Farm Land Used
	kW	kW	kW	litres	ha	%
Biodiesel Electricity Production + Vehicles	50 + 50				180	45
	50 + 50	100			140	35
	50 + 50	200			125	31
Biodiesel CHP + Vehicles	30 + 30				140	35
	25 + 25		30	2000	120	30
	25 + 25	50	50	2500	105	26
		100	50	2500	100	25
Biodiesel CHP + Vehicles + Biogas CHP	20 + 20		30	2000	110	27.5
	20 + 20	50	50	2500	95	24
Biodiesel CHP + Electric Vehicles	20 + 20	180	50	2000	70	17.5

Table 8.2: Supply Options for Biodiesel Use

From the results summarised above, it can be seen that, where biodiesel is used in engines to produce electricity alone, that this is an inefficient use of the fuel supply. The use of the fuel for CHP generation instantly reduces the required plant size and the amount of fuel necessary. When considering the use of CHP it is important to get the balance between the electricity and heat demand as close to the heat to electricity ratio for the relevant plant as possible, which, in this case is 1.44:1 at full load, increasing at partial load. As the heat demands in this case study are a lot greater than the electricity demands, if the engines are run, as the only supply, to follow both the electricity and heat demands, this will still result in substantial losses. However, if the engine sets are run at set levels between the electricity demand and the heat demand, the extra electricity produced can be used to heat water, which can be used for district heating, or stored in insulated tanks. Excess heat production may also be used to heat the stored water. This approach requires adequate prediction of electricity and heat load to allow the operating levels for the engines to be set, but does substantially reduce the amount of land required for biodiesel production.

The introduction of wind turbines again helps reduce the amount of land required for biodiesel production by increasing the available electricity, reducing the required engine load, and increasing the amount of electrical water heating and storage. Further increases in wind power provision above 100kW do not provide a significant reduction in land requirements due to its intermittent nature and link with climate conditions. The use of biogas CHP run continuously alongside the biodiesel CHP plant is also a consideration. This also reduces the land and plant size requirements, as shown in Table 8.2.

If the diesel engines were to be run constantly, this would simplify the operating conditions, but would result in substantial excesses of electricity and heat, particularly during the night. This excess electricity could be used for re-charging electric vehicles and heating water, and the excess heat could also be stored as hot water. This, together with the use of some wind-generated electricity, could substantially reduce the amount of land required for the energy crops.

8.3.5 Ethanol Production and Use

Ethanol can be used in a system in exactly the same way as biodiesel, using appropriate vehicles and engines. Analysis for this case and climate shows that similar results and trends are produced as for the analysis of the use of biodiesel, but with 30% less land being required in general. This is due, mainly, to the higher yield of ethanol per hectare of land (despite the lower energy density of ethanol), and the similar energy requirements for the fermentation process compared with the transesterification process. This may make the production and use of ethanol a more desirable option if there is a limited amount of land available, and the fermentation process also requires less raw material import. It is more common however, to have existing diesel generating plant in grid-isolated areas, which is often an important short-term consideration.

8.4 Case study Conclusions

The list of possible supply combinations given here is not meant to be exhaustive, but has been used to show the versatility and usefulness of MERIT for this type of analysis, and to show the way in which the program can be used to aid informed decision-making. This study highlights the limitations of intermittent supplies used on their own, and stresses the need for fuelled reserve, storage and/or a good use for excess electricity. The use of potentially available waste, energy crops, and derived fuels for spinning reserve is considered, and there potential use in a 100% RE system is shown. The benefits of including CHP production are emphasized, along with the importance of the heat to electricity supply and demand balance, which can be gained through diversity of supply and storage options.

As there is limited land available on this island, the simplest and best option would appear to be the use of substantial wind power provision, converting any excess electricity produced into hydrogen for use in vehicles, catalytic heaters and fuel cells. This is the simplest option to run, requires the smallest land use, and gives the least amount of losses. The storage requirement for hydrogen is not excessive, and could be easily achieved using suitable underground tanks. This option can also be supplemented by the use of constantly run biogas CHP generating plant in order to solve a waste disposal problem if desired, while still maintaining ease of operation.

This chapter has shown the way in which MERIT can be used to provide an analysis of the possible supply combinations for a given area and demand set, with particular emphasis on the extra functionality provided by the additions to the program outlined in this thesis. This type of temporal analysis, and the ability to consider the use of intermittent sources, complemented by sustainably fuelled spinning reserve and storage, will prove useful in the design of sustainable energy systems with a high percentage of new and renewable energy sources. However, there are still ways in which the scope and functionality of this program can be increased, and these will be considered in Chapter 9, which also presents the conclusions of this work.

8.5 References

[1] Personal Correspondence, B. Graves, Isle of Muck

[2] Energy Efficiency Office, Department of the Environment, “Introduction to Energy Efficiency in Buildings” Series (1994 onwards)

[3] S.V. Allera and A.G. Horsburgh, “Load Profiling for Energy Trading and Settlements in the UK Electricity Markets”, October 1998, London

[4] Noren Corfiz, “Typical Load shapes for Six Categories of Swedish Commercial Buildings”, Lund Institute of Technology, 1997

[5] Personal Correspondence, Peter Smyth, Territory Sales Manager, JCB Agricultural

[6] D. Palmer, “Biogas – Energy from Animal Waste”, Solar Energy Research Institute, May 1981

9 Conclusions and Recommendations

The main findings of this thesis are summarised in this chapter, and recommendations are made for ways in which the quantitative and temporal demand and supply matching tool developed here can be further enhanced in order to additionally increase its scope and applicability.

9.1 Conclusions

This thesis has highlighted the need for sustainable energy development, and has shown that, in order to analyse the complete energy needs of an area, the energy demands for electricity, heat, hot water and transport must be taken into consideration. As there are complex quantitative and temporal demand and supply matching issues involved in the design of such systems, the need for a decision support framework that will aid the technical design of efficient and reliable sustainable energy systems, has been shown. This system will support the planning for, and encourage, future sustainable energy system development.

The components required to build a reliable and efficient sustainable energy supply system with a wide range of possible supplies for electricity, heat, hot water and transportation were considered. The important role in such systems of a variety of energy storage devices and sustainable fuels as spinning reserve, and also as a form of storage, was highlighted. The important role of combined heat and power generation and district-heating provision was also discussed, as a means of providing better fuel utilisation. Existing methods for sustainable energy system design assessment were considered, and from an evaluation of the strengths and weaknesses of these methods, a computer program has been developed which will perform temporal and quantitative demand and supply matching, in order to assess the viability of different supply mixes for different demand scenarios.

This program was developed from an existing program (MERIT) which allowed the matching of a variety of demand sets, made up for any given area and location, with intermittent supplies (wind and solar technologies), and auxiliary supplies (batteries, diesel engines, flywheels and pumped storage systems). The introduction to this program of methods for generating sustainable fuels derived from waste and biomass sources and hydrogen from excess electricity, the definition and matching of transportation demands, and a range of load following supplies and supplies that use these fuels (engines, turbines, fuel cells, vehicles, electrolysers, space and water heaters, heat and hot water storage systems), has greatly increased its functionality and applicability.

The program produced allows half-hourly or more frequent demand profiles to be chosen or created, and matched with a range of different supply scenarios, in order to find a range of technically feasible solutions for a given area and range of supply options. The half-hourly production profiles of sustainable fuels derived from waste and biomass are modelled using feedstock availability times and amounts, and easily available manufacturers' or process data. Any energy requirements for these processes are also taken into consideration, and half-hourly profiles for these demands are also created and added to the chosen demand profiles when matching supply and demand.

Supply technologies that use fuel and/or follow demand are considered after the chosen demands have been matched with the chosen intermittent supplies. Any number of these plant types may be chosen for use, and the order in which they are applied allows different supply strategies to be evaluated. Again, easily available manufacturers' data is used in order to estimate the performance of these supplies, which may be set to different refuelling or operation strategies (i.e. following the heat demand, electricity demand or both, or used at different set load percentages at different times of the day and year). The output and performance of these supplies will, therefore, depend on the residual energy demands, any excess supplies, and/or appropriate fuel availability. Based on these factors, the energy supply profiles and required inputs for each technology chosen can be modelled and used for demand and supply matching.

The matching procedure allows various observations to be made in order to assess the viability and comparative merits of different supply scenarios, and, through these, technically viable plant types and sizing, storage types and sizing, and control strategies can be ascertained for a range of suitable options, depending on available local resources. The final, preffered solution, however, will depend on a range of other factors, including cost of equipment, current available subsidies, existing plant, projected future demand, available land etc.

To prove the applicability and usefulness of the changes made to the MERIT software, a case study was completed for a hypothetical small island off the west coast of Scotland. This study highlighted the limitations of using intermittent supplies on their own, and showed the benefit of creating integrated systems that provide storage and spinning reserve to complement the use of intermittent sources. The complex balances which exist when designing such a system, especially when combined heat and power generation is being considered, were shown, and the way in which MERIT could be used to investigate these issues in order to find a range of technically feasible solutions for a given demand set and range of possible supplies was demonstrated.

The developments made to the MERIT system have extended the scope and applicability of the software, and have helped create a flexible and generic demand and supply matching tool that can allow informed decisions to be made when designing integrated sustainable energy supply systems for the supply of electricity, heat, hot water and transport. This system will aid the making of informed decisions about suitable overall energy provision for smaller areas, and will help guide the transition towards higher percentage sustainable energy provision in larger areas, as this becomes economically attractive.

9.2 Further Work

There are various different ways in which MERIT could be developed in order to increase its scope and applicability further. These may include the incorporation of further demand types and supply technologies, and adding increased versatility and realism.

9.2.1 Desalination Plant and Clean Water Demand

The demand for clean drinking water could also be considered in MERIT as, although it is not an energy demand, desalination plant are being increasingly used as a useful outlet for excess electricity from intermittent renewable or other supplies, especially on islands where clean drinking water is scarce and there is an abundant supply of sea water [1,2]. The inclusion of clean water demand and desalination plant definition would allow the sizing of desalination plant and water storage tanks, to ensure that the demand for clean drinking water can be met in areas where clean water supply is a significant problem. Also, for the fuel production technologies that require substantial amounts of water (e.g. fermentation, electrolysis), water demands could also be produced along with the energy demand profiles attached to these processes, where necessary, and added to the demands on matching in the same manner as the energy demand profiles.

Excess electricity would be used to make clean water, and the amount being produced would be compared with the clean water demand. If extra water was available it would be added to a storage profile similar to that for the derived fuel storage, if there was not enough to meet the demand the excess needed would be subtracted from the profile. The option could be given to use all excess electricity to produce water, with unlimited storage (to allow the necessary storage tank size to be ascertained), or to use the excess electricity to keep a certain size of tank full if possible. The stored contents and new production would be used to meet demand where possible.

9.2.2 Further Demand Development

To allow the analysis of demand sets that include industrial processes, it would be useful to be able to specify demands for process steam (or high-grade heat and low-grade heat), and mechanical work. This would be particularly useful in the analysis of buildings or communities where excess heat from CHP generation is to be used for a particular industrial process, or where the analysis of energy use in integrated industrial processes and buildings is being considered. The introduction of cooling demands, and suitable auxiliary plant to meet these requirements, may also be a useful addition to the program. This would allow the analysis of air conditioning needs in hot climates, and in buildings where large numbers of computers require constant cooling.

The introduction of demand side management measures in order to improve the match between the demand and supply profiles would be of benefit [3]. Methods of using excess electricity in a useful manner, other than the use of storage devices, have already been considered for the heating and storage of hot water, and by the use of electric storage heaters. Further measures to enable demand reduction and load levelling could also be introduced, including, for example, the use of load-shedding of interruptible supplies. A method for quantifying demand reduction measures in new buildings, and the effect of retrofitted measures on existing buildings, would also be useful. This could take the form of load profile reduction at the demand definition stage.

9.2.3 Further Supply Development

Further intermittent supply technologies could be incorporated into the program, including wave, tidal, and run-of-the river hydroelectric power generation. The modelling of a solar thermal Stirling engine would also be an interesting addition for the analysis of areas with high insolation. The use of heat pumps as a method for meeting heat demands is enjoying increased interest. These act in the same way as a refrigerator, with the cold side being placed outside, or in an area requiring cooling, and the hot side (heat exchanger) placed in the area to be heated [4]. The performance of heat pumps is affected by ambient temperature, and they work best in colder climates.

Another useful addition to the program would be a model for the Regenesys energy storage system, recently developed by National Power, which is effectively a cross between battery and regenerative electrolyser/fuel cell technology [5]. Using low cost and environmentally benign materials, it combines the high efficiencies of batteries with the separate storage of a hydrogen production and storage system. The result is a system with a fast response, high electricity-to-electricity efficiency and one in which the power output and storage capacity can be specified separately.

The main difference between the Regenesys system and electrolyser/fuel cell technology is that the electricity is stored as 'charged' electrolytes rather than hydrogen and one central system is used for charging and discharging (receiving and generating). The 'charged' and 'uncharged' electrolytes are stored in separate tanks and the level of charge depends on the ratio between the two. The storage capacity is limited only by the size of the electrolyte tanks, and the output does not vary with the amount of charge. As the Regenesys system technology is modular, the efficiency does not vary with plant size so anything from 5W to 500MW would be feasible. This flexibility makes it suitable for a large range of uses from small-scale autonomous renewable generation systems to use in much larger-scale electricity supply networks to allow greater use of variable renewable generation.

The engine model described in this thesis could be enhanced to allow more engines to run simultaneously, in order to increase efficiency and lessen the impact of outages and downtime for maintenance. The option could also be given to run the engines at minimum load when the demand is less than this, so that the demand can be met, and use can be made of the excess electricity and heat.

9.2.4 Larger Geographical Areas

When considering the use of intermittent supplies whose outputs depend on weather patterns, it is important to vary their siting to help compensate for their intermittent nature. As only one climate file is used for the prediction of the outputs of intermittent sources, this may give misleading results when larger geographical areas are being considered. To avoid this, some variation could be introduced in order to allow generation from different locations to be considered.

When considering larger geographical areas, it will become more important to take into account the potential pipeline losses for district heating systems, the potential pipeline losses for biogas or hydrogen distribution, and electricity transmission losses. The actual siting of potential supplies and demands, the location of feedstocks for fuel consumption, and the method of fuel distribution and use will require to be considered in more detail, to allow a full analysis of potential generation options.

9.2.5 Matching

With the introduction of the ability to use multiple load following devices, and the fact that changing the order in which these technologies are used can dramatically affect the system performance, the number of possible demand and supply combinations has increased substantially. The current auto search facility available at the matching stage of the program can search for the best match between the demands and the intermittent supplies, and one auxiliary supply if desired. If this were to be extended to search all possible combinations of demand and supply, with the auxiliary supplies being used in all possible orders, the process would take an excessively long time. It would, therefore, be worth investigating the use of search procedures in other fields of study, in order to develop an intelligent or learning algorithm that could be employed to help find a range of optimum solutions, based, if required, on user selectable criteria. Optimisation techniques could also be incorporated, such as the genetic algorithm used by Seeling-Hochmuth [6], in order to increase the speed and effectiveness of the auto search procedure.

This thesis has described the development of a decision support framework that will aid the design of sustainable energy systems, for the supply of electricity, heat, hot water and transportation, through the use of temporal and quantitative demand and supply matching. This will allow informed decisions to be made about the technical feasibility of supply mix and control strategies, plant type and sizing, suitable fuel production, fuel and energy storage type and sizing, and required spinning reserve, for any given area and range of supply options. This decision support framework will aid the design of both small-scale and large-scale future renewable energy supply systems, allow transitional periods to be effectively managed, and encourage and advance state-of-the-art deployment as sustainable energy supply systems become more economically desirable.

9.3 References

[1] A.G. Rassu, "Towards 100% RES Supply in La Maddalena Island - Sardinia", Proc. of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2001

[2] M. Cendagorta Galarza Lopez, "Tenerife 100% RES Strategy", Proc. of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2001

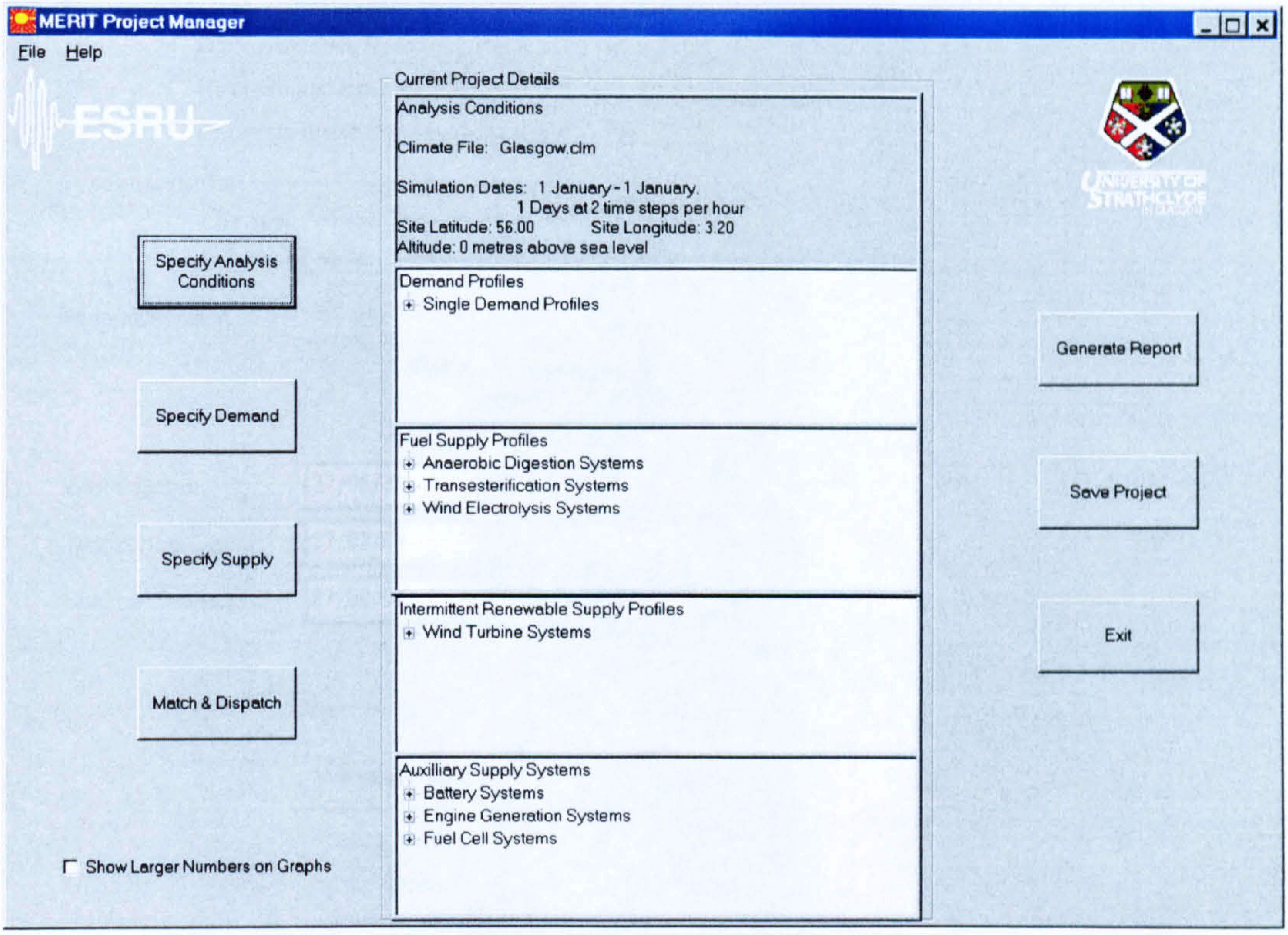
[3] P.Taylor, "Increased renewable energy penetration on island power systems through distributed fuzzy load control", Proc. of the Int. Conf. "Renewable Energies for Islands. Towards 100% RES Supply", Chania, Crete, Greece, 14-16 June 2001

[4] Energy Efficiency Best Practice Programme, "Heat Pumps in the UK: Current Status and Activities", Energy Efficiency Office, Department of the Environment, www.energy-efficiency.gov.uk, 0800 585794

[5] A. Price, S. Bartley, S. Male, G. Cooley, ' A novel approach to utility scale energy storage', Power Engineering Journal, 1999, Vol. 13, No. 3, pp 122-129

[6] G. C. Seeling-Hochmuth, 'A combined optimisation concept for the design and operation strategy of hybrid-PV energy systems', Solar Energy, 1997, Vol. 61, No. 2, pp 77-87

Appendix 1: Program Windows



Current Project Details

Analysis Conditions

Climate File: Glasgow.clm

Simulation Dates: 1 January - 1 January.
1 Days at 2 time steps per hour
Site Latitude: 56.00 Site Longitude: 3.20
Altitude: 0 metres above sea level

Demand Profiles
- Single Demand Profiles

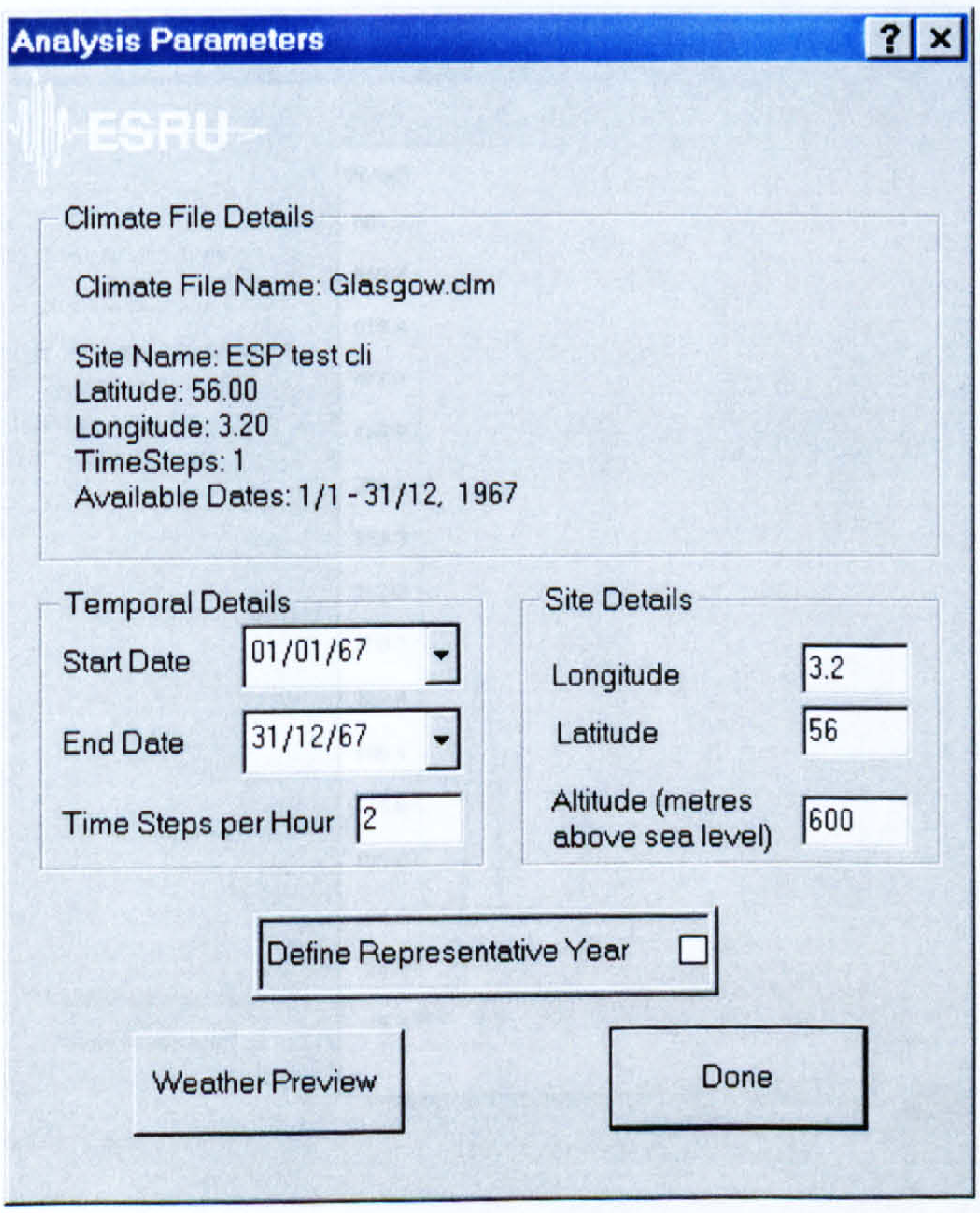
Fuel Supply Profiles
- Anaerobic Digestion Systems
- Transesterification Systems
- Wind Electrolysis Systems

Intermittent Renewable Supply Profiles
- Wind Turbine Systems

Auxilliary Supply Systems
- Battery Systems
- Engine Generation Systems
- Fuel Cell Systems

☐ Show Larger Numbers on Graphs

Figure A1.1: Main Program Window



Climate File Details

Climate File Name: Glasgow.clm

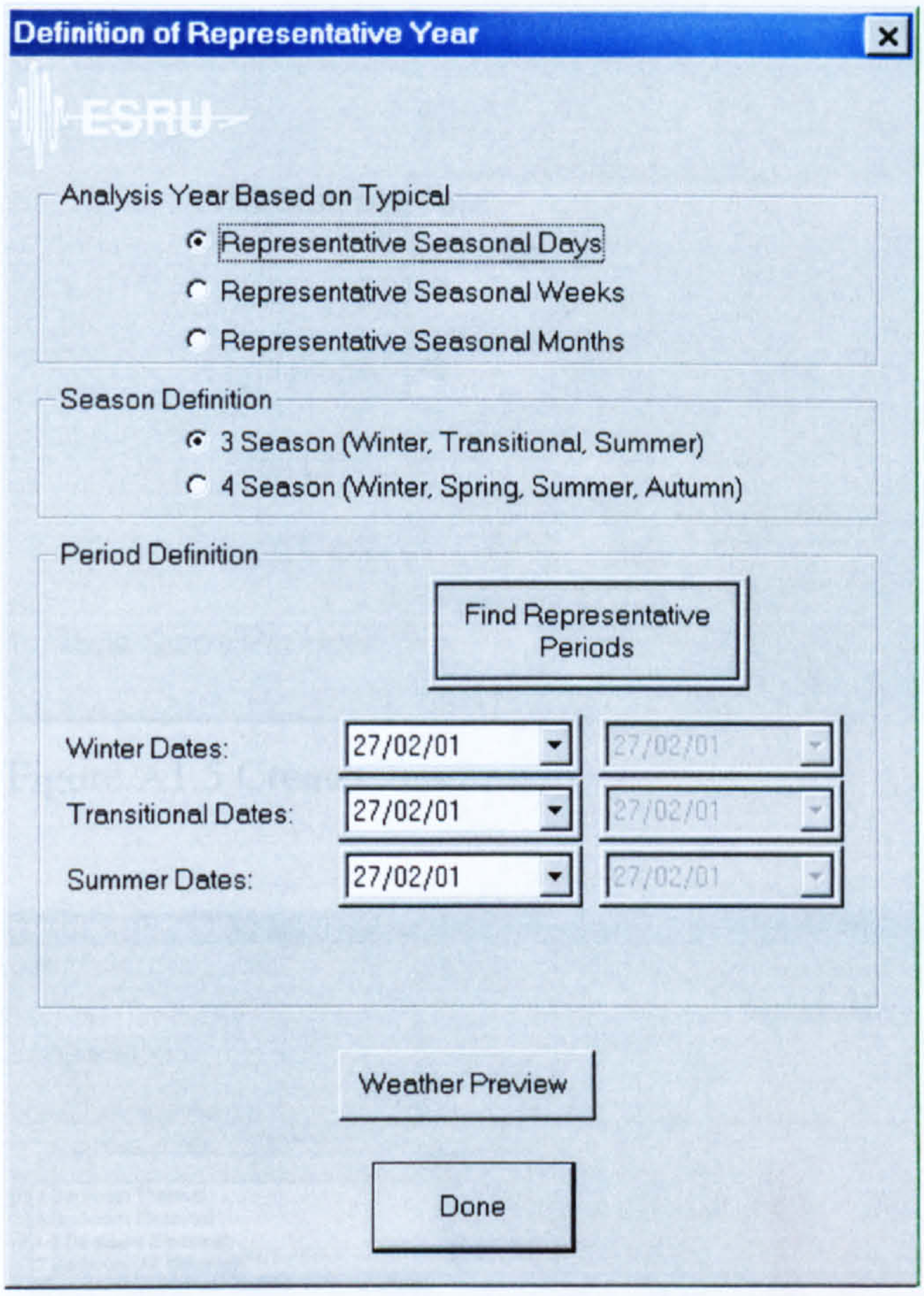
Site Name: ESP test cli
Latitude: 56.00
Longitude: 3.20
TimeSteps: 1
Available Dates: 1/1 - 31/12, 1967

Temporal Details
Start Date: 01/01/67
End Date: 31/12/67
Time Steps per Hour: 2

Site Details
Longitude: 3.2
Latitude: 56
Altitude (metres above sea level): 600

Define Representative Year ☐

Figure A1.2: Analysis Parameters Window

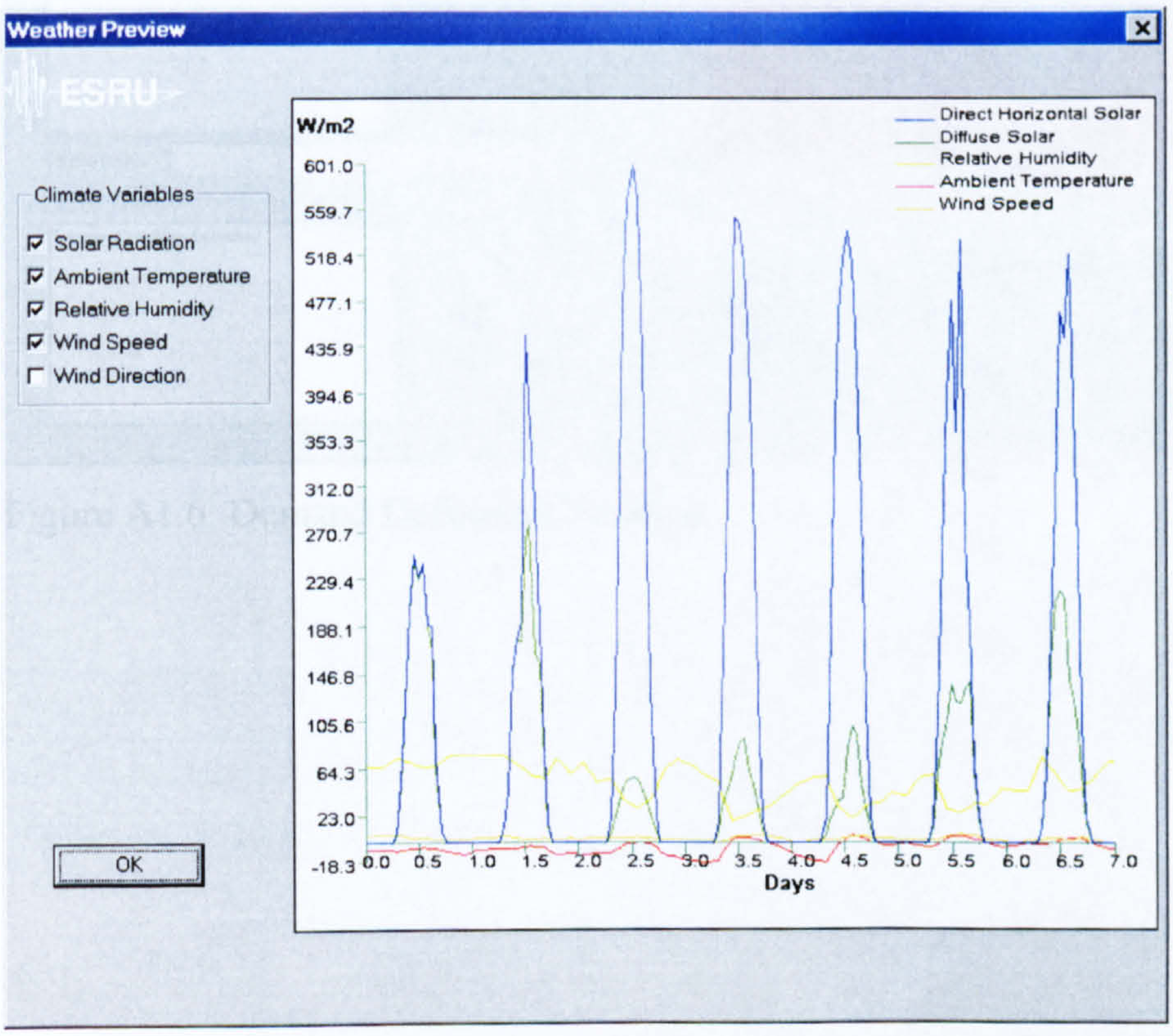


Analysis Year Based on Typical
● Representative Seasonal Days
○ Representative Seasonal Weeks
○ Representative Seasonal Months

Season Definition
● 3 Season (Winter, Transitional, Summer)
○ 4 Season (Winter, Spring, Summer, Autumn)

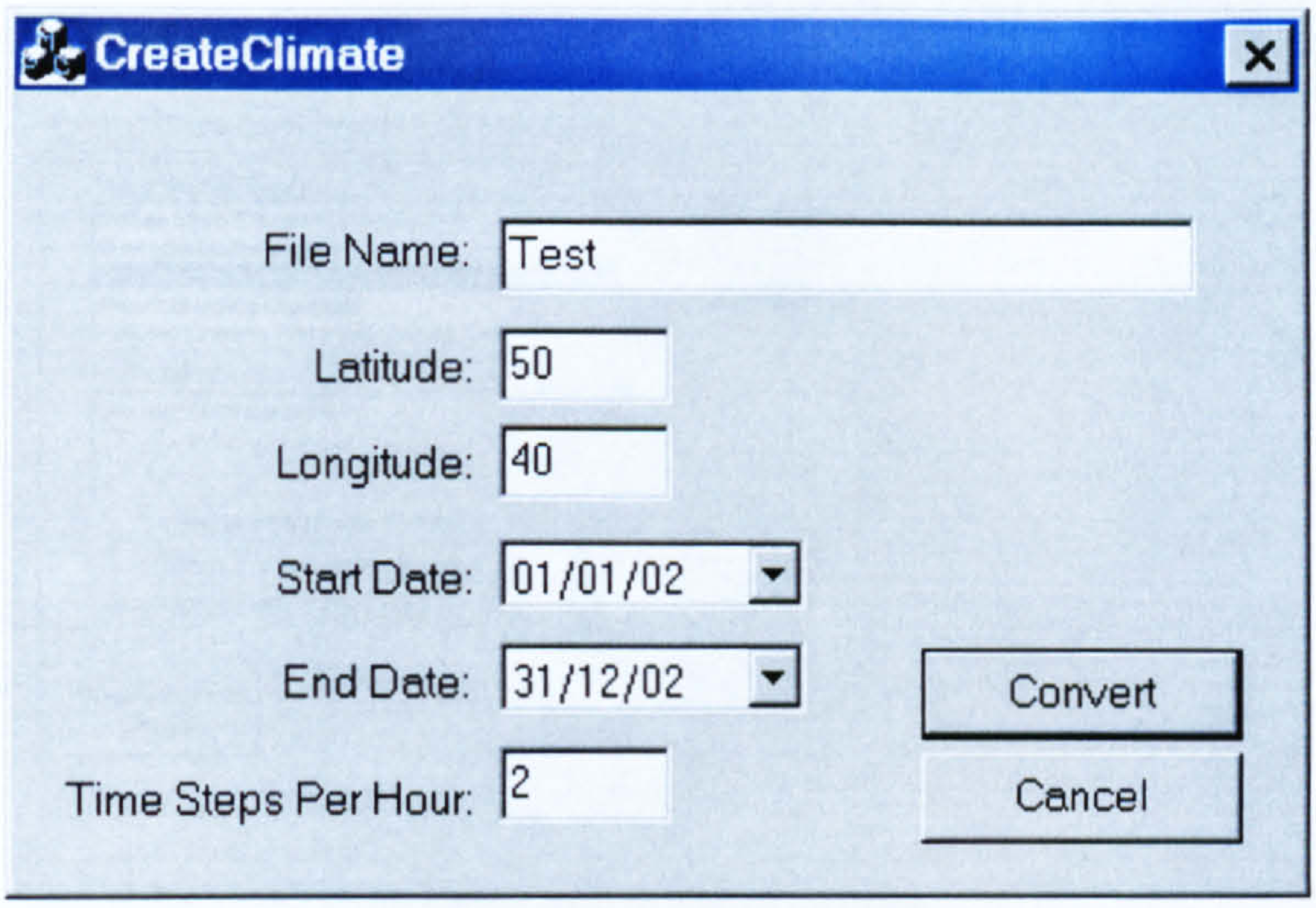
Period Definition
Winter Dates: 27/02/01 27/02/01
Transitional Dates: 27/02/01 27/02/01
Summer Dates: 27/02/01 27/02/01

Figure A1.3: Representative Period Definition Window



Climate Variables
☑ Solar Radiation
☑ Ambient Temperature
☑ Relative Humidity
☑ Wind Speed
☐ Wind Direction

Figure A1.4: Weather Preview Window



CreateClimate

File Name: Test

Latitude: 50

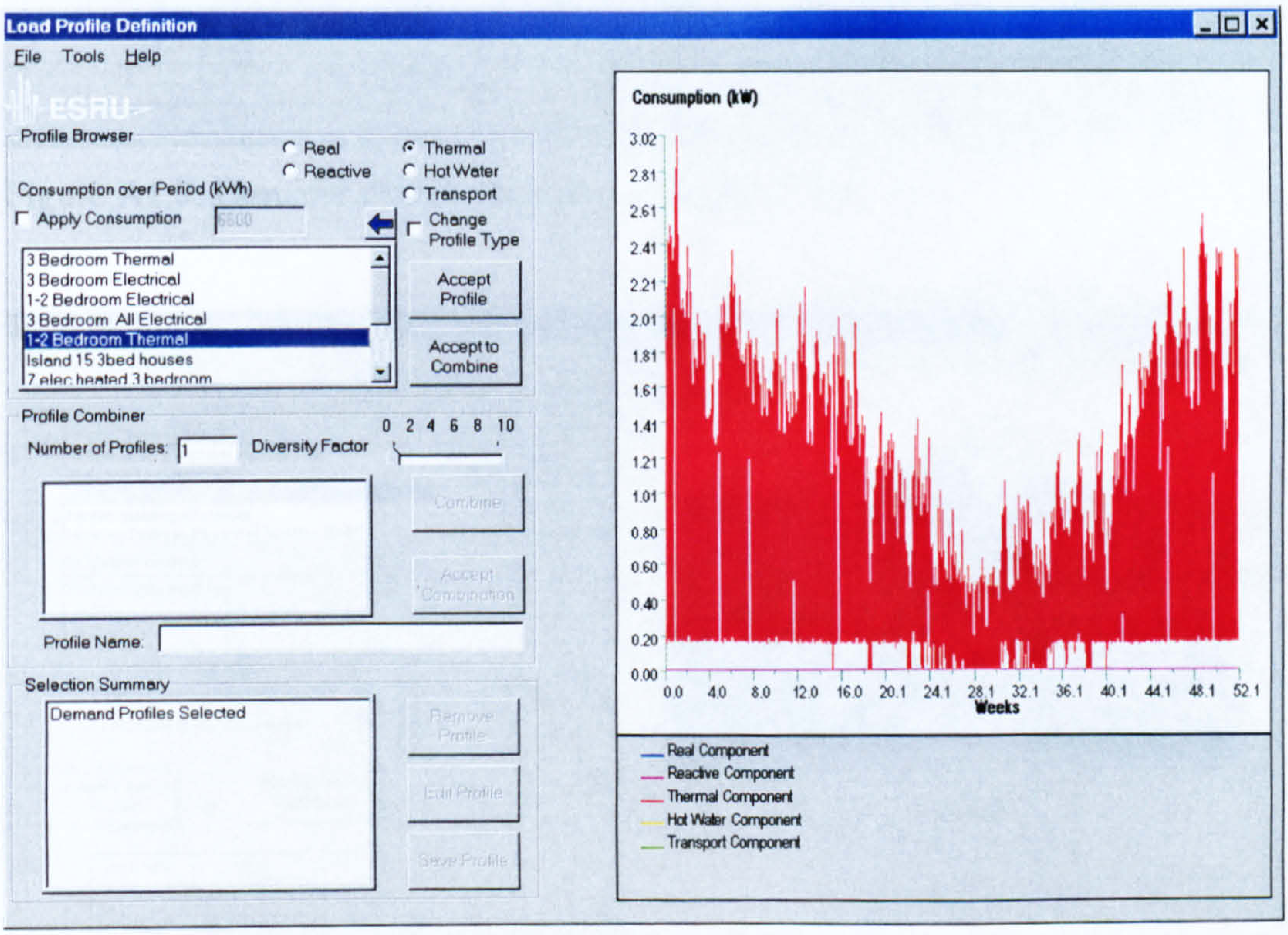
Longitude: 40

Start Date: 01/01/02

End Date: 31/12/02

Time Steps Per Hour: 2

Figure A1.5 CreateClimate.exe



Load Profile Definition

Profile Browser

○ Real
○ Reactive
● Thermal
○ Hot Water
○ Transport

Consumption over Period (kWh)

☐ Apply Consumption 6600

☐ Change Profile Type

3 Bedroom Thermal
3 Bedroom Electrical
1-2 Bedroom Electrical
3 Bedroom All Electrical
1-2 Bedroom Thermal
Island 15 3bed houses
7 elec heated 3 bedroom

Profile Combiner

Number of Profiles: 1

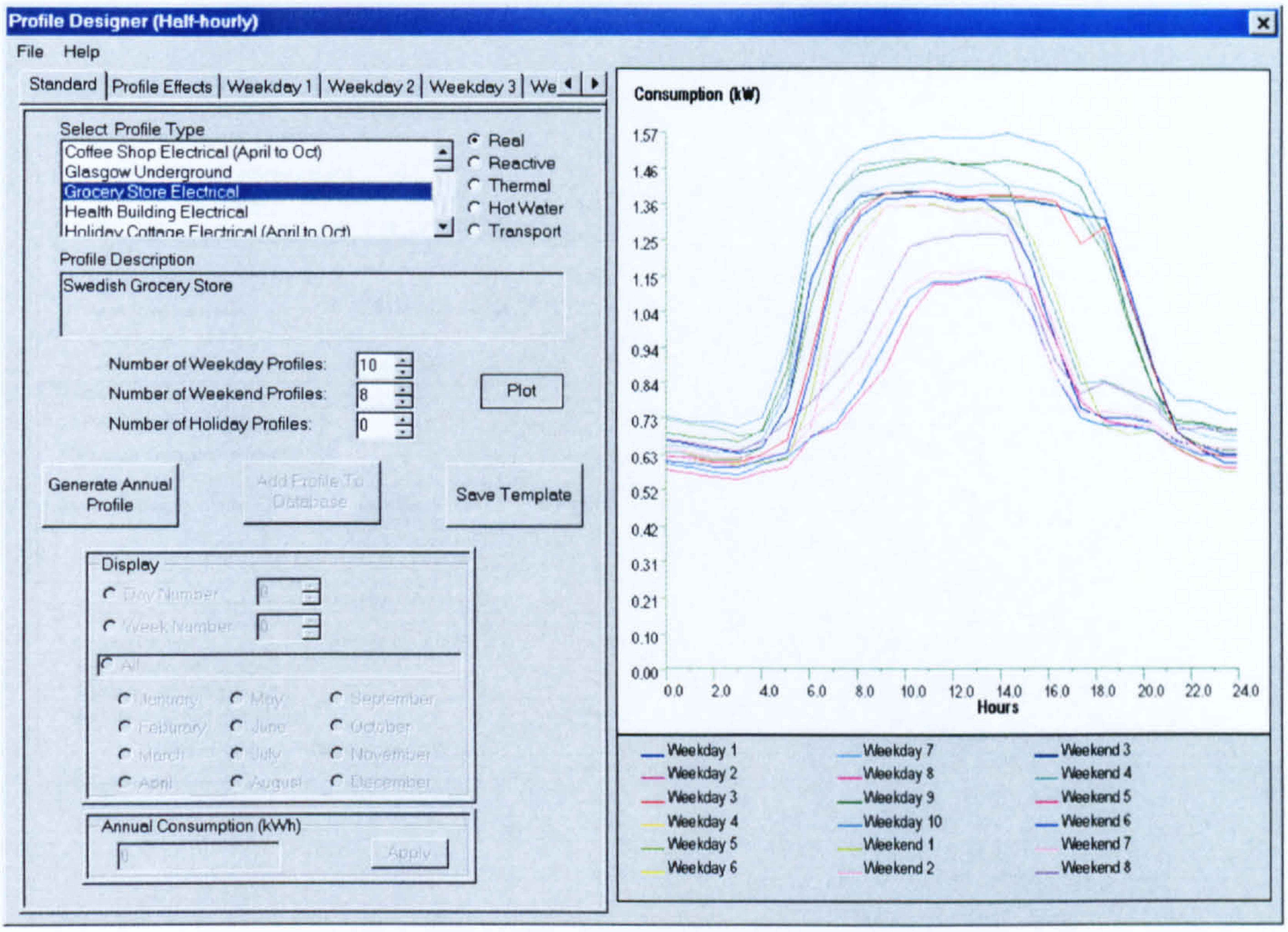
Diversity Factor

Profile Name:

Selection Summary

Demand Profiles Selected

Figure A1.6: Demand Definition Window



Select Profile Type: Grocery Store Electrical

● Real

Profile Description: Swedish Grocery Store

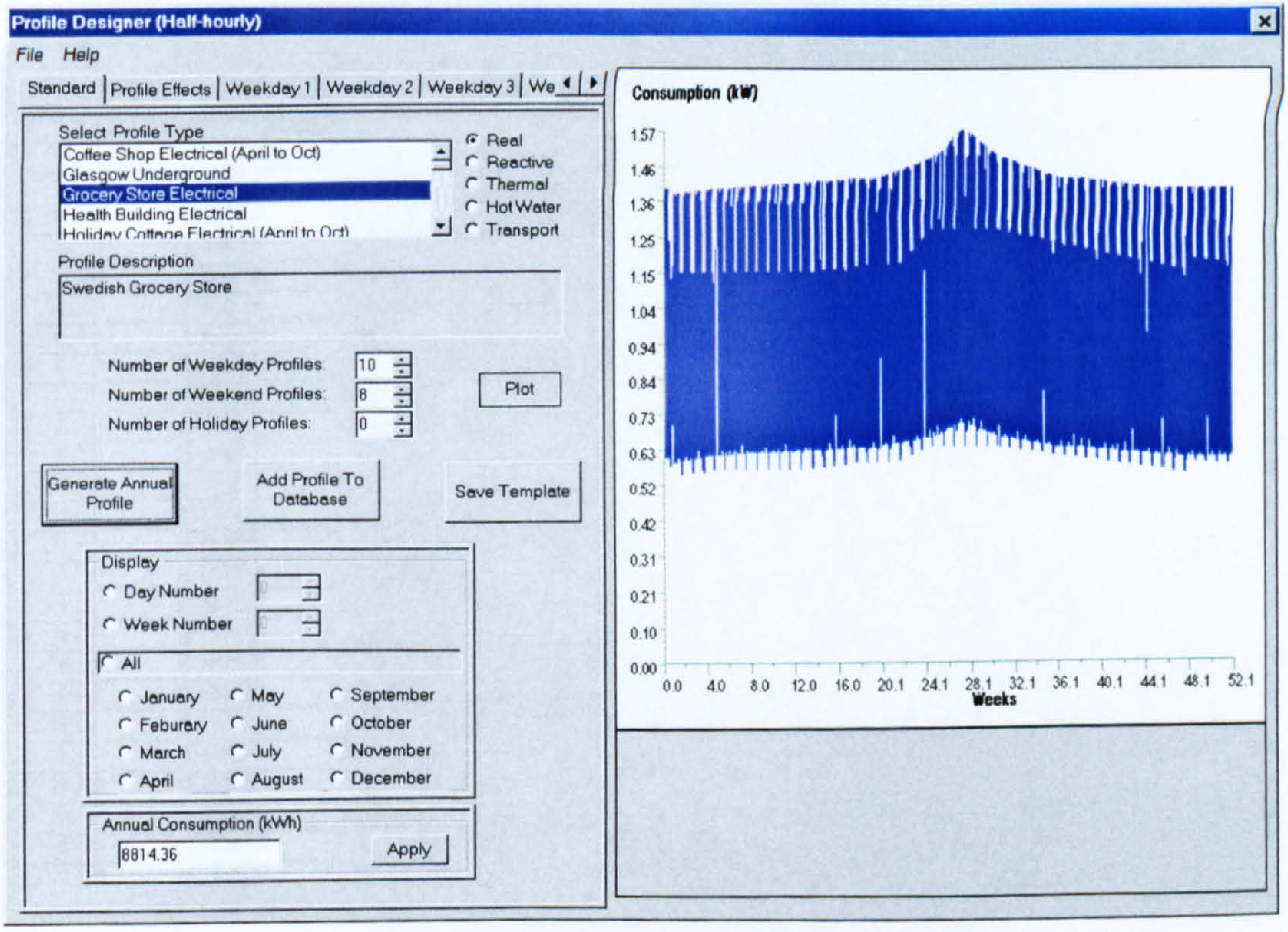
Number of Weekday Profiles: 10

Number of Weekend Profiles: 8

Number of Holiday Profiles: 0

Annual Consumption (kWh): 0

Figure A1.7: Demand Profile Designer - Standard Tab (1)



Select Profile Type: Grocery Store Electrical

● Real

Profile Description: Swedish Grocery Store

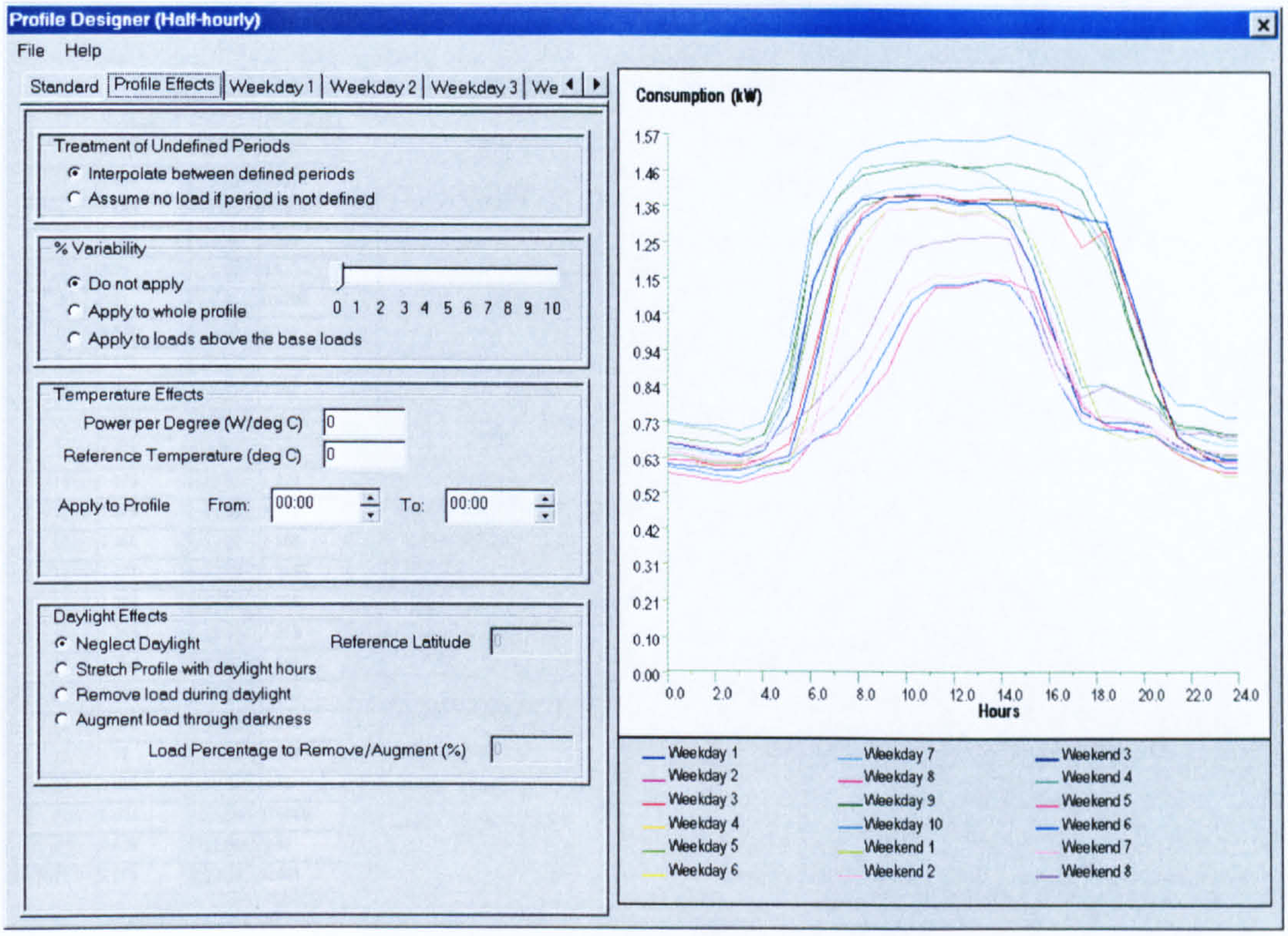
Number of Weekday Profiles: 10

Number of Weekend Profiles: 8

Number of Holiday Profiles: 0

Annual Consumption (kWh): 8814.36

Figure A1.8: Demand Profile Designer - Standard Tab (2)



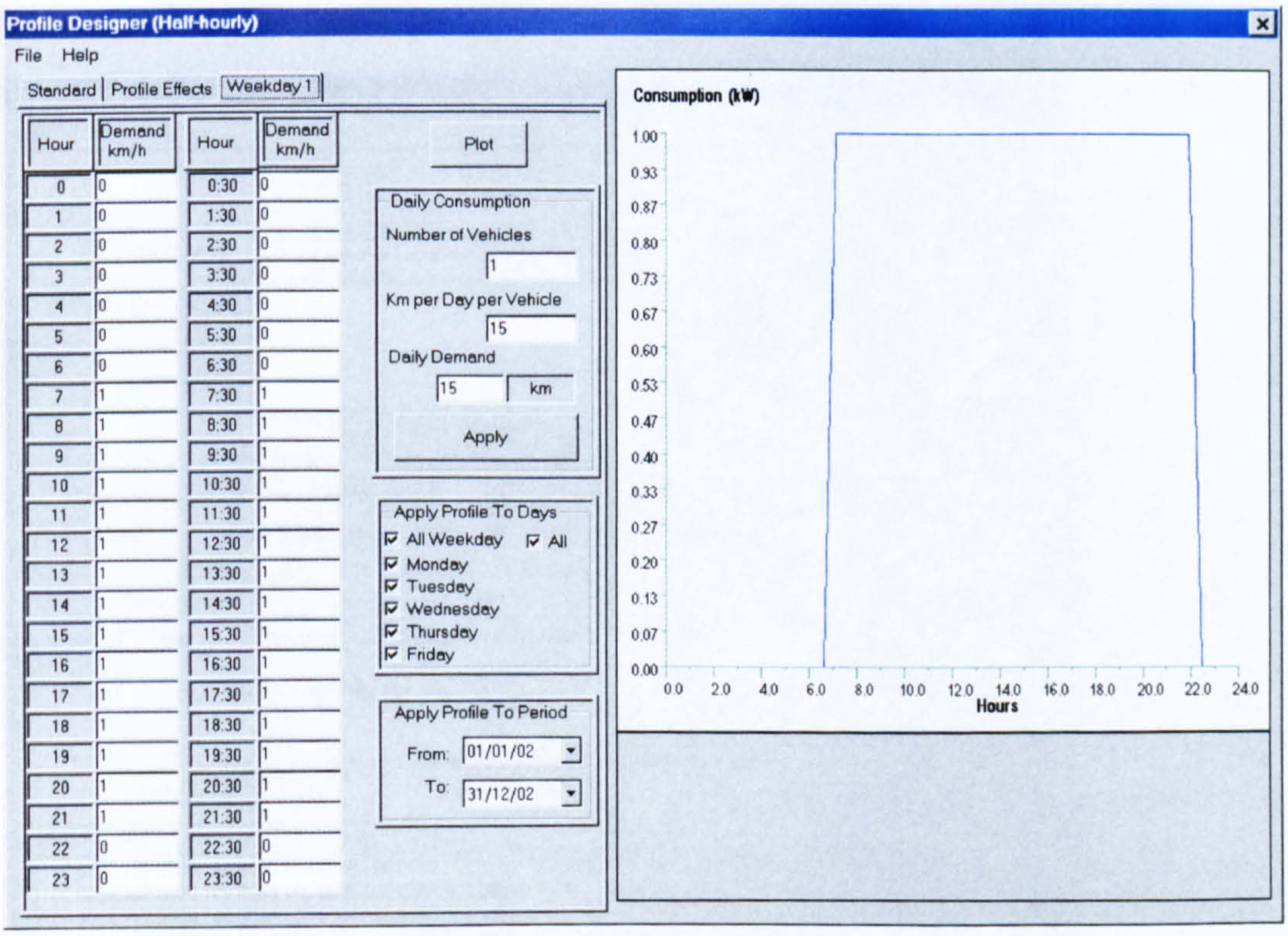
Treatment of Undefined Periods
● Interpolate between defined periods
○ Assume no load if period is not defined

% Variability
● Do not apply
○ Apply to whole profile
○ Apply to loads above the base loads
0 1 2 3 4 5 6 7 8 9 10

Temperature Effects
Power per Degree (W/deg C) 0
Reference Temperature (deg C) 0
Apply to Profile From: 00:00 To: 00:00

Daylight Effects
● Neglect Daylight
○ Stretch Profile with daylight hours
○ Remove load during daylight
○ Augment load through darkness
Reference Latitude 0
Load Percentage to Remove/Augment (%) 0

Figure A1.9: Demand Profile Designer - Profile Effects Tab



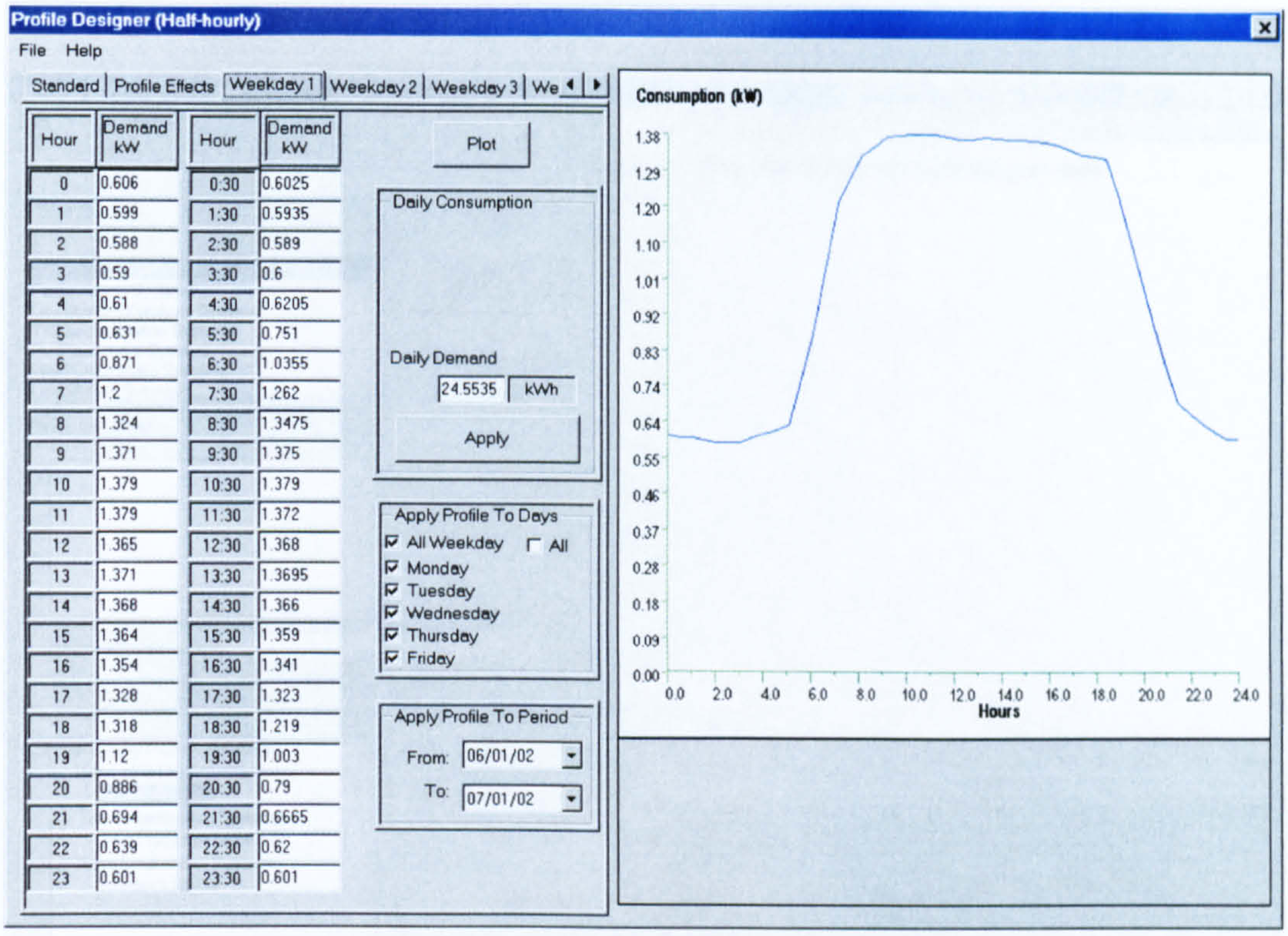
Hour	Demand km/h	Hour	Demand km/h
0	0	0:30	0
1	0	1:30	0
2	0	2:30	0
3	0	3:30	0
4	0	4:30	0
5	0	5:30	0
6	0	6:30	0
7	1	7:30	1
8	1	8:30	1
9	1	9:30	1
10	1	10:30	1
11	1	11:30	1
12	1	12:30	1
13	1	13:30	1
14	1	14:30	1
15	1	15:30	1
16	1	16:30	1
17	1	17:30	1
18	1	18:30	1
19	1	19:30	1
20	1	20:30	1
21	1	21:30	1
22	0	22:30	0
23	0	23:30	0

Daily Consumption
Number of Vehicles 1
Km per Day per Vehicle 15
Daily Demand 15 km

Apply Profile To Days
☑ All Weekday ☑ All
☑ Monday
☑ Tuesday
☑ Wednesday
☑ Thursday
☑ Friday

Apply Profile To Period
From: 01/01/02
To: 31/12/02

Figure A1.10: Demand Profile Designer - Profile Tab (1)



Hour	Demand kW	Hour	Demand kW
0	0.606	0:30	0.6025
1	0.599	1:30	0.5935
2	0.588	2:30	0.589
3	0.59	3:30	0.6
4	0.61	4:30	0.6205
5	0.631	5:30	0.751
6	0.871	6:30	1.0355
7	1.2	7:30	1.262
8	1.324	8:30	1.3475
9	1.371	9:30	1.375
10	1.379	10:30	1.379
11	1.379	11:30	1.372
12	1.365	12:30	1.368
13	1.371	13:30	1.3695
14	1.368	14:30	1.366
15	1.364	15:30	1.359
16	1.354	16:30	1.341
17	1.328	17:30	1.323
18	1.318	18:30	1.219
19	1.12	19:30	1.003
20	0.886	20:30	0.79
21	0.694	21:30	0.6665
22	0.639	22:30	0.62
23	0.601	23:30	0.601

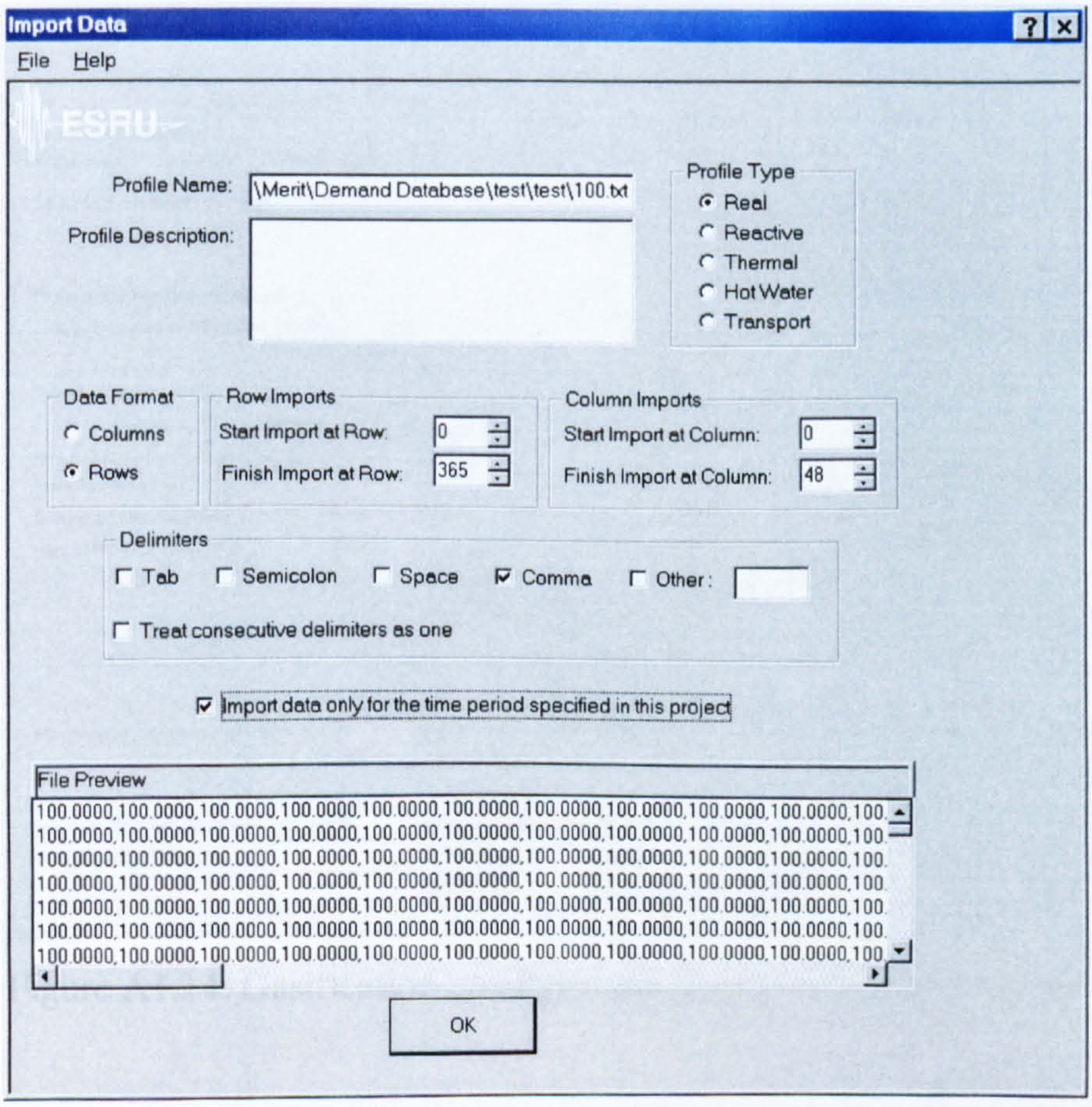
Daily Consumption

Daily Demand 24.5535 kWh

Apply Profile To Days
☑ All Weekday ☐ All
☑ Monday
☑ Tuesday
☑ Wednesday
☑ Thursday
☑ Friday

Apply Profile To Period
From: 06/01/02
To: 07/01/02

Figure A1.11: Demand Profile Designer - Profile Tab (2)



Profile Name: \Merit\Demand Database\test\test\100.txt

Profile Description:

Profile Type
● Real
○ Reactive
○ Thermal
○ Hot Water
○ Transport

Data Format
○ Columns
● Rows

Row Imports
Start Import at Row: 0
Finish Import at Row: 365

Column Imports
Start Import at Column: 0
Finish Import at Column: 48

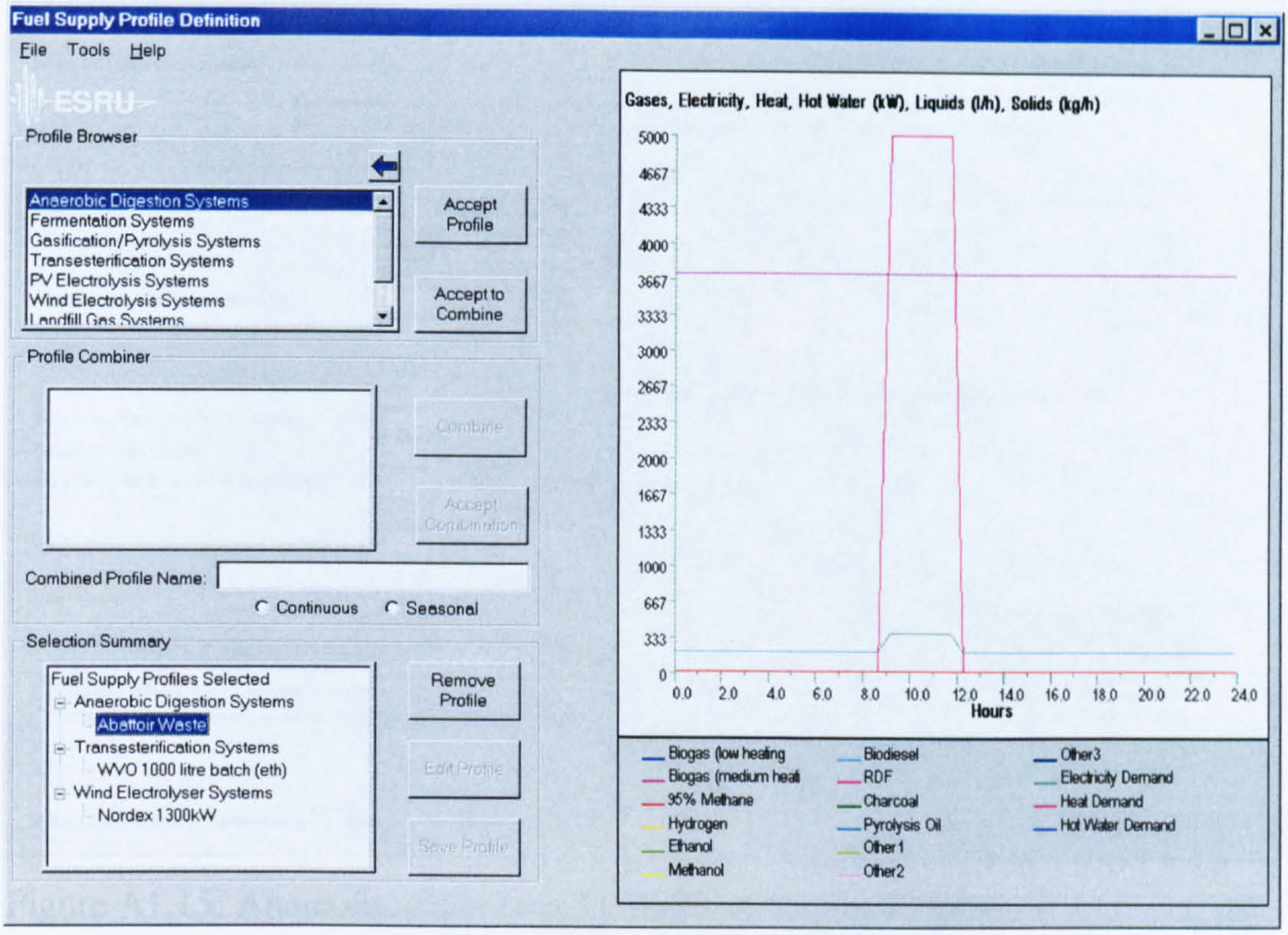
Delimiters
☐ Tab ☐ Semicolon ☐ Space ☑ Comma ☐ Other:
☐ Treat consecutive delimiters as one

☑ Import data only for the time period specified in this project

File Preview

```
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.0000,100.
```

Figure A1.12: Import Data Window



Profile Browser:
- Anaerobic Digestion Systems
- Fermentation Systems
- Gasification/Pyrolysis Systems
- Transesterification Systems
- PV Electrolysis Systems
- Wind Electrolysis Systems
- Landfill Gas Systems

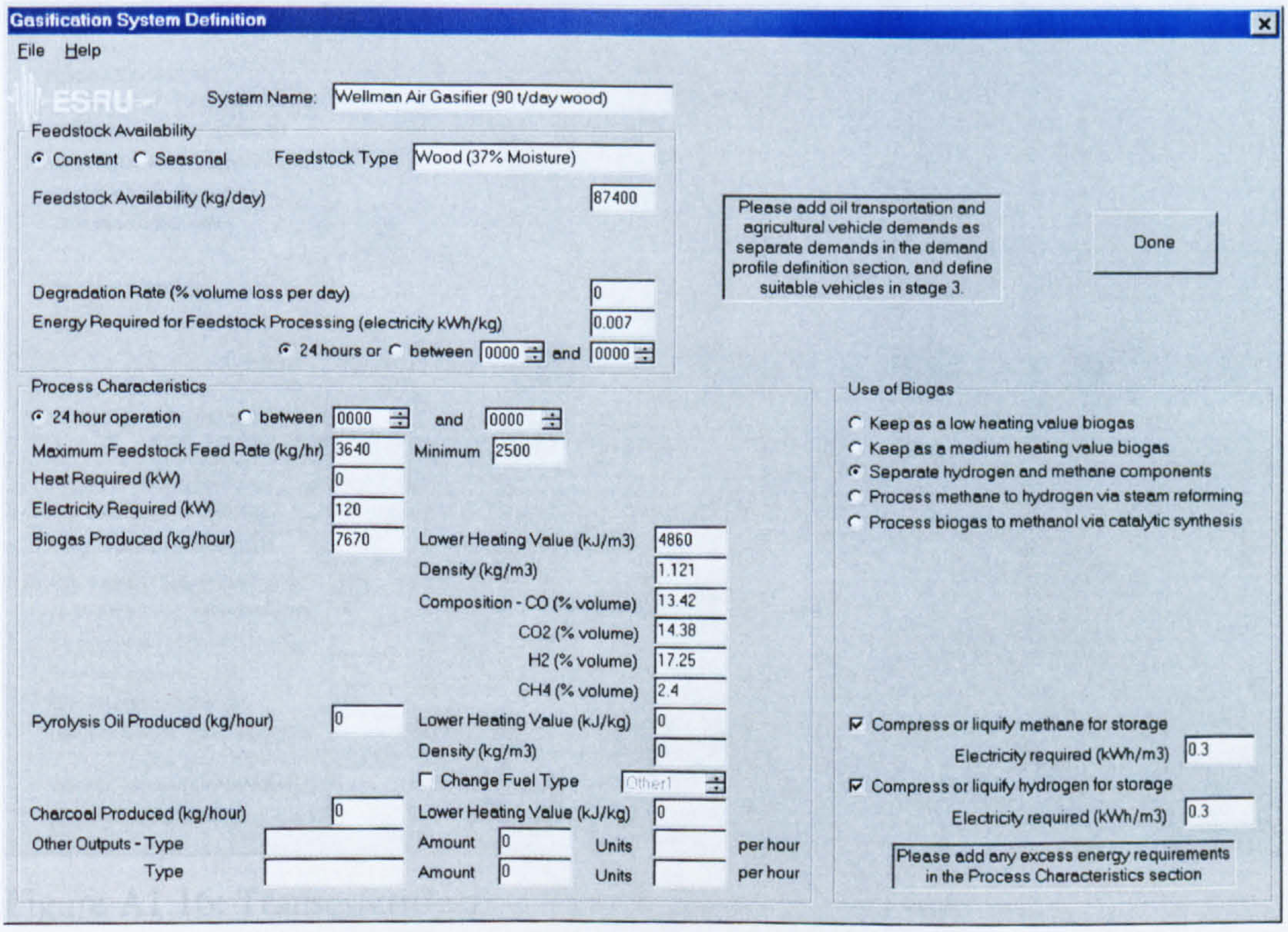
Combined Profile Name:

○ Continuous ○ Seasonal

Selection Summary

- Fuel Supply Profiles Selected
  - Anaerobic Digestion Systems
    - Abattoir Waste
  - Transesterification Systems
    - WVO 1000 litre batch (eth)
  - Wind Electrolyser Systems
    - Nordex 1300kW

Figure A1.13: Derived Fuel Supply Window



System Name: Wellman Air Gasifier (90 t/day wood)

Feedstock Availability

● Constant ○ Seasonal

Feedstock Type: Wood (37% Moisture)

Feedstock Availability (kg/day): 87400

Degradation Rate (% volume loss per day): 0

Energy Required for Feedstock Processing (electricity kWh/kg): 0.007

● 24 hours or ○ between 0000 and 0000

Please add oil transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Process Characteristics

● 24 hour operation ○ between 0000 and 0000

Maximum Feedstock Feed Rate (kg/hr): 3640 Minimum: 2500

Heat Required (kW): 0

Electricity Required (kW): 120

Biogas Produced (kg/hour): 7670

Lower Heating Value (kJ/m3): 4860

Density (kg/m3): 1.121

Composition - CO (% volume): 13.42

CO2 (% volume): 14.38

H2 (% volume): 17.25

CH4 (% volume): 2.4

Pyrolysis Oil Produced (kg/hour): 0

Lower Heating Value (kJ/kg): 0

Density (kg/m3): 0

☐ Change Fuel Type: Other1

Charcoal Produced (kg/hour): 0

Lower Heating Value (kJ/kg): 0

Other Outputs - Type: Amount 0 Units per hour

Type: Amount 0 Units per hour

Use of Biogas

○ Keep as a low heating value biogas

○ Keep as a medium heating value biogas

● Separate hydrogen and methane components

○ Process methane to hydrogen via steam reforming

○ Process biogas to methanol via catalytic synthesis

☑ Compress or liquify methane for storage

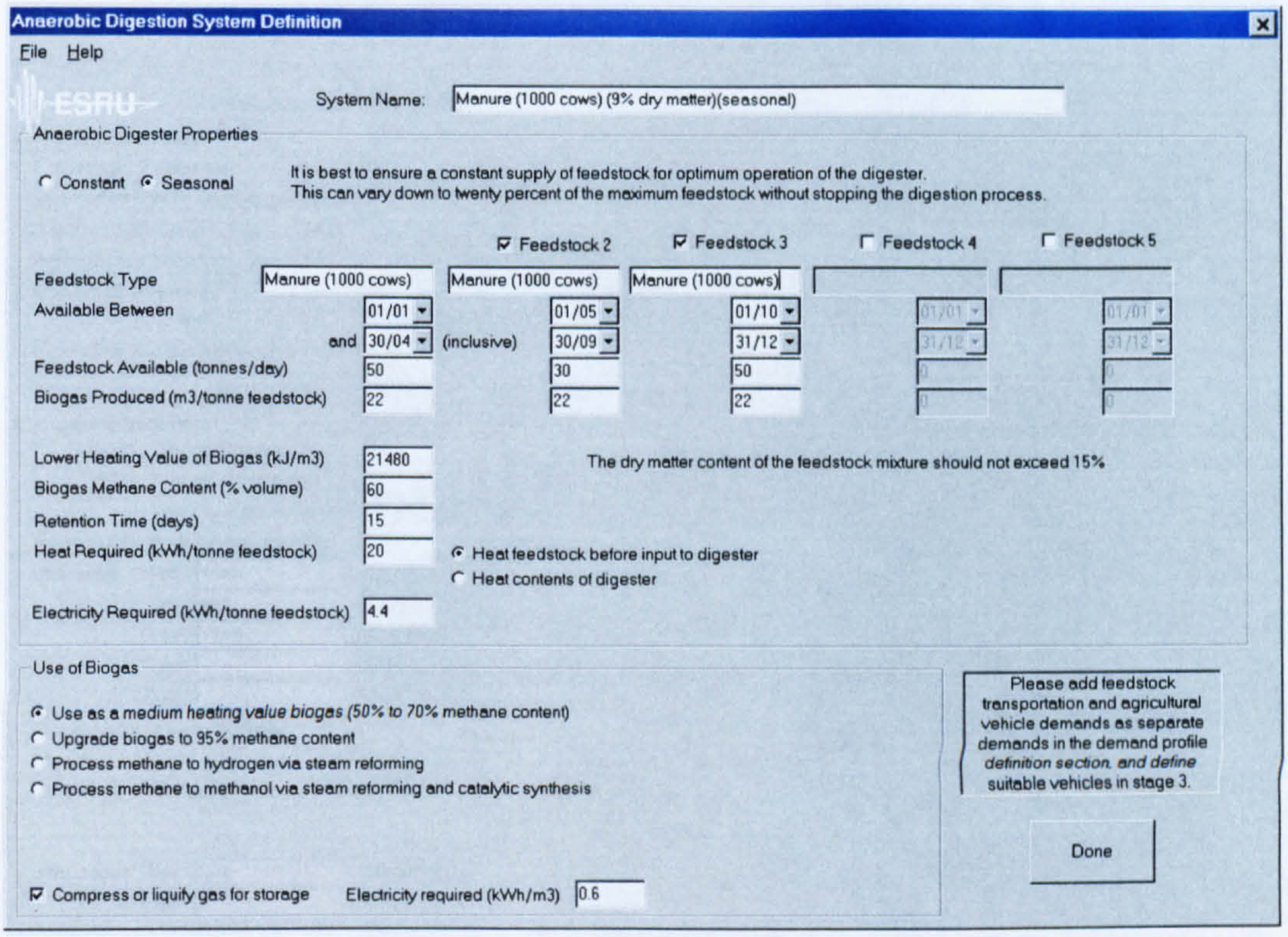
Electricity required (kWh/m3): 0.3

☑ Compress or liquify hydrogen for storage

Electricity required (kWh/m3): 0.3

Please add any excess energy requirements in the Process Characteristics section

Figure A1.14: Gasification and Pyrolysis System Definition Window



Anaerobic Digestion System Definition

File Help

System Name: Manure (1000 cows) (9% dry matter)(seasonal)

Anaerobic Digester Properties

○ Constant ● Seasonal

It is best to ensure a constant supply of feedstock for optimum operation of the digester.
This can vary down to twenty percent of the maximum feedstock without stopping the digestion process.

		☑ Feedstock 2	☑ Feedstock 3	☐ Feedstock 4	☐ Feedstock 5
Feedstock Type	Manure (1000 cows)	Manure (1000 cows)	Manure (1000 cows)		
Available Between	01/01	01/05	01/10	01/01	01/01
and	30/04	30/09	31/12	31/12	31/12
Feedstock Available (tonnes/day)	50	30	50	0	0
Biogas Produced (m3/tonne feedstock)	22	22	22	0	0

(inclusive)

Lower Heating Value of Biogas (kJ/m3) 21480

Biogas Methane Content (% volume) 60

Retention Time (days) 15

Heat Required (kWh/tonne feedstock) 20

Electricity Required (kWh/tonne feedstock) 4.4

The dry matter content of the feedstock mixture should not exceed 15%

● Heat feedstock before input to digester
○ Heat contents of digester

Use of Biogas

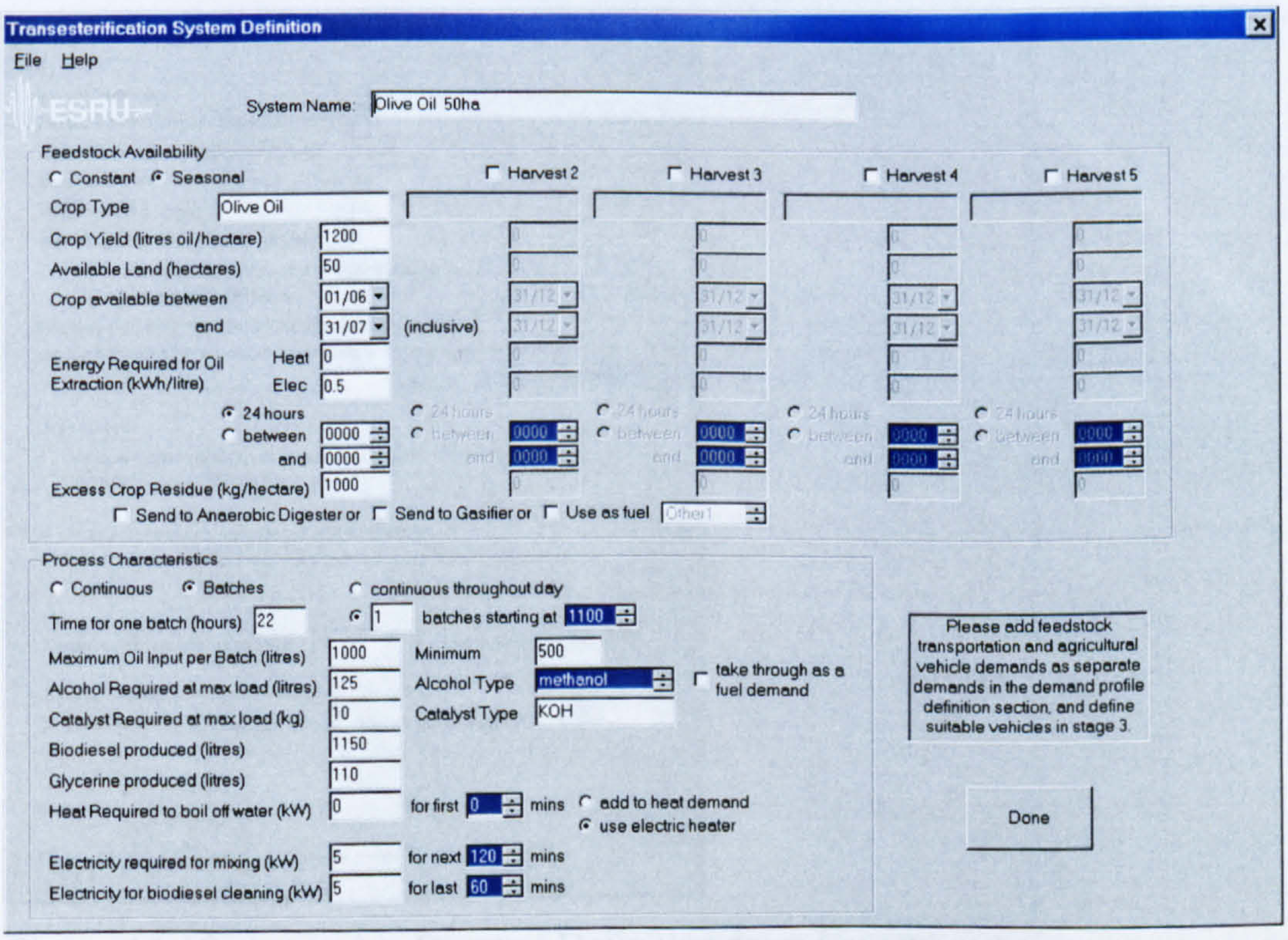
● Use as a medium heating value biogas (50% to 70% methane content)
○ Upgrade biogas to 95% methane content
○ Process methane to hydrogen via steam reforming
○ Process methane to methanol via steam reforming and catalytic synthesis

☑ Compress or liquify gas for storage Electricity required (kWh/m3) 0.6

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Done

Figure A1.15: Anaerobic Digestion System Definition Window



Transesterification System Definition

File Help

System Name: Olive Oil 50ha

Feedstock Availability

○ Constant ● Seasonal

		☐ Harvest 2	☐ Harvest 3	☐ Harvest 4	☐ Harvest 5
Crop Type	Olive Oil				
Crop Yield (litres oil/hectare)	1200	0	0	0	0
Available Land (hectares)	50	0	0	0	0
Crop available between	01/06	31/12	31/12	31/12	31/12
and	31/07	31/12	31/12	31/12	31/12
Energy Required for Oil Extraction (kWh/litre) Heat	0	0	0	0	0
Elec	0.5	0	0	0	0
	● 24 hours	○ 24 hours	○ 24 hours	○ 24 hours	○ 24 hours
○ between	0000	0000	0000	0000	0000
and	0000	0000	0000	0000	0000
Excess Crop Residue (kg/hectare)	1000	0	0	0	0

(inclusive)

☐ Send to Anaerobic Digester or ☐ Send to Gasifier or ☐ Use as fuel Other1

Process Characteristics

○ Continuous ● Batches

○ continuous throughout day

Time for one batch (hours) 22

● 1 batches starting at 1100

Maximum Oil Input per Batch (litres) 1000 Minimum 500

Alcohol Required at max load (litres) 125 Alcohol Type methanol ☐ take through as a fuel demand

Catalyst Required at max load (kg) 10 Catalyst Type KOH

Biodiesel produced (litres) 1150

Glycerine produced (litres) 110

Heat Required to boil off water (kW) 0 for first 0 mins ○ add to heat demand ● use electric heater

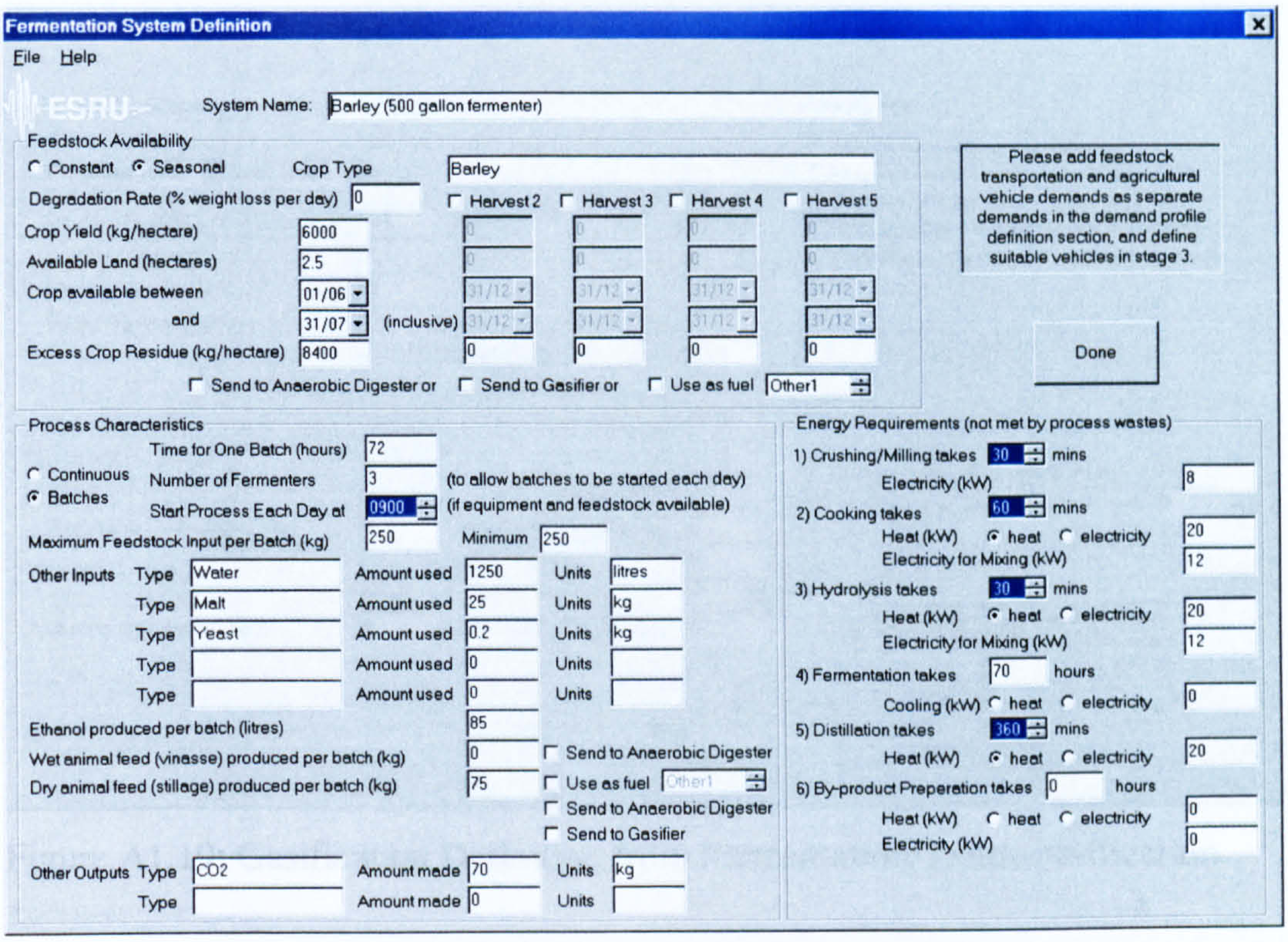
Electricity required for mixing (kW) 5 for next 120 mins

Electricity for biodiesel cleaning (kW) 5 for last 60 mins

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Done

Figure A1.16: Transesterification System Definition Window



System Name: Barley (500 gallon fermenter)

Feedstock Availability

○ Constant ● Seasonal

Crop Type: Barley

Degradation Rate (% weight loss per day): 0

Crop Yield (kg/hectare): 6000

Available Land (hectares): 2.5

Crop available between 01/06 and 31/07 (inclusive)

Excess Crop Residue (kg/hectare): 8400

☐ Harvest 2 ☐ Harvest 3 ☐ Harvest 4 ☐ Harvest 5

☐ Send to Anaerobic Digester or ☐ Send to Gasifier or ☐ Use as fuel Other1

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Process Characteristics

○ Continuous ● Batches

Time for One Batch (hours): 72

Number of Fermenters: 3 (to allow batches to be started each day)

Start Process Each Day at 0900 (if equipment and feedstock available)

Maximum Feedstock Input per Batch (kg): 250 Minimum: 250

Other Inputs Type: Water	Amount used: 1250	Units: litres
Type: Malt	Amount used: 25	Units: kg
Type: Yeast	Amount used: 0.2	Units: kg
Type:	Amount used: 0	Units:
Type:	Amount used: 0	Units:

Ethanol produced per batch (litres): 85

Wet animal feed (vinasse) produced per batch (kg): 0 ☐ Send to Anaerobic Digester

Dry animal feed (stillage) produced per batch (kg): 75 ☐ Use as fuel Other1 ☐ Send to Anaerobic Digester ☐ Send to Gasifier

Other Outputs Type: CO2 Amount made: 70 Units: kg

Type: Amount made: 0 Units:

Energy Requirements (not met by process wastes)

1) Crushing/Milling takes 30 mins
Electricity (kW): 8

2) Cooking takes 60 mins
Heat (kW): ● heat ○ electricity 20
Electricity for Mixing (kW): 12

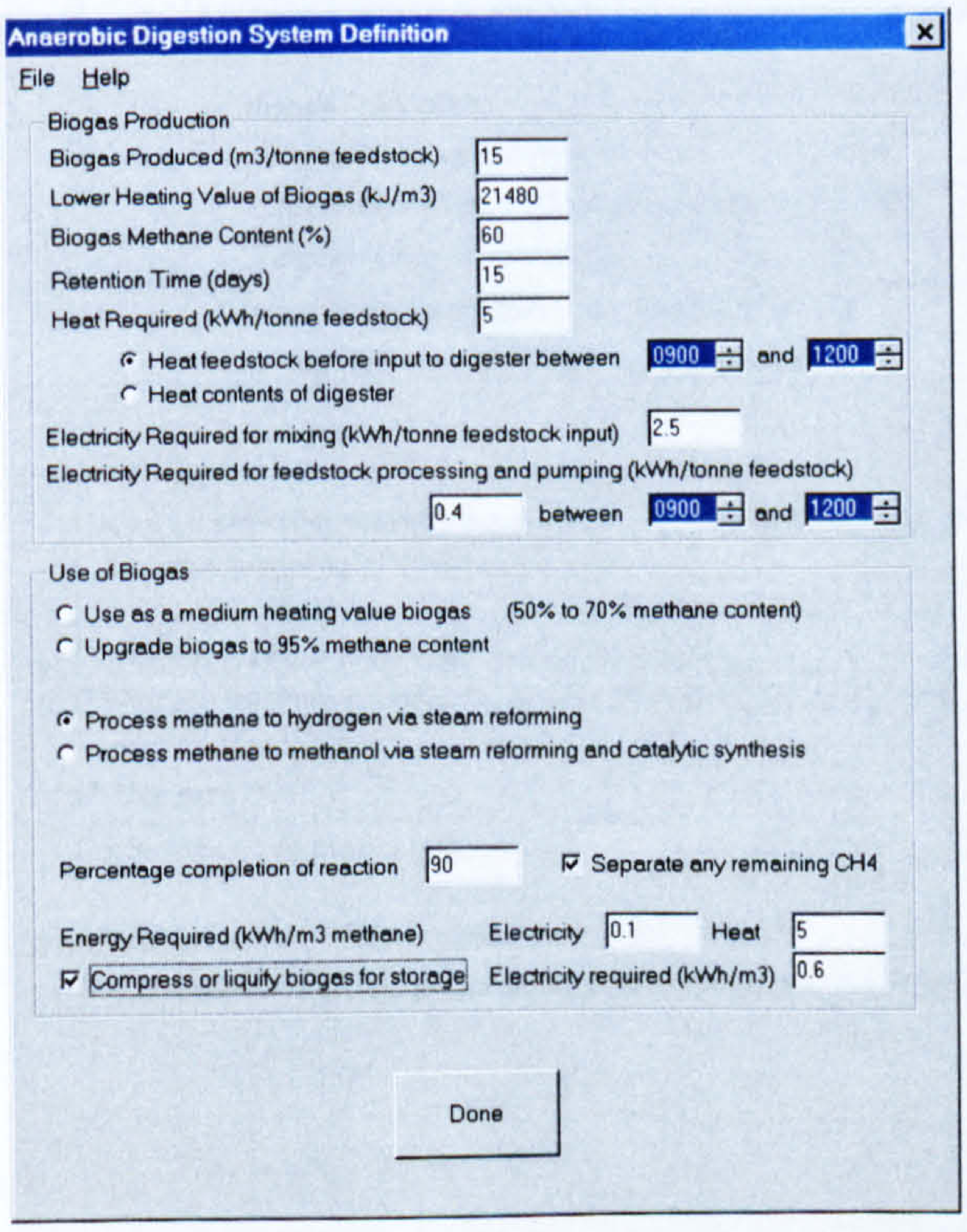
3) Hydrolysis takes 30 mins
Heat (kW): ● heat ○ electricity 20
Electricity for Mixing (kW): 12

4) Fermentation takes 70 hours
Cooling (kW): ○ heat ○ electricity 0

5) Distillation takes 360 mins
Heat (kW): ● heat ○ electricity 20

6) By-product Preperation takes 0 hours
Heat (kW): ○ heat ○ electricity 0
Electricity (kW): 0

Figure A1.17: Fermentation System Definition Window



Biogas Production

Biogas Produced (m3/tonne feedstock): 15

Lower Heating Value of Biogas (kJ/m3): 21480

Biogas Methane Content (%): 60

Retention Time (days): 15

Heat Required (kWh/tonne feedstock): 5

● Heat feedstock before input to digester between 0900 and 1200

○ Heat contents of digester

Electricity Required for mixing (kWh/tonne feedstock input): 2.5

Electricity Required for feedstock processing and pumping (kWh/tonne feedstock): 0.4 between 0900 and 1200

Use of Biogas

○ Use as a medium heating value biogas (50% to 70% methane content)

○ Upgrade biogas to 95% methane content

● Process methane to hydrogen via steam reforming

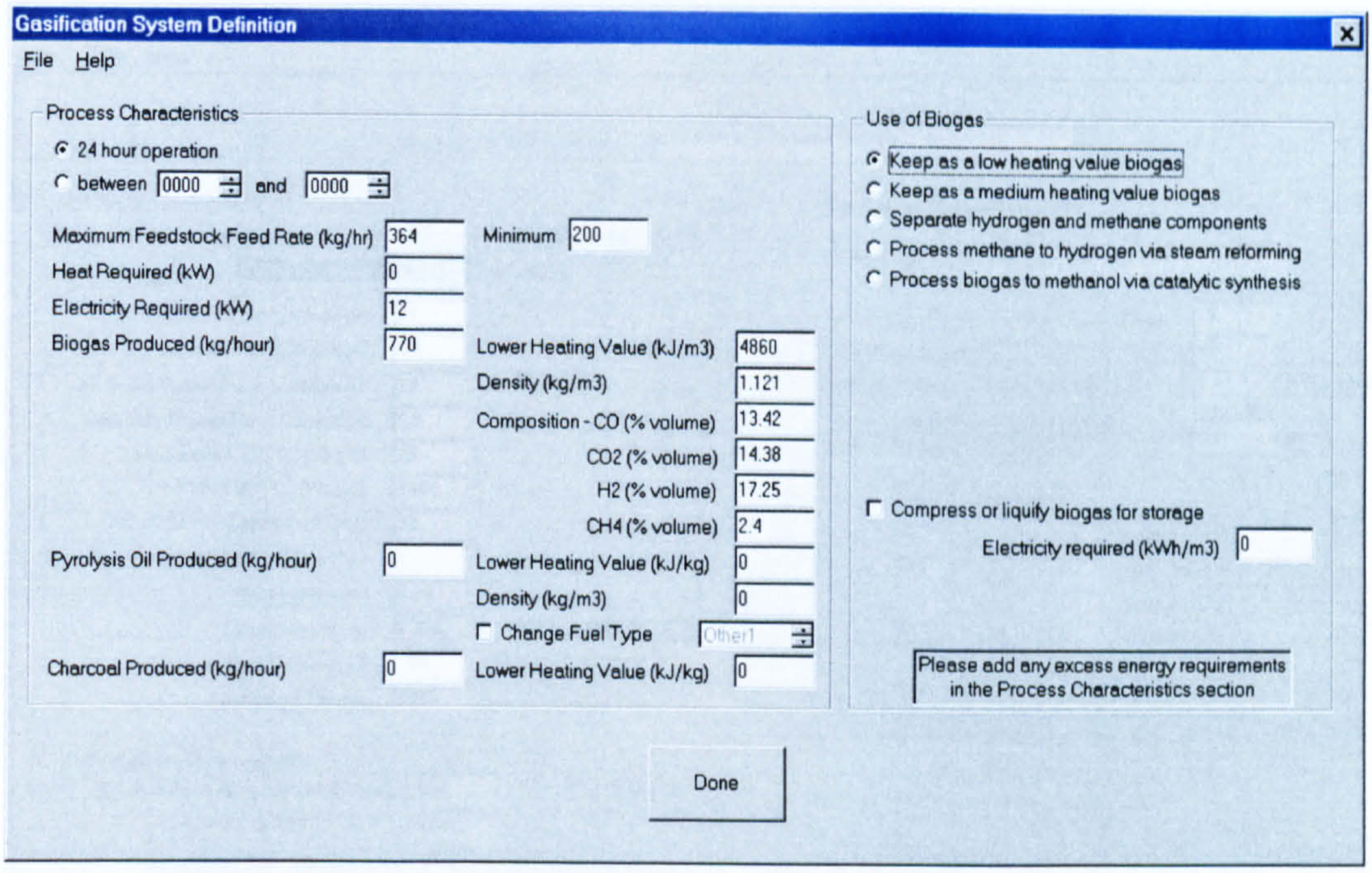
○ Process methane to methanol via steam reforming and catalytic synthesis

Percentage completion of reaction: 90 ☑ Separate any remaining CH4

Energy Required (kWh/m3 methane): Electricity 0.1 Heat 5

☑ Compress or liquify biogas for storage Electricity required (kWh/m3): 0.6

Figure A1.18: Anaerobic Digester Definition from Fermentation / Transesterification Window



Gasification System Definition

File Help

Process Characteristics

● 24 hour operation

○ between 0000 and 0000

Maximum Feedstock Feed Rate (kg/hr) 364

Minimum 200

Heat Required (kW) 0

Electricity Required (kW) 12

Biogas Produced (kg/hour) 770

Lower Heating Value (kJ/m3) 4860

Density (kg/m3) 1.121

Composition - CO (% volume) 13.42

CO2 (% volume) 14.38

H2 (% volume) 17.25

CH4 (% volume) 2.4

Pyrolysis Oil Produced (kg/hour) 0

Lower Heating Value (kJ/kg) 0

Density (kg/m3) 0

☐ Change Fuel Type Other1

Charcoal Produced (kg/hour) 0

Lower Heating Value (kJ/kg) 0

Use of Biogas

● Keep as a low heating value biogas

○ Keep as a medium heating value biogas

○ Separate hydrogen and methane components

○ Process methane to hydrogen via steam reforming

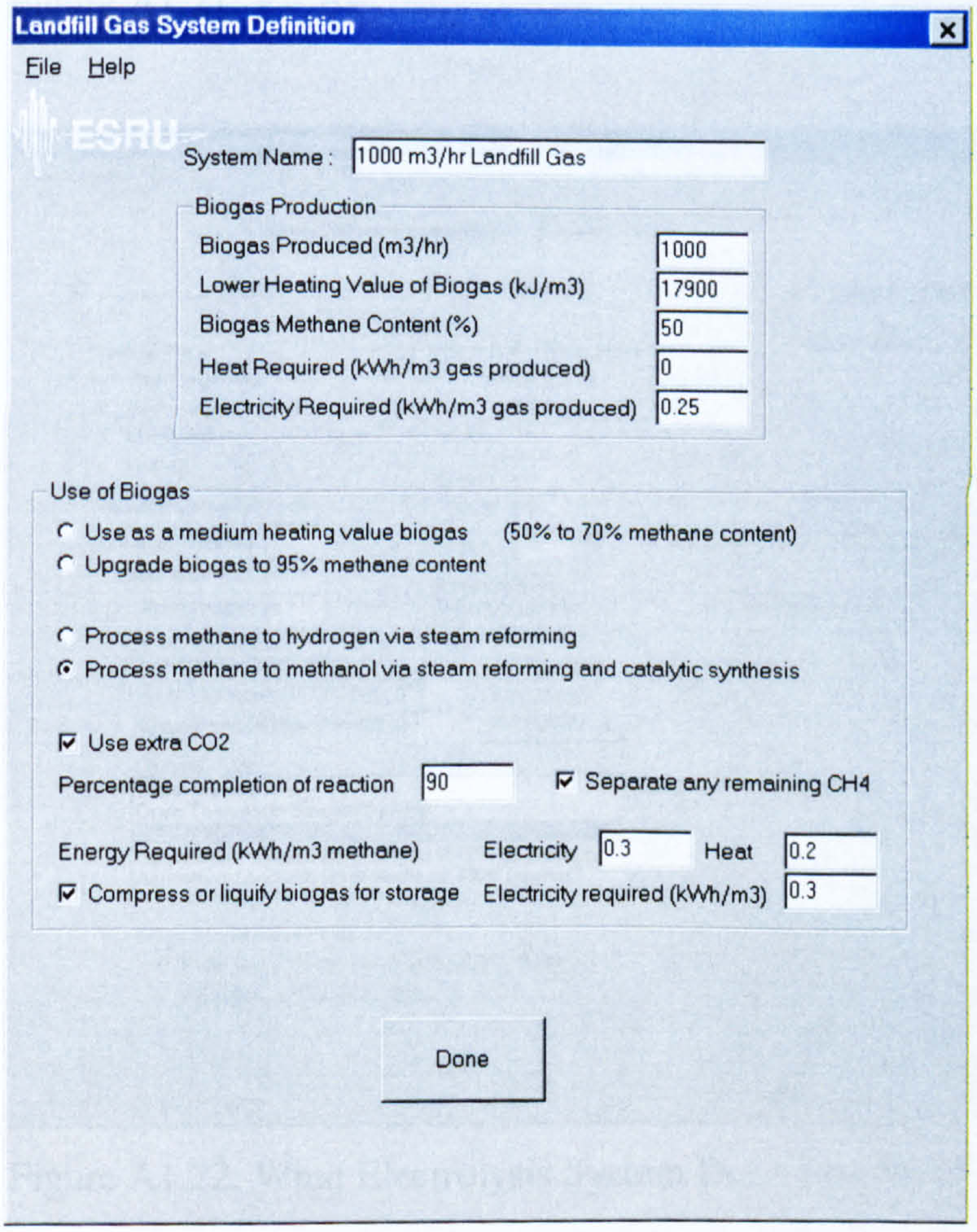
○ Process biogas to methanol via catalytic synthesis

☐ Compress or liquify biogas for storage

Electricity required (kWh/m3) 0

Please add any excess energy requirements in the Process Characteristics section

Figure A1.19: Gasification Definition from Fermentation/Transesterification



Landfill Gas System Definition

File Help

System Name : 1000 m3/hr Landfill Gas

Biogas Production

Biogas Produced (m3/hr) 1000

Lower Heating Value of Biogas (kJ/m3) 17900

Biogas Methane Content (%) 50

Heat Required (kWh/m3 gas produced) 0

Electricity Required (kWh/m3 gas produced) 0.25

Use of Biogas

○ Use as a medium heating value biogas (50% to 70% methane content)

○ Upgrade biogas to 95% methane content

○ Process methane to hydrogen via steam reforming

● Process methane to methanol via steam reforming and catalytic synthesis

☑ Use extra CO2

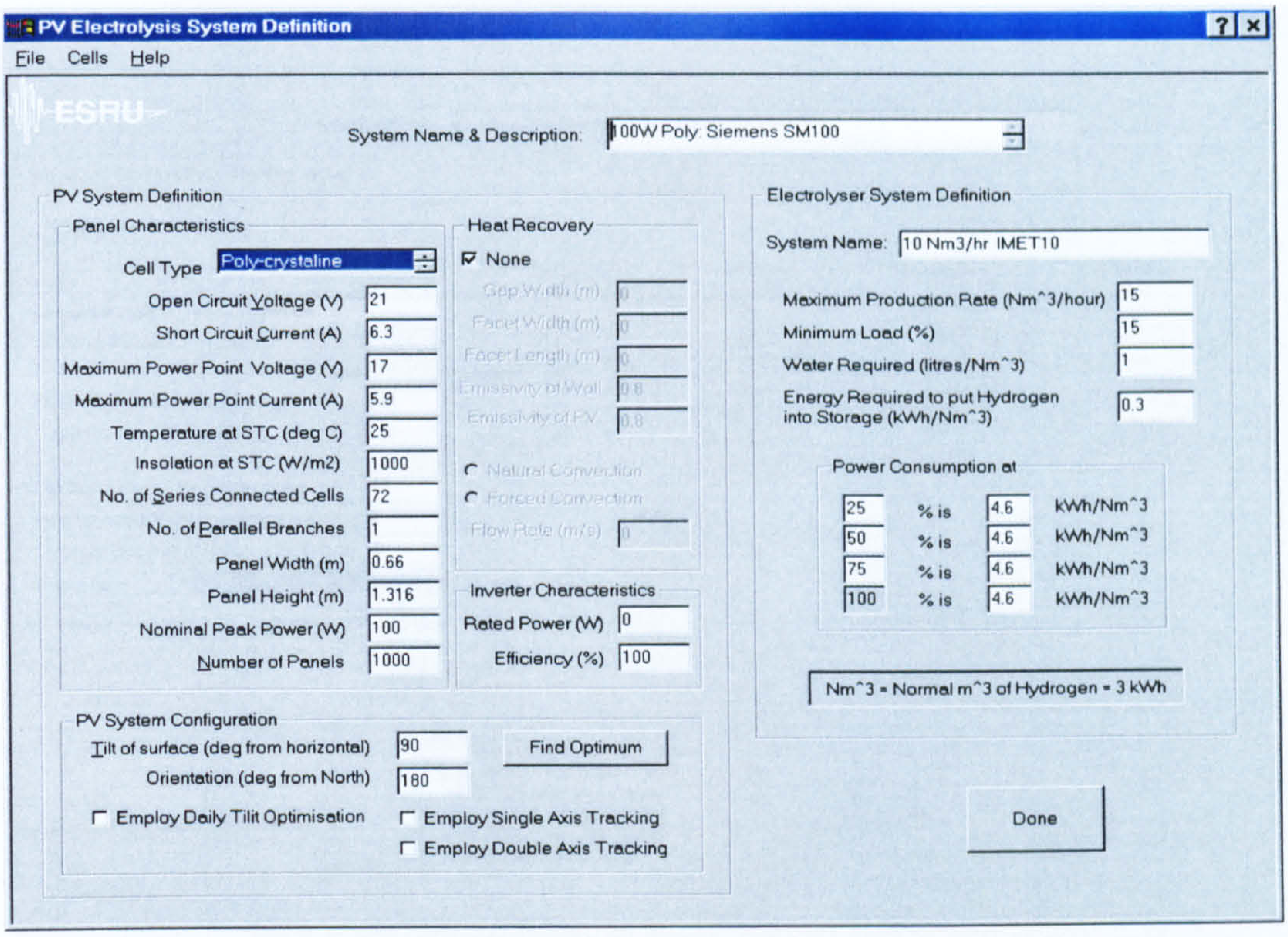
Percentage completion of reaction 90

☑ Separate any remaining CH4

Energy Required (kWh/m3 methane) Electricity 0.3 Heat 0.2

☑ Compress or liquify biogas for storage Electricity required (kWh/m3) 0.3

Figure A1.20: Landfill Gas Processing System Definition Window


PV Electrolysis System Definition

System Name & Description: 100W Poly Siemens SM100

PV System Definition

Panel Characteristics

Cell Type: Poly-crystaline

Open Circuit Voltage (V): 21

Short Circuit Current (A): 6.3

Maximum Power Point Voltage (V): 17

Maximum Power Point Current (A): 5.9

Temperature at STC (deg C): 25

Insolation at STC (W/m2): 1000

No. of Series Connected Cells: 72

No. of Parallel Branches: 1

Panel Width (m): 0.66

Panel Height (m): 1.316

Nominal Peak Power (W): 100

Number of Panels: 1000

Heat Recovery

☑ None

Gap Width (m): 0

Facet Width (m): 0

Facet Length (m): 0

Emissivity of Wall: 0.8

Emissivity of PV: 0.8

○ Natural Convection

○ Forced Convection

Flow Rate (m/s): 0

Inverter Characteristics

Rated Power (W): 0

Efficiency (%): 100

PV System Configuration

Tilt of surface (deg from horizontal): 90

Orientation (deg from North): 180

☐ Employ Daily Tilt Optimisation

☐ Employ Single Axis Tracking

☐ Employ Double Axis Tracking

Electrolyser System Definition

System Name: 10 Nm3/hr IMET10

Maximum Production Rate (Nm^3/hour): 15

Minimum Load (%): 15

Water Required (litres/Nm^3): 1

Energy Required to put Hydrogen into Storage (kWh/Nm^3): 0.3

Power Consumption at

25 % is 4.6 kWh/Nm^3

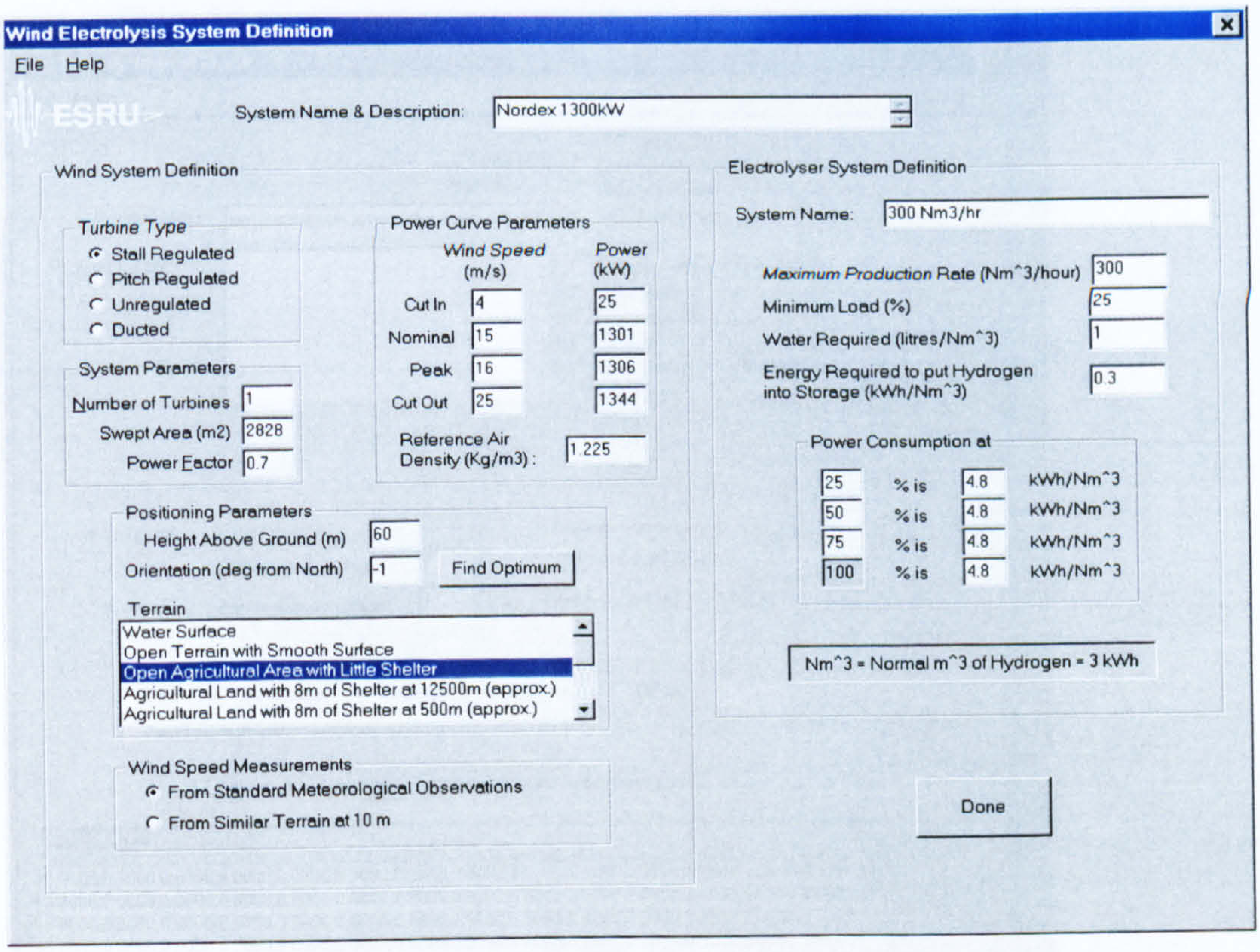
50 % is 4.6 kWh/Nm^3

75 % is 4.6 kWh/Nm^3

100 % is 4.6 kWh/Nm^3

Nm^3 = Normal m^3 of Hydrogen = 3 kWh

Figure A1.21: PV Electrolysis System Definition Window


Wind Electrolysis System Definition

System Name & Description: Nordex 1300kW

Wind System Definition

Turbine Type

● Stall Regulated

○ Pitch Regulated

○ Unregulated

○ Ducted

System Parameters

Number of Turbines: 1

Swept Area (m2): 2828

Power Factor: 0.7

Power Curve Parameters

	Wind Speed (m/s)	Power (kW)
Cut In	4	25
Nominal	15	1301
Peak	16	1306
Cut Out	25	1344

Reference Air Density (Kg/m3): 1.225

Positioning Parameters

Height Above Ground (m): 60

Orientation (deg from North): -1

Terrain

Water Surface

Open Terrain with Smooth Surface

Open Agricultural Area with Little Shelter

Agricultural Land with 8m of Shelter at 12500m (approx.)

Agricultural Land with 8m of Shelter at 500m (approx.)

Wind Speed Measurements

● From Standard Meteorological Observations

○ From Similar Terrain at 10 m

Electrolyser System Definition

System Name: 300 Nm3/hr

Maximum Production Rate (Nm^3/hour): 300

Minimum Load (%): 25

Water Required (litres/Nm^3): 1

Energy Required to put Hydrogen into Storage (kWh/Nm^3): 0.3

Power Consumption at

25 % is 4.8 kWh/Nm^3

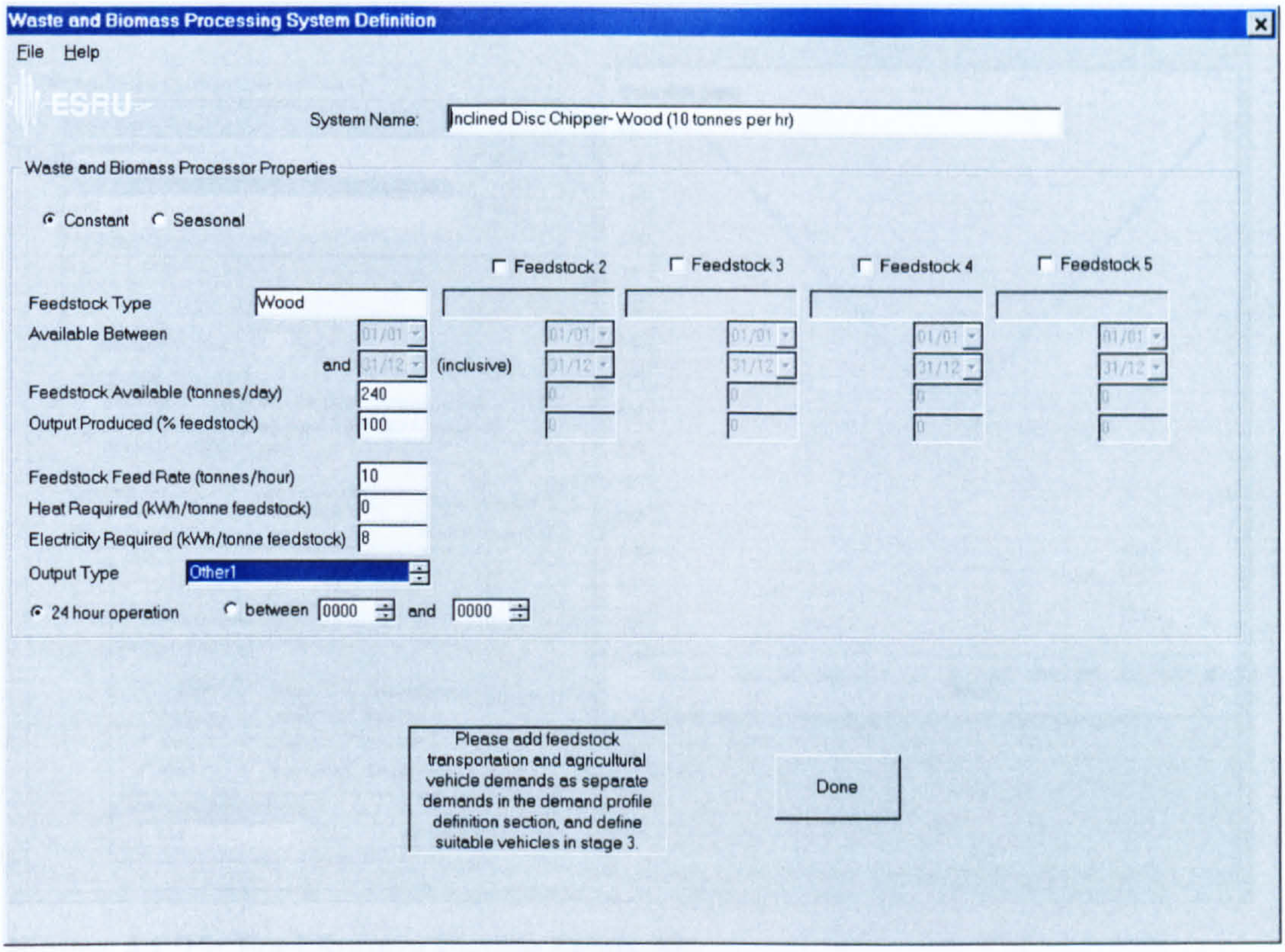
50 % is 4.8 kWh/Nm^3

75 % is 4.8 kWh/Nm^3

100 % is 4.8 kWh/Nm^3

Nm^3 = Normal m^3 of Hydrogen = 3 kWh

Figure A1.22: Wind Electrolysis System Definition Window



System Name: Inclined Disc Chipper- Wood (10 tonnes per hr)

Waste and Biomass Processor Properties

● Constant ○ Seasonal

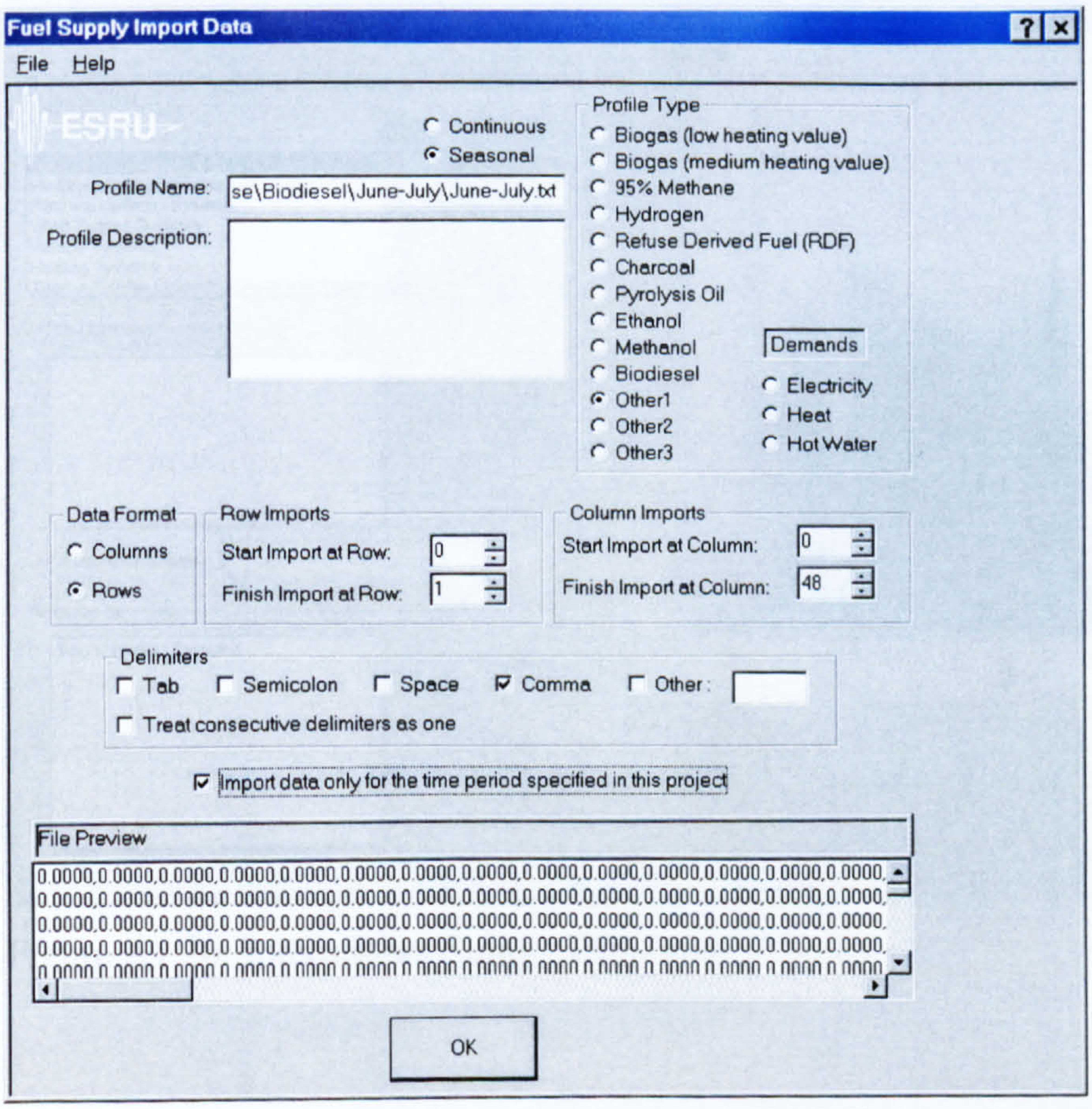
☐ Feedstock 2 ☐ Feedstock 3 ☐ Feedstock 4 ☐ Feedstock 5

Feedstock Type	Wood				
Available Between	01/01	01/01	01/01	01/01	01/01
and (inclusive)	31/12	31/12	31/12	31/12	31/12
Feedstock Available (tonnes/day)	240	0	0	0	0
Output Produced (% feedstock)	100	0	0	0	0

Feedstock Feed Rate (tonnes/hour) 10
Heat Required (kWh/tonne feedstock) 0
Electricity Required (kWh/tonne feedstock) 8
Output Type Other1
● 24 hour operation ○ between 0000 and 0000

Please add feedstock transportation and agricultural vehicle demands as separate demands in the demand profile definition section, and define suitable vehicles in stage 3.

Figure A1.23: Waste and Biomass Processing System Definition Window



○ Continuous
● Seasonal

Profile Name: se\Biodiesel\June-July\June-July.txt

Profile Description:

Profile Type
○ Biogas (low heating value)
○ Biogas (medium heating value)
○ 95% Methane
○ Hydrogen
○ Refuse Derived Fuel (RDF)
○ Charcoal
○ Pyrolysis Oil
○ Ethanol
○ Methanol
○ Biodiesel
● Other1
○ Other2
○ Other3

Demands
○ Electricity
○ Heat
○ Hot Water

Data Format
○ Columns
● Rows

Row Imports
Start Import at Row: 0
Finish Import at Row: 1

Column Imports
Start Import at Column: 0
Finish Import at Column: 48

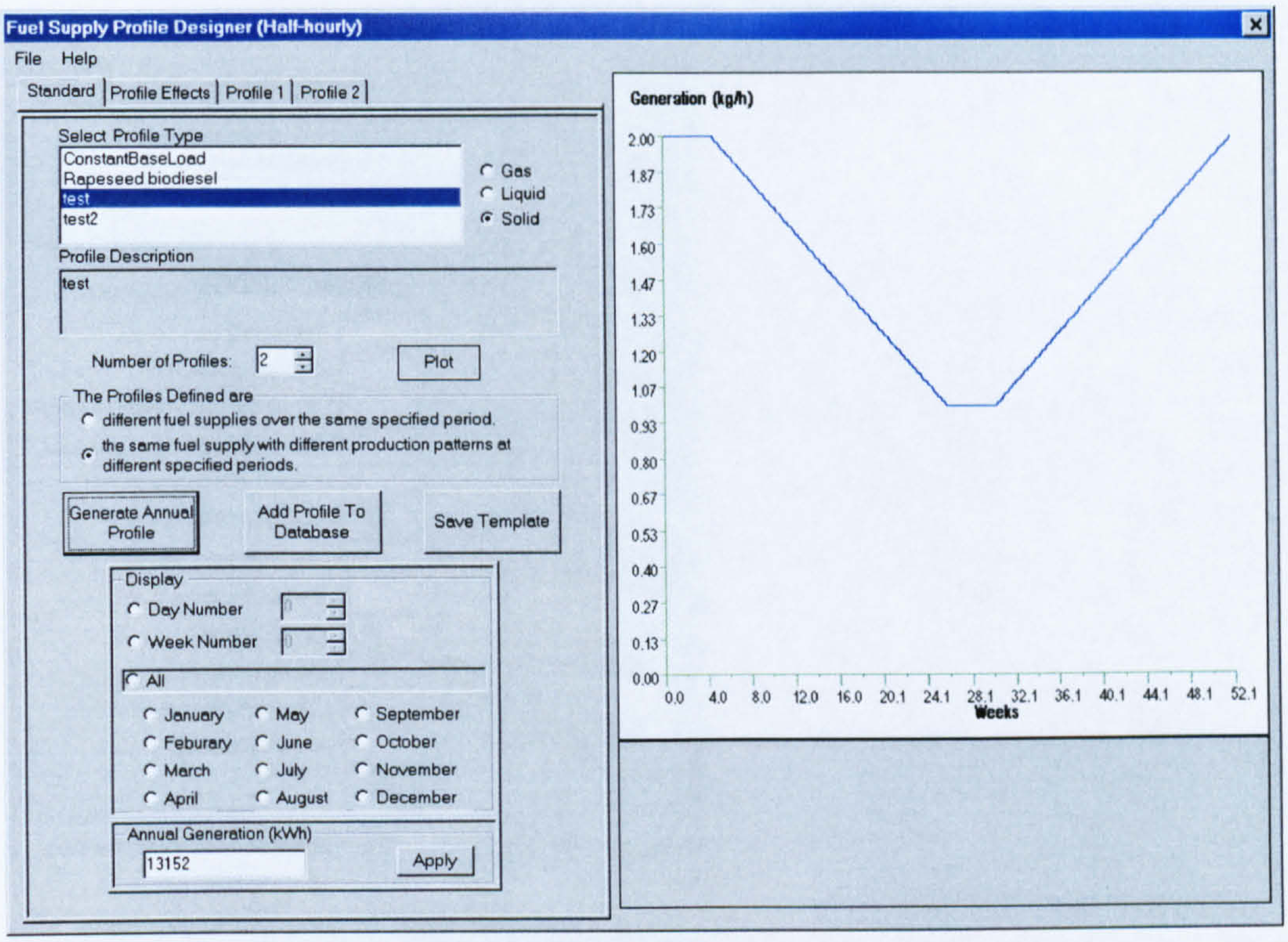
Delimiters
☐ Tab ☐ Semicolon ☐ Space ☑ Comma ☐ Other:
☐ Treat consecutive delimiters as one

☑ Import data only for the time period specified in this project

File Preview

```
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
```

Figure A1.24: Fuel Supply Data Import Window



Select Profile Type: test

● Solid

Profile Description: test

Number of Profiles: 2

The Profiles Defined are

○ different fuel supplies over the same specified period.

● the same fuel supply with different production patterns at different specified periods.

Annual Generation (kWh): 13152

Figure A1.25: Fuel Supply Profile Designer

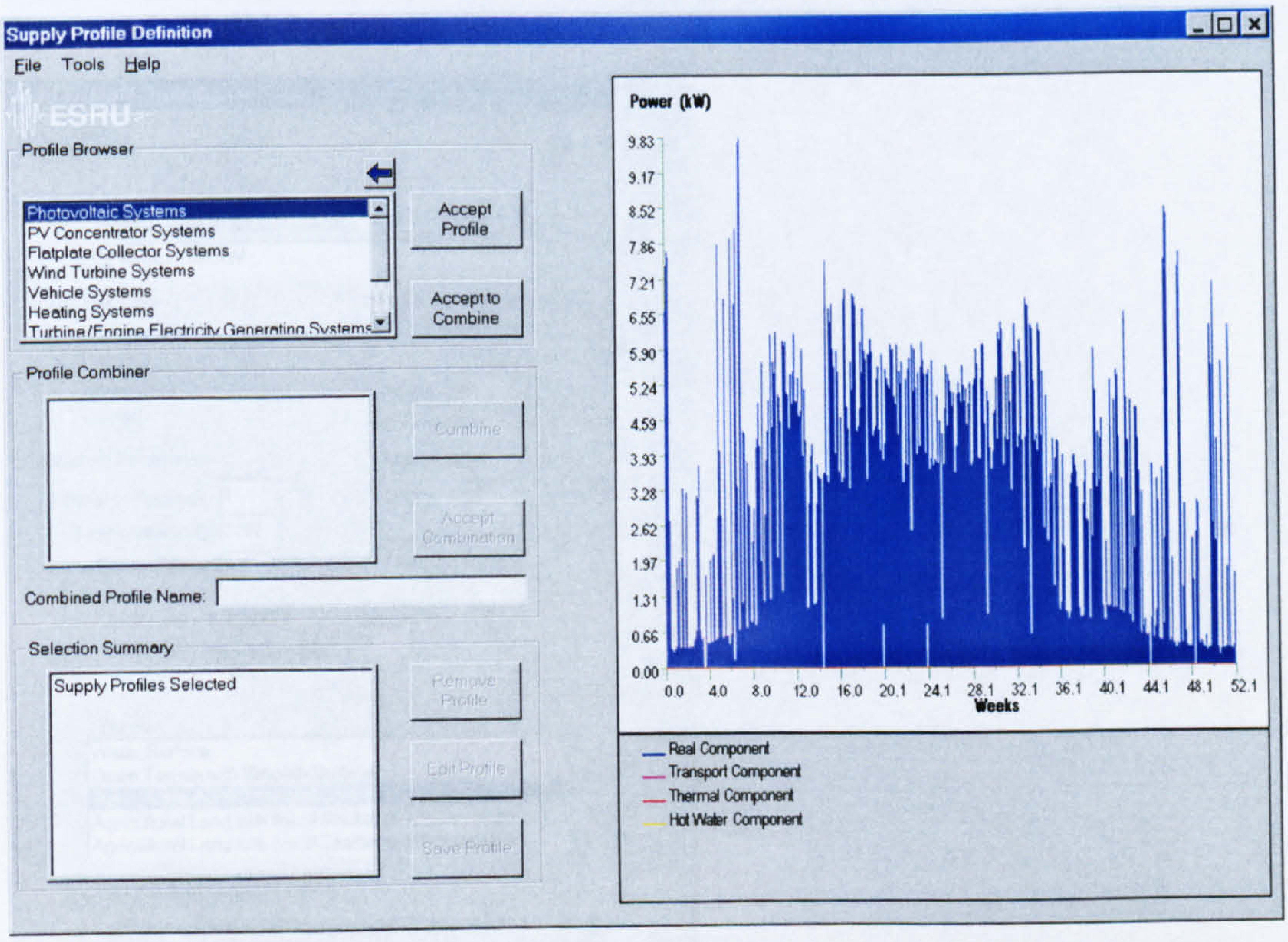
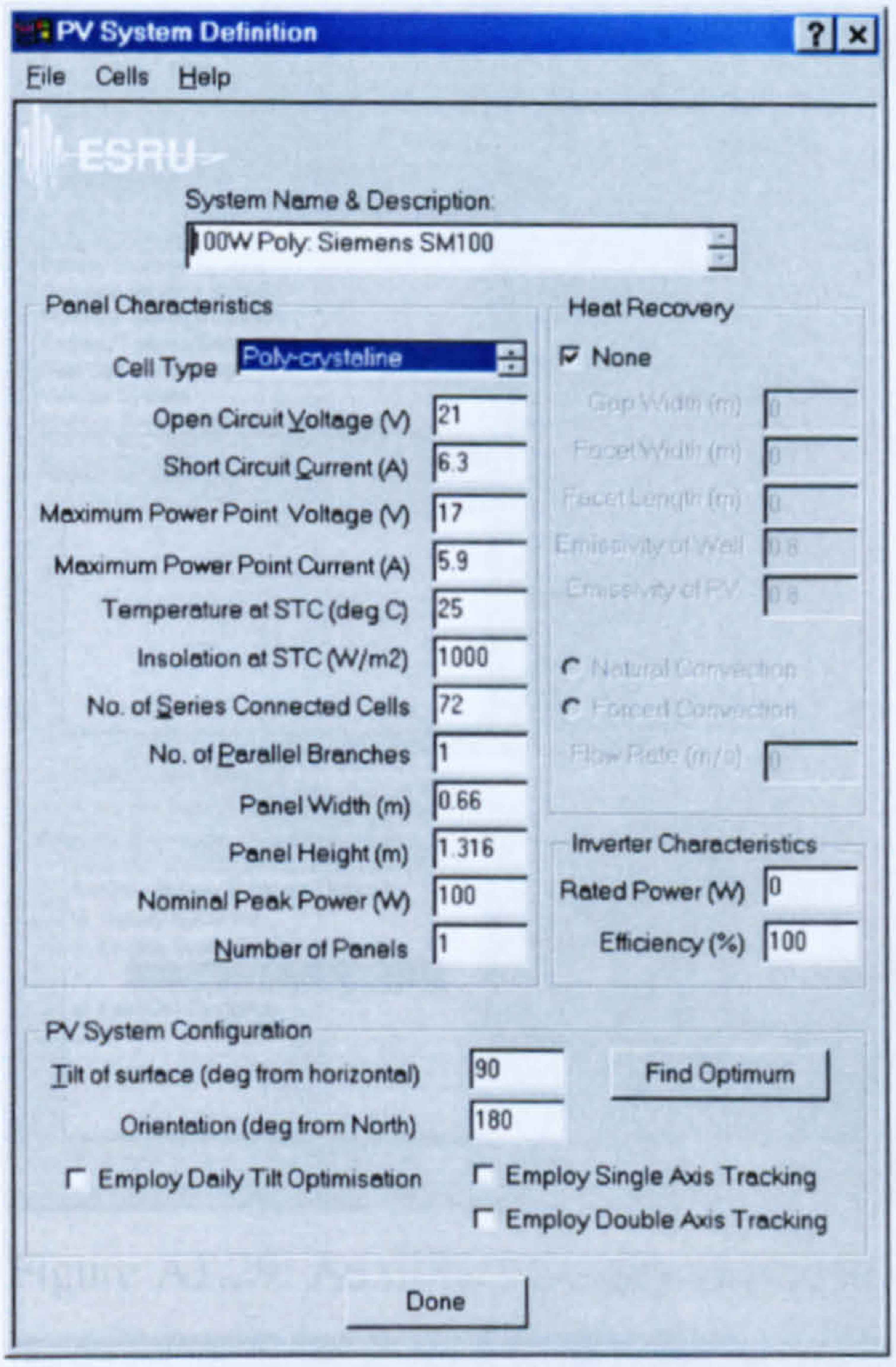


Figure A1.26: Intermittent Supply Definition Window


PV System Definition

System Name & Description: 100W Poly: Siemens SM100

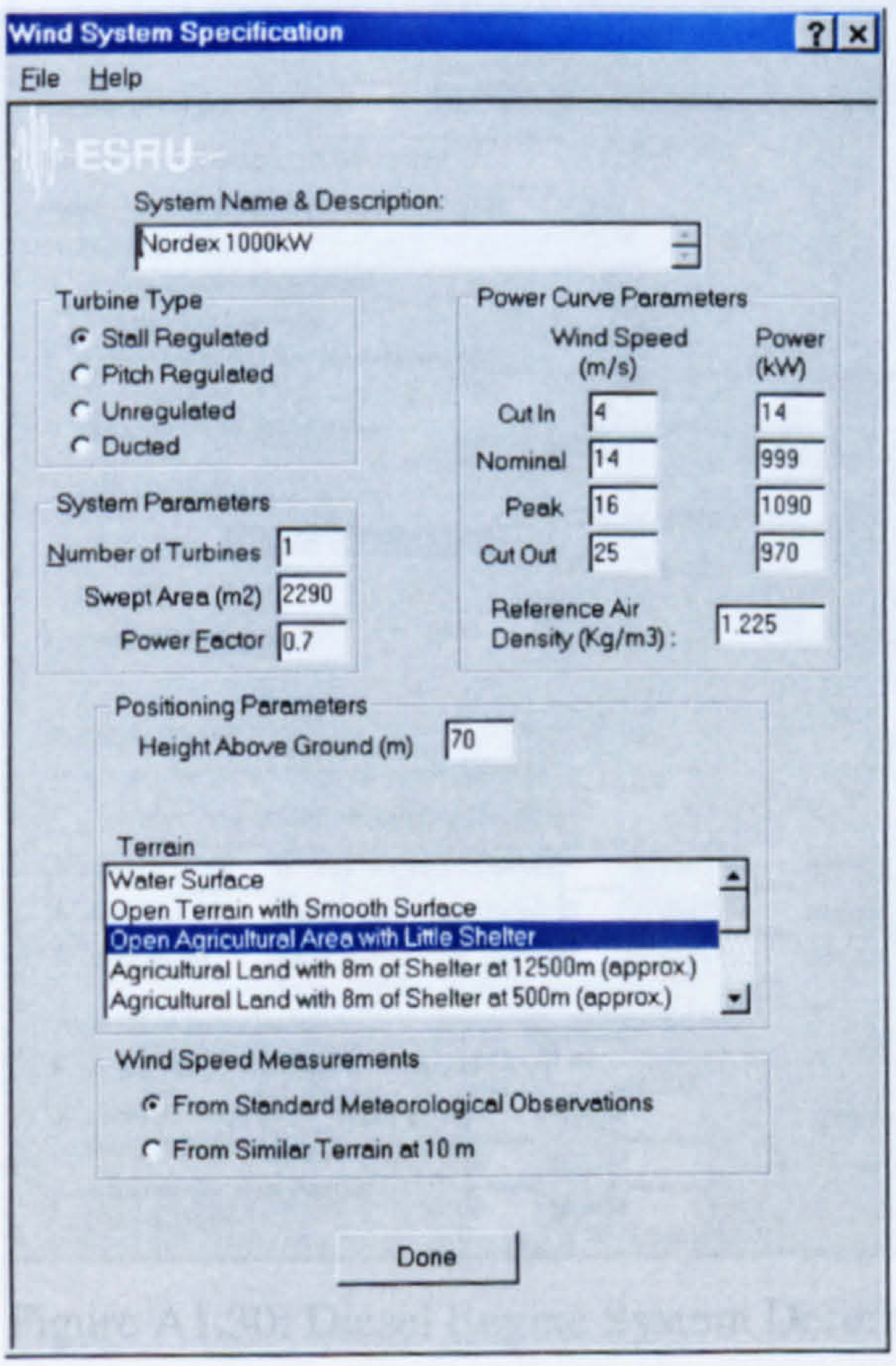
Panel Characteristics
Cell Type: Poly-crystaline
Open Circuit Voltage (V): 21
Short Circuit Current (A): 6.3
Maximum Power Point Voltage (V): 17
Maximum Power Point Current (A): 5.9
Temperature at STC (deg C): 25
Insolation at STC (W/m2): 1000
No. of Series Connected Cells: 72
No. of Parallel Branches: 1
Panel Width (m): 0.66
Panel Height (m): 1.316
Nominal Peak Power (W): 100
Number of Panels: 1

Heat Recovery
☑ None
Gap Width (m): 0
Facet Width (m): 0
Facet Length (m): 0
Emissivity of Wall: 0.8
Emissivity of PV: 0.8
○ Natural Convection
○ Forced Convection
Flow Rate (m/s): 0

Inverter Characteristics
Rated Power (W): 0
Efficiency (%): 100

PV System Configuration
Tilt of surface (deg from horizontal): 90
Orientation (deg from North): 180
☐ Employ Daily Tilt Optimisation
☐ Employ Single Axis Tracking
☐ Employ Double Axis Tracking

Figure A1.27 PV System Definition Window


Wind System Specification

System Name & Description: Nordex 1000kW

Turbine Type
● Stall Regulated
○ Pitch Regulated
○ Unregulated
○ Ducted

System Parameters
Number of Turbines: 1
Swept Area (m2): 2290
Power Factor: 0.7

Power Curve Parameters

	Wind Speed (m/s)	Power (kW)
Cut In	4	14
Nominal	14	999
Peak	16	1090
Cut Out	25	970

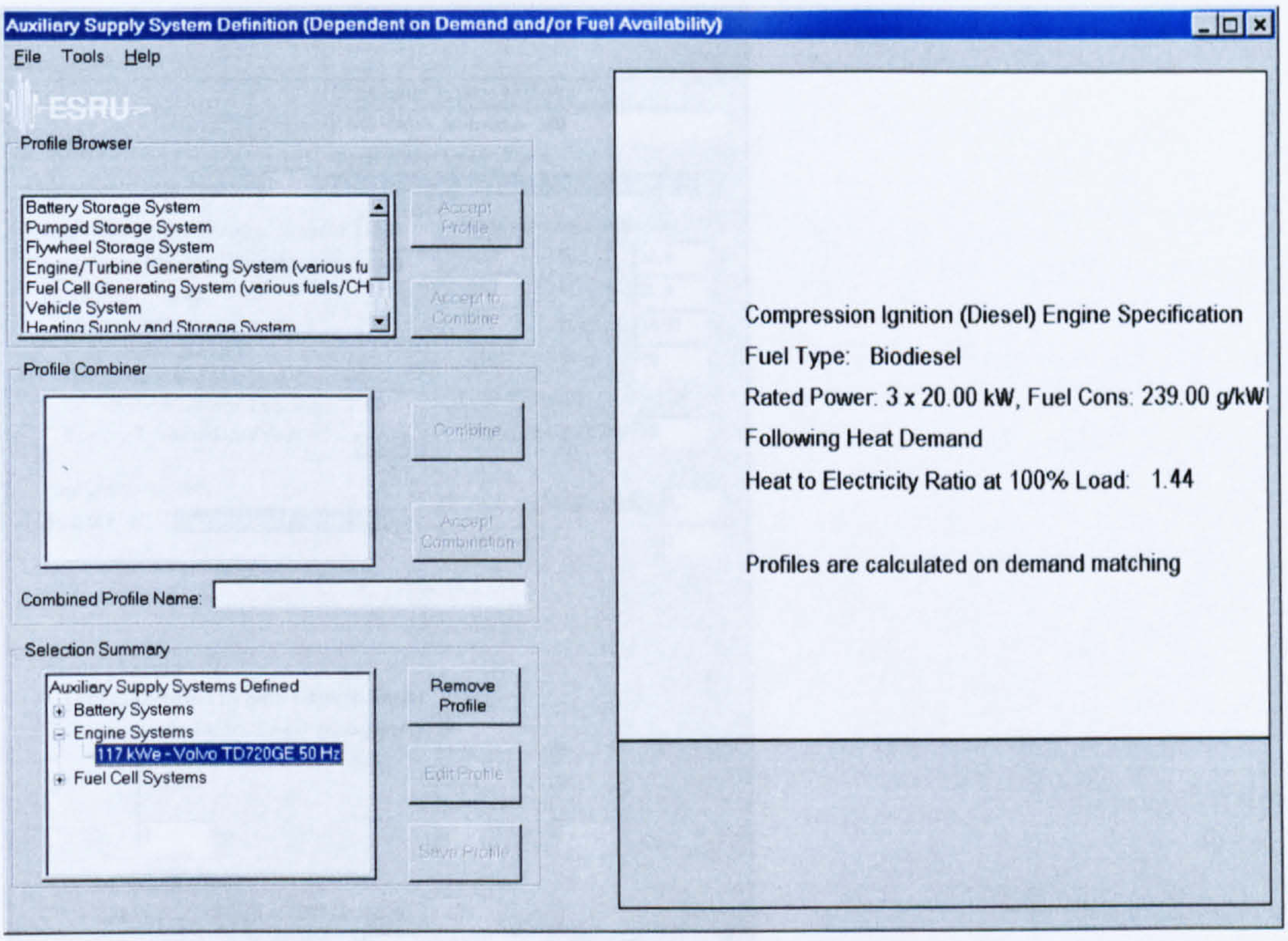
Reference Air Density (Kg/m3): 1.225

Positioning Parameters
Height Above Ground (m): 70

Terrain
Water Surface
Open Terrain with Smooth Surface
Open Agricultural Area with Little Shelter
Agricultural Land with 8m of Shelter at 12500m (approx.)
Agricultural Land with 8m of Shelter at 500m (approx.)

Wind Speed Measurements
● From Standard Meteorological Observations
○ From Similar Terrain at 10 m

Figure A1.28 Wind Turbine System Definition Window



Profile Browser

- Battery Storage System
- Pumped Storage System
- Flywheel Storage System
- Engine/Turbine Generating System (various fu
- Fuel Cell Generating System (various fuels/CH
- Vehicle System
- Heating Supply and Storage System

Profile Combiner

Combined Profile Name:

Selection Summary

- Auxiliary Supply Systems Defined
  - Battery Systems
  - Engine Systems
    - 117 kWe - Volvo TD720GE 50 Hz
  - Fuel Cell Systems

Compression Ignition (Diesel) Engine Specification

Fuel Type: Biodiesel

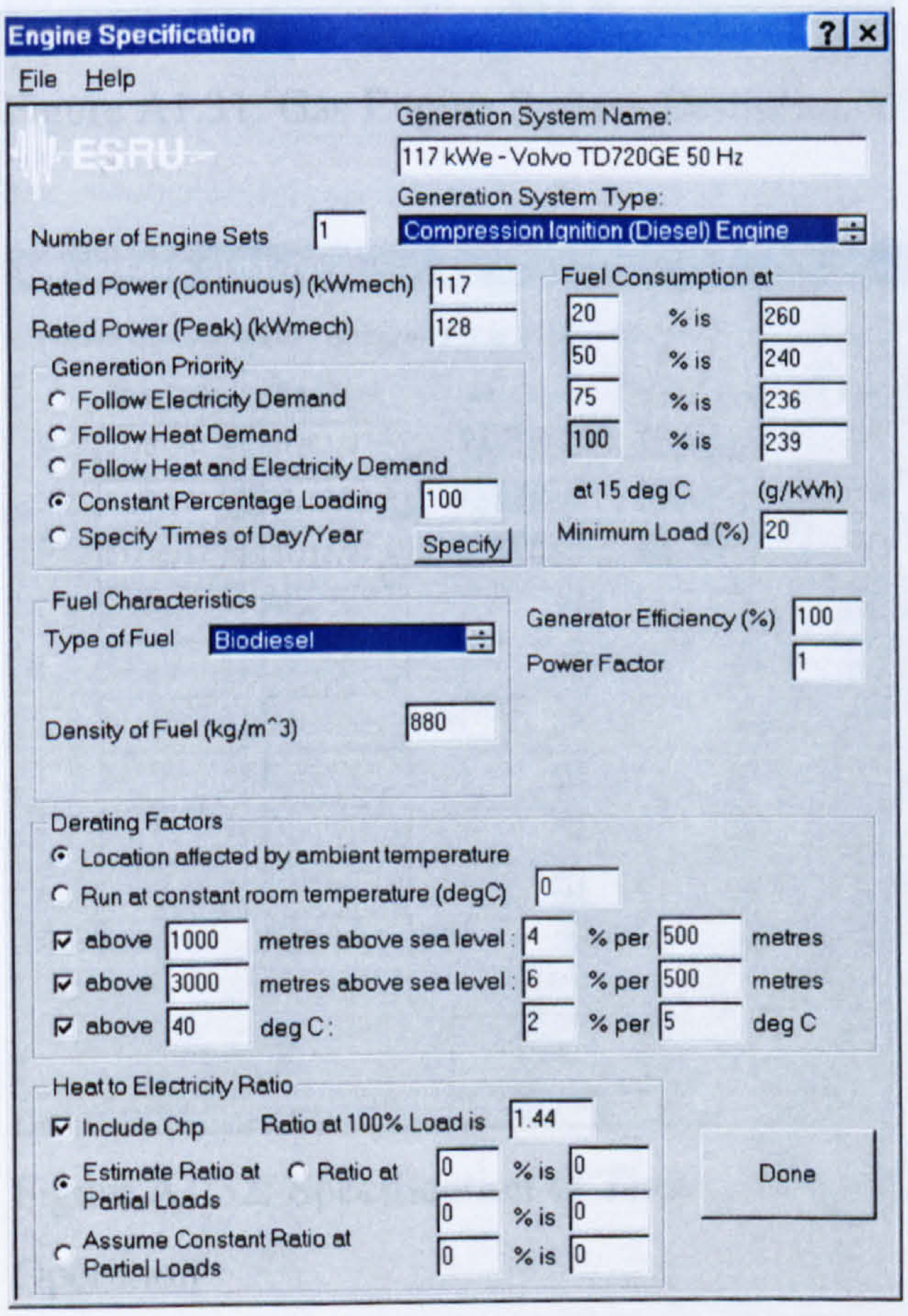
Rated Power: 3 x 20.00 kW, Fuel Cons: 239.00 g/kW

Following Heat Demand

Heat to Electricity Ratio at 100% Load: 1.44

Profiles are calculated on demand matching

Figure A1.29: Auxilliary Supply Definition Window



Generation System Name: 117 kWe - Volvo TD720GE 50 Hz

Generation System Type: Compression Ignition (Diesel) Engine

Number of Engine Sets: 1

Rated Power (Continuous) (kWmech): 117

Rated Power (Peak) (kWmech): 128

Generation Priority
- ○ Follow Electricity Demand
- ○ Follow Heat Demand
- ○ Follow Heat and Electricity Demand
- ● Constant Percentage Loading: 100
- ○ Specify Times of Day/Year

Fuel Consumption at
- 20 % is 260
- 50 % is 240
- 75 % is 236
- 100 % is 239

at 15 deg C (g/kWh)

Minimum Load (%): 20

Fuel Characteristics
- Type of Fuel: Biodiesel
- Density of Fuel (kg/m^3): 880

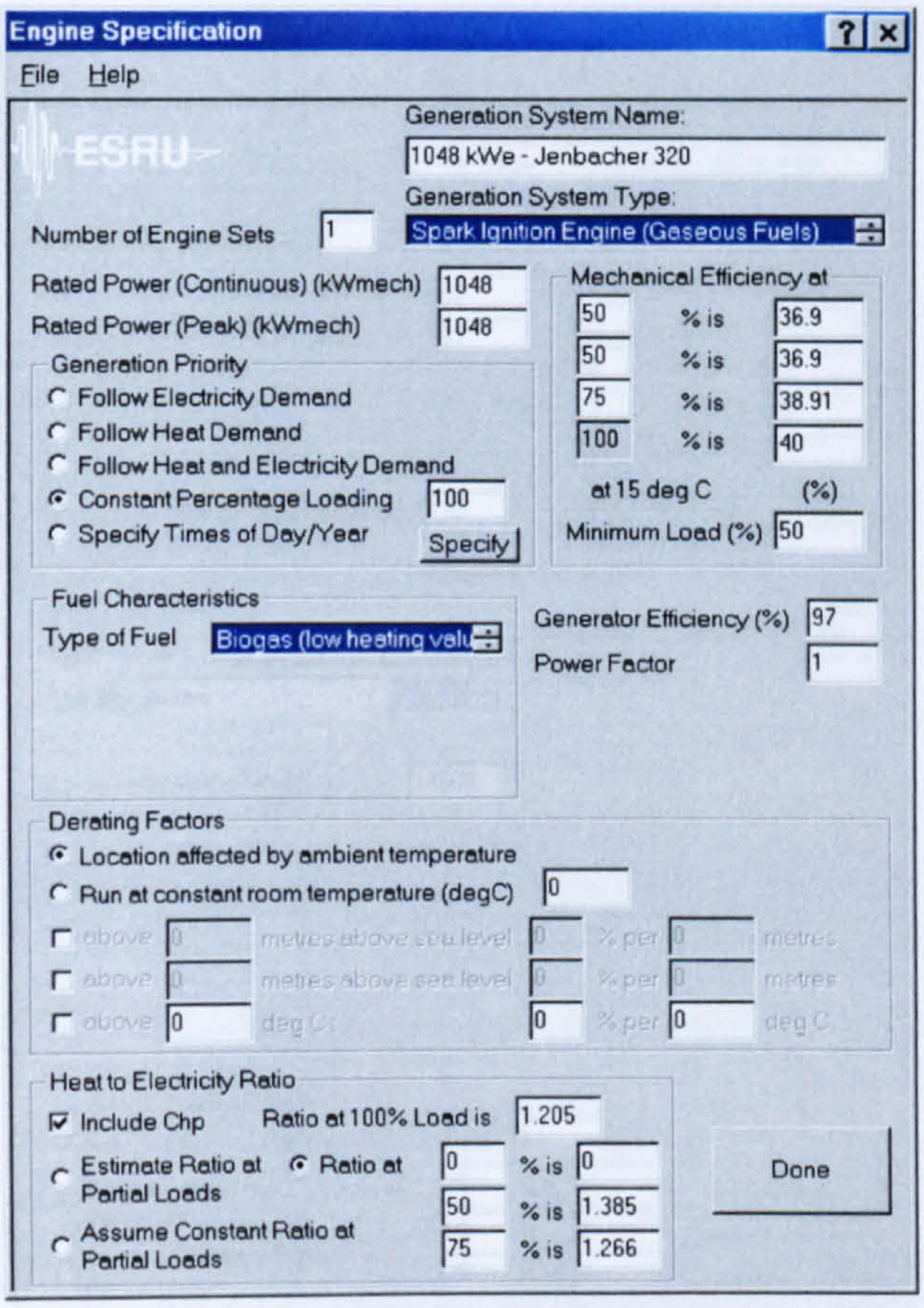
Generator Efficiency (%): 100

Power Factor: 1

Derating Factors
- ● Location affected by ambient temperature
- ○ Run at constant room temperature (degC): 0
- ☑ above 1000 metres above sea level : 4 % per 500 metres
- ☑ above 3000 metres above sea level : 6 % per 500 metres
- ☑ above 40 deg C : 2 % per 5 deg C

Heat to Electricity Ratio
- ☑ Include Chp
- Ratio at 100% Load is 1.44
- ● Estimate Ratio at Partial Loads
- ○ Assume Constant Ratio at Partial Loads
- ○ Ratio at
  - 0 % is 0
  - 0 % is 0
  - 0 % is 0

Figure A1.30: Diesel Engine System Definition Window



Generation System Name: 1048 kWe - Jenbacher 320

Generation System Type: Spark Ignition Engine (Gaseous Fuels)

Number of Engine Sets 1

Rated Power (Continuous) (kWmech) 1048

Rated Power (Peak) (kWmech) 1048

Generation Priority
- ○ Follow Electricity Demand
- ○ Follow Heat Demand
- ○ Follow Heat and Electricity Demand
- ● Constant Percentage Loading 100
- ○ Specify Times of Day/Year

Mechanical Efficiency at
- 50 % is 36.9
- 50 % is 36.9
- 75 % is 38.91
- 100 % is 40

at 15 deg C (%)

Minimum Load (%) 50

Fuel Characteristics

Type of Fuel Biogas (low heating valu

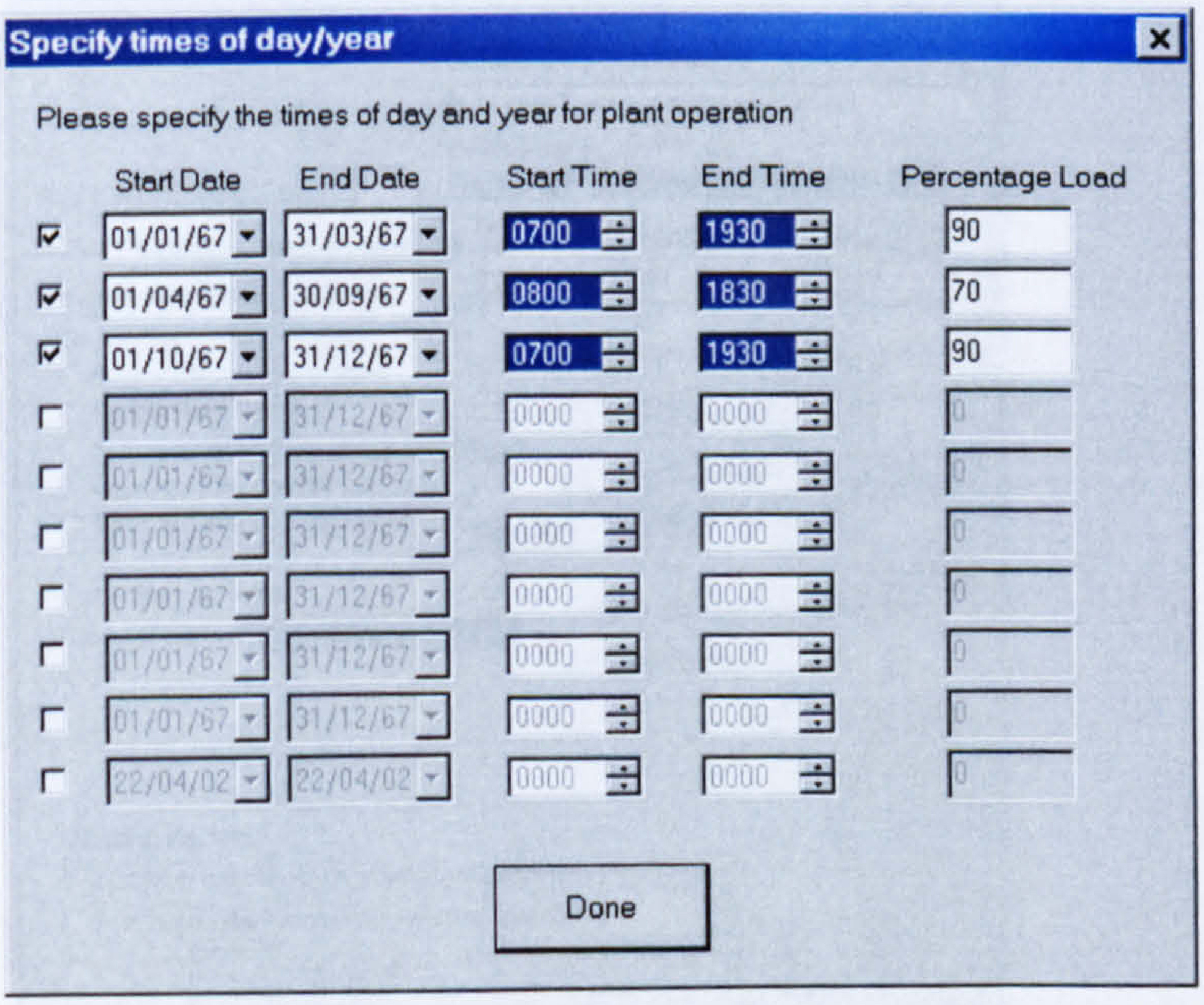
Generator Efficiency (%) 97

Power Factor 1

Derating Factors
- ● Location affected by ambient temperature
- ○ Run at constant room temperature (degC) 0
- ☐ above 0 metres above sea level 0 % per 0 metres
- ☐ above 0 metres above sea level 0 % per 0 metres
- ☐ above 0 deg C 0 % per 0 deg C

Heat to Electricity Ratio
- ☑ Include Chp Ratio at 100% Load is 1.205
- ○ Estimate Ratio at Partial Loads
- ● Ratio at 0 % is 0
- 50 % is 1.385
- 75 % is 1.266
- ○ Assume Constant Ratio at Partial Loads

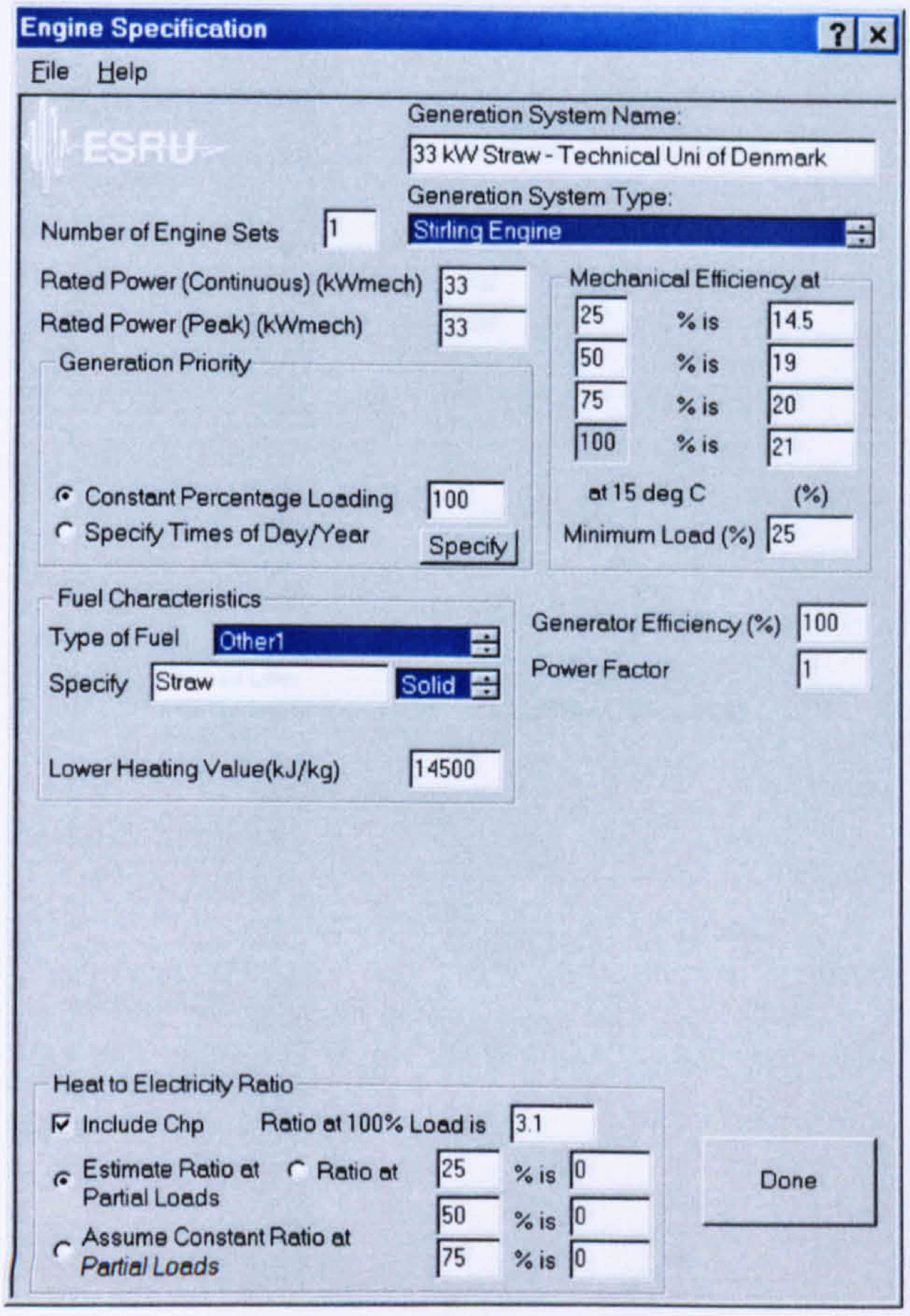
Figure A1.31: Gas Engine System Definition Window



Please specify the times of day and year for plant operation

	Start Date	End Date	Start Time	End Time	Percentage Load
☑	01/01/67	31/03/67	0700	1930	90
☑	01/04/67	30/09/67	0800	1830	70
☑	01/10/67	31/12/67	0700	1930	90
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	01/01/67	31/12/67	0000	0000	0
☐	22/04/02	22/04/02	0000	0000	0

Figure A1.32: Specification of Times of Day/Year for Engine/Turbine Operation



Engine Specification

File Help

Generation System Name: 33 kW Straw - Technical Uni of Denmark

Generation System Type: Stirling Engine

Number of Engine Sets: 1

Rated Power (Continuous) (kWmech): 33

Rated Power (Peak) (kWmech): 33

Mechanical Efficiency at

25 % is 14.5

50 % is 19

75 % is 20

100 % is 21

at 15 deg C (%)

Minimum Load (%): 25

Generation Priority

● Constant Percentage Loading: 100

○ Specify Times of Day/Year — Specify

Fuel Characteristics

Type of Fuel: Other1

Specify: Straw — Solid

Lower Heating Value(kJ/kg): 14500

Generator Efficiency (%): 100

Power Factor: 1

Heat to Electricity Ratio

☑ Include Chp — Ratio at 100% Load is 3.1

● Estimate Ratio at Partial Loads

○ Ratio at

25 % is 0

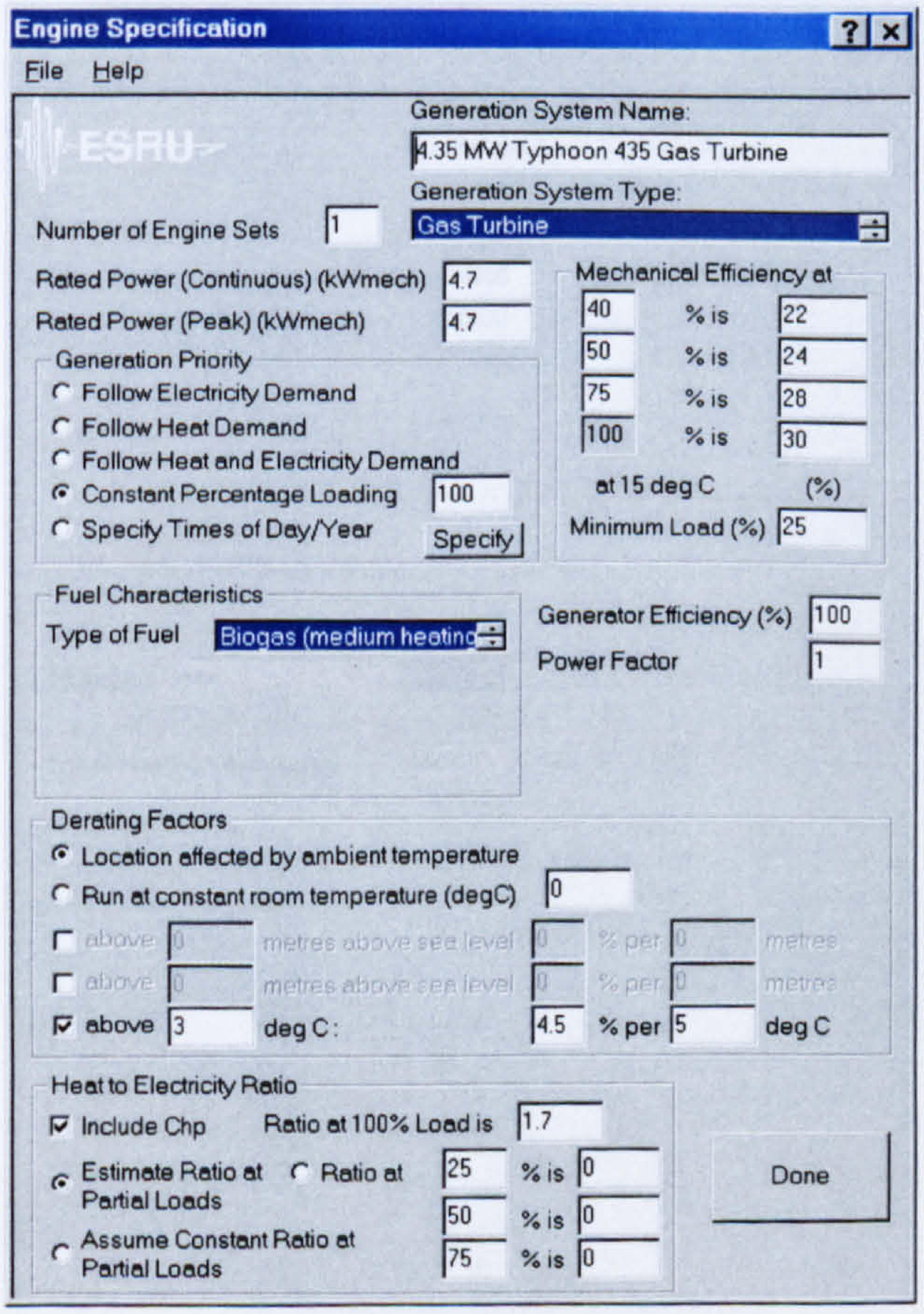
50 % is 0

75 % is 0

○ Assume Constant Ratio at Partial Loads

Done

Figure A1.33: Stirling Engine System Definition Window



Engine Specification

File Help

Generation System Name: 4.35 MW Typhoon 435 Gas Turbine

Generation System Type: Gas Turbine

Number of Engine Sets: 1

Rated Power (Continuous) (kWmech): 4.7

Rated Power (Peak) (kWmech): 4.7

Mechanical Efficiency at

40 % is 22

50 % is 24

75 % is 28

100 % is 30

at 15 deg C (%)

Minimum Load (%): 25

Generation Priority

○ Follow Electricity Demand

○ Follow Heat Demand

○ Follow Heat and Electricity Demand

● Constant Percentage Loading: 100

○ Specify Times of Day/Year — Specify

Fuel Characteristics

Type of Fuel: Biogas (medium heating

Generator Efficiency (%): 100

Power Factor: 1

Derating Factors

● Location affected by ambient temperature

○ Run at constant room temperature (degC): 0

☐ above 0 metres above sea level 0 % per 0 metres

☐ above 0 metres above sea level 0 % per 0 metres

☑ above 3 deg C: 4.5 % per 5 deg C

Heat to Electricity Ratio

☑ Include Chp — Ratio at 100% Load is 1.7

● Estimate Ratio at Partial Loads

○ Ratio at

25 % is 0

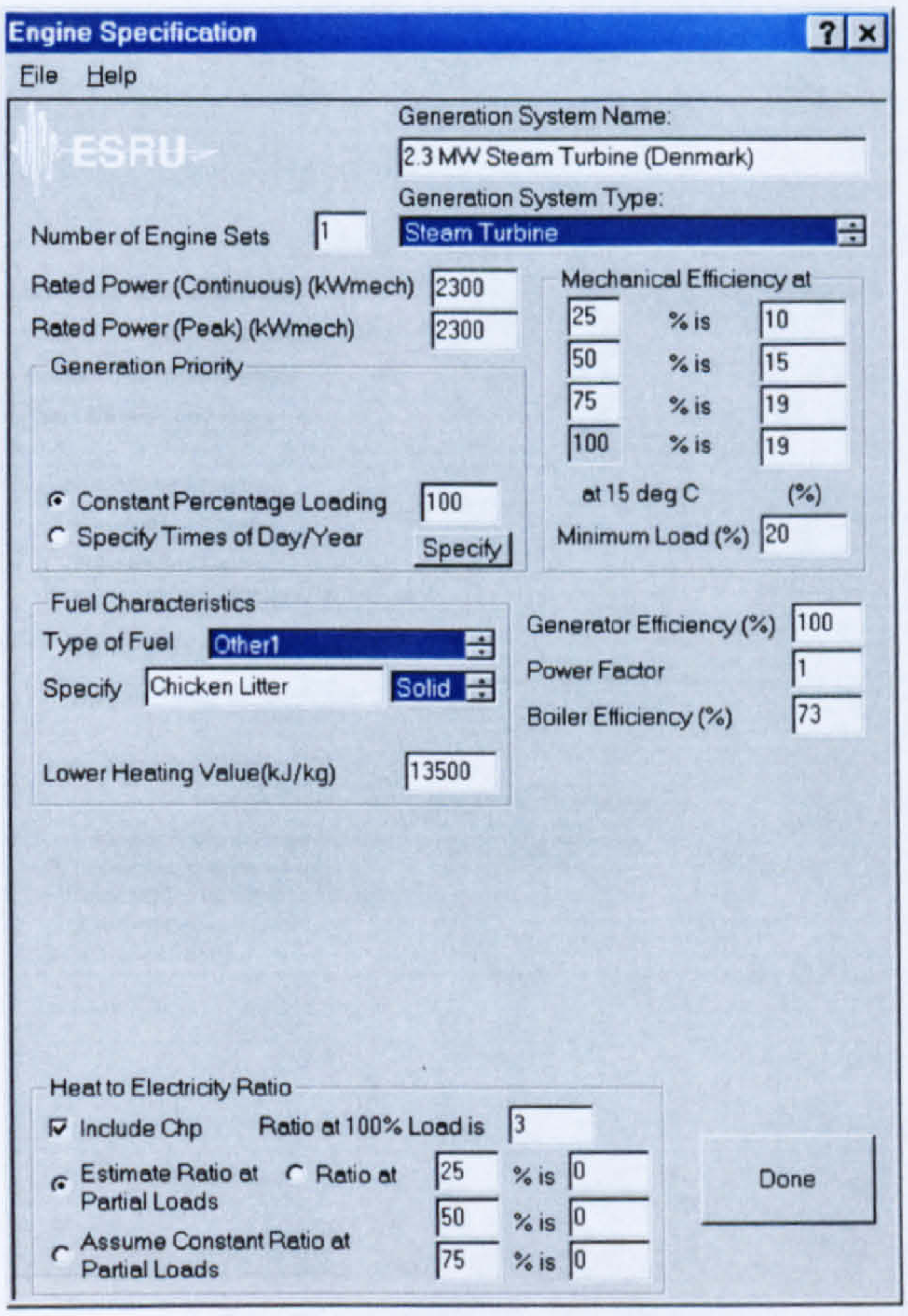
50 % is 0

75 % is 0

○ Assume Constant Ratio at Partial Loads

Done

Figure A1.34: Gas Turbine System Definition Window



Generation System Name: 2.3 MW Steam Turbine (Denmark)

Generation System Type: Steam Turbine

Number of Engine Sets: 1

Rated Power (Continuous) (kWmech): 2300

Rated Power (Peak) (kWmech): 2300

Generation Priority
● Constant Percentage Loading: 100
○ Specify Times of Day/Year [Specify]

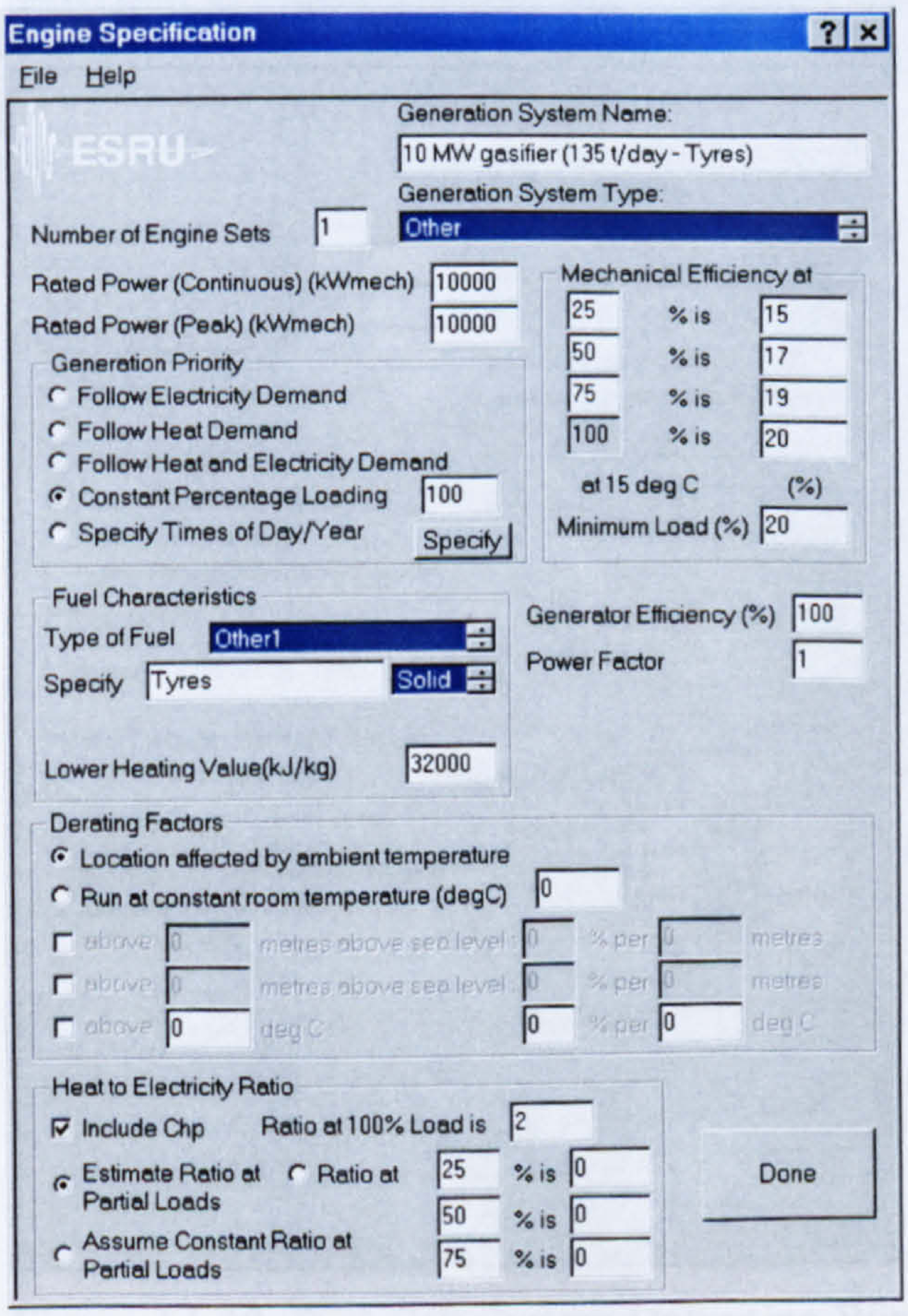
Mechanical Efficiency at
25 % is 10
50 % is 15
75 % is 19
100 % is 19
at 15 deg C (%)
Minimum Load (%): 20

Fuel Characteristics
Type of Fuel: Other1
Specify: Chicken Litter — Solid
Lower Heating Value(kJ/kg): 13500

Generator Efficiency (%): 100
Power Factor: 1
Boiler Efficiency (%): 73

Heat to Electricity Ratio
☑ Include Chp — Ratio at 100% Load is: 3
● Estimate Ratio at Partial Loads
○ Ratio at 25 % is 0
50 % is 0
75 % is 0
○ Assume Constant Ratio at Partial Loads

Figure A1.35: Steam Turbine System Definition Window



Generation System Name: 10 MW gasifier (135 t/day - Tyres)

Generation System Type: Other

Number of Engine Sets: 1

Rated Power (Continuous) (kWmech): 10000

Rated Power (Peak) (kWmech): 10000

Generation Priority
○ Follow Electricity Demand
○ Follow Heat Demand
○ Follow Heat and Electricity Demand
● Constant Percentage Loading: 100
○ Specify Times of Day/Year [Specify]

Mechanical Efficiency at
25 % is 15
50 % is 17
75 % is 19
100 % is 20
at 15 deg C (%)
Minimum Load (%): 20

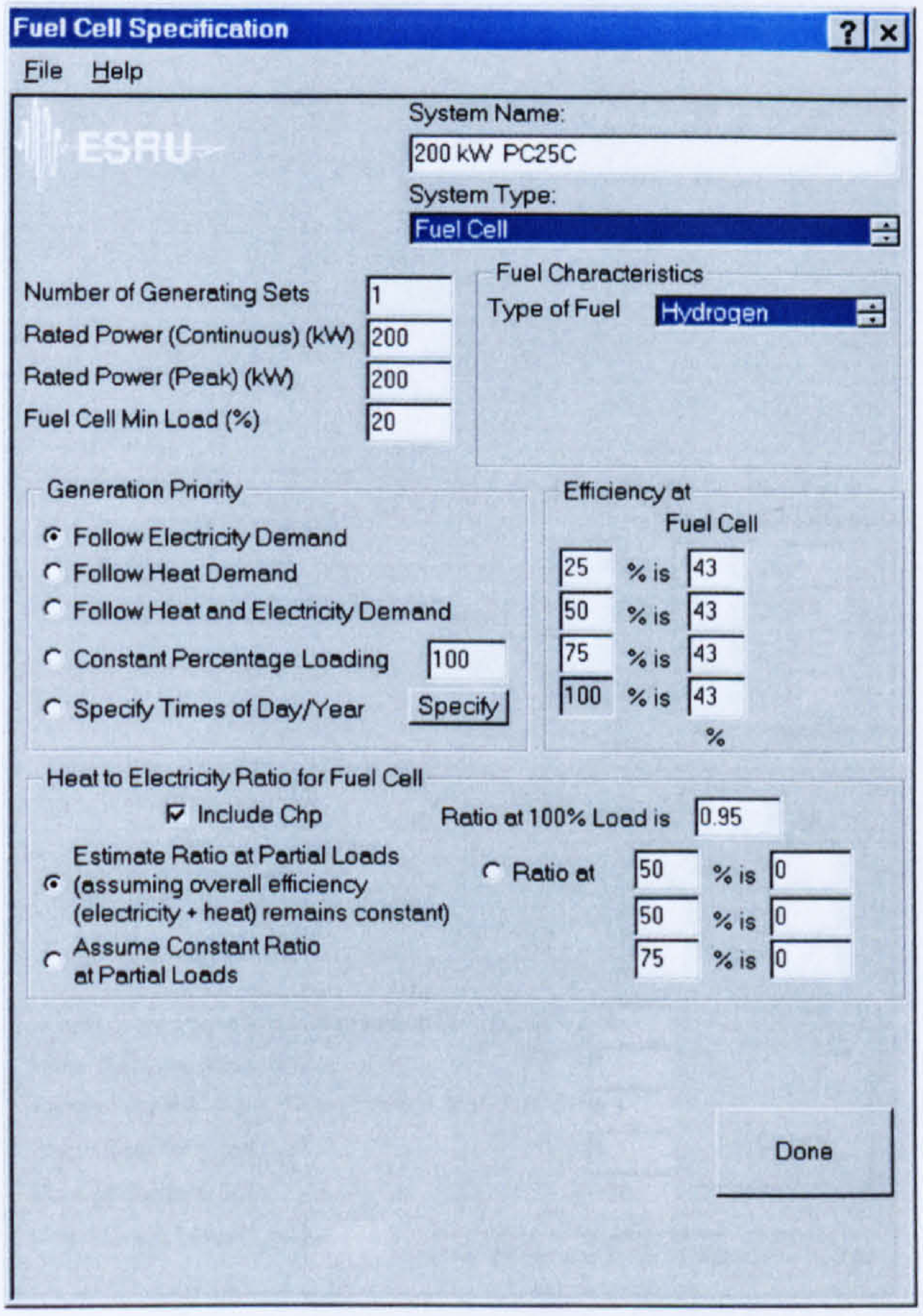
Fuel Characteristics
Type of Fuel: Other1
Specify: Tyres — Solid
Lower Heating Value(kJ/kg): 32000

Generator Efficiency (%): 100
Power Factor: 1

Derating Factors
● Location affected by ambient temperature
○ Run at constant room temperature (degC): 0
☐ above 0 metres above sea level 0 % per 0 metres
☐ above 0 metres above sea level 0 % per 0 metres
☐ above 0 deg C 0 % per 0 deg C

Heat to Electricity Ratio
☑ Include Chp — Ratio at 100% Load is: 2
● Estimate Ratio at Partial Loads
○ Ratio at 25 % is 0
50 % is 0
75 % is 0
○ Assume Constant Ratio at Partial Loads

Figure A1.36: Tyre Gasification (Other) System Definition Window



System Name: 200 kW PC25C

System Type: Fuel Cell

Number of Generating Sets: 1

Rated Power (Continuous) (kW): 200

Rated Power (Peak) (kW): 200

Fuel Cell Min Load (%): 20

Fuel Characteristics

Type of Fuel: Hydrogen

Generation Priority

- ● Follow Electricity Demand
- ○ Follow Heat Demand
- ○ Follow Heat and Electricity Demand
- ○ Constant Percentage Loading: 100
- ○ Specify Times of Day/Year — Specify

Efficiency at Fuel Cell

25 % is 43 %
50 % is 43 %
75 % is 43 %
100 % is 43 %

Heat to Electricity Ratio for Fuel Cell

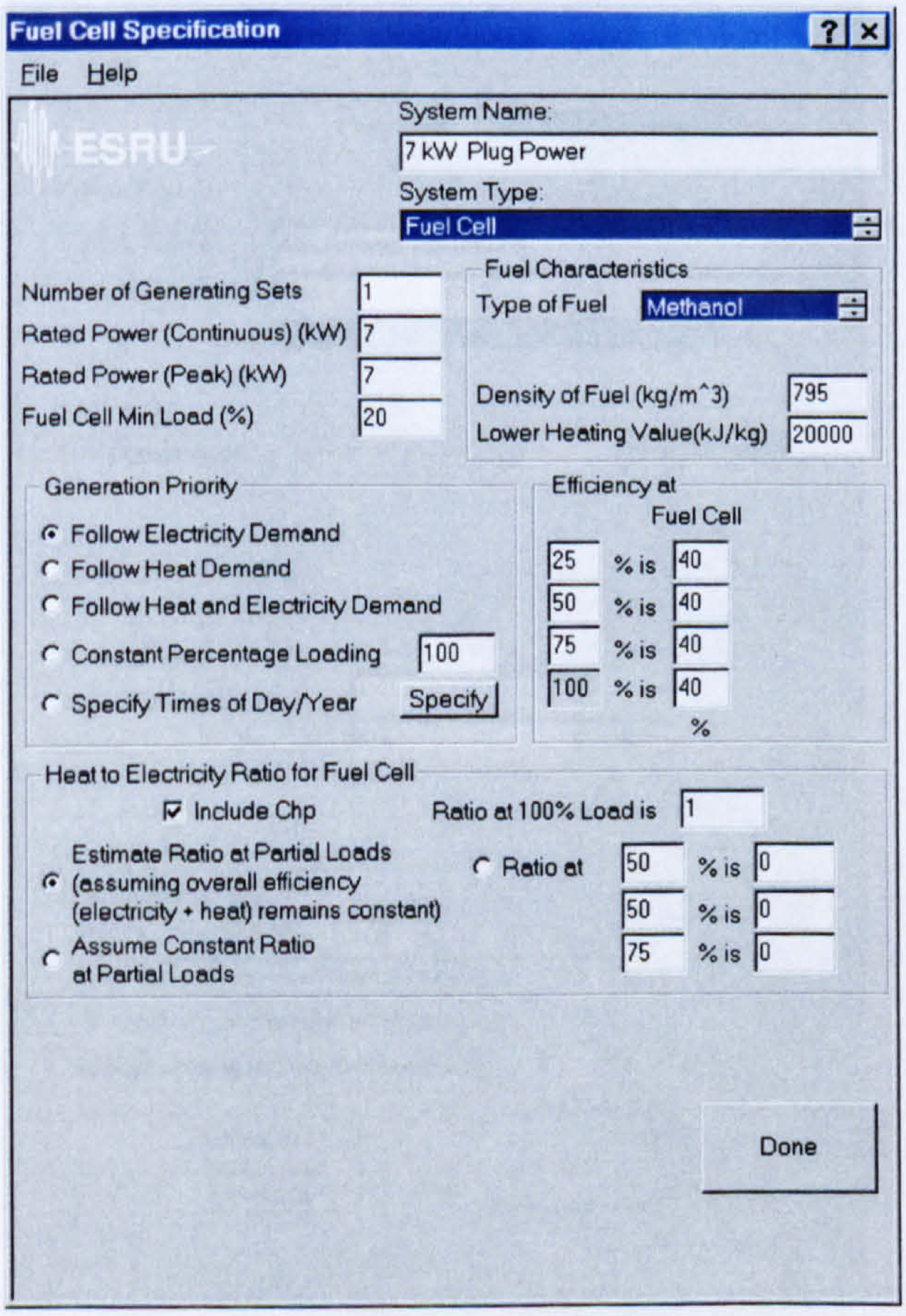
☑ Include Chp

Ratio at 100% Load is: 0.95

- ● Estimate Ratio at Partial Loads (assuming overall efficiency (electricity + heat) remains constant)
- ○ Assume Constant Ratio at Partial Loads
- ○ Ratio at

50 % is 0
50 % is 0
75 % is 0

Figure A1.37: Fuel Cell System Definition Window – Hydrogen Fuel



System Name: 7 kW Plug Power

System Type: Fuel Cell

Number of Generating Sets: 1

Rated Power (Continuous) (kW): 7

Rated Power (Peak) (kW): 7

Fuel Cell Min Load (%): 20

Fuel Characteristics

Type of Fuel: Methanol

Density of Fuel (kg/m^3): 795

Lower Heating Value(kJ/kg): 20000

Generation Priority

- ● Follow Electricity Demand
- ○ Follow Heat Demand
- ○ Follow Heat and Electricity Demand
- ○ Constant Percentage Loading: 100
- ○ Specify Times of Day/Year — Specify

Efficiency at Fuel Cell

25 % is 40 %
50 % is 40 %
75 % is 40 %
100 % is 40 %

Heat to Electricity Ratio for Fuel Cell

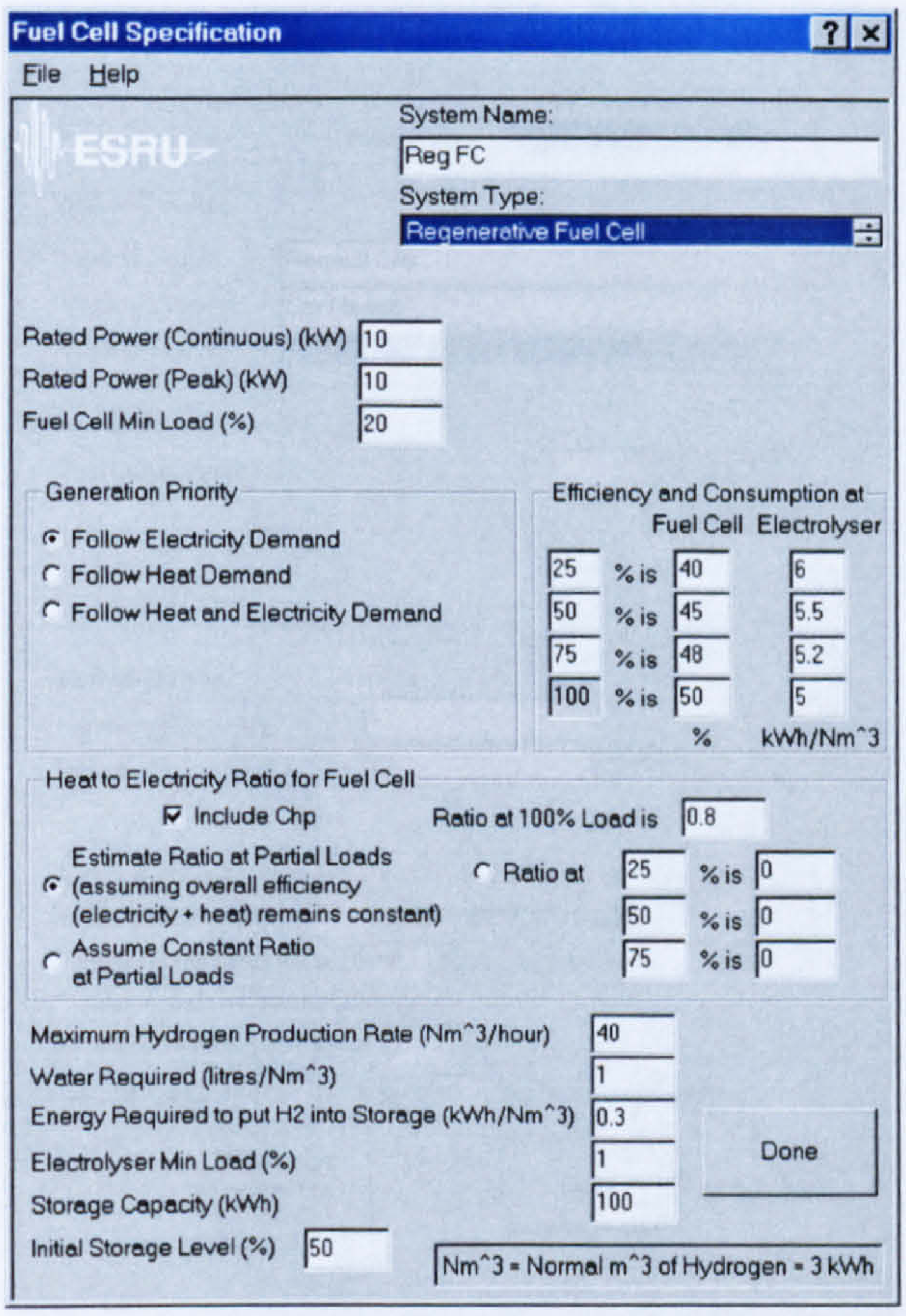
☑ Include Chp

Ratio at 100% Load is: 1

- ● Estimate Ratio at Partial Loads (assuming overall efficiency (electricity + heat) remains constant)
- ○ Assume Constant Ratio at Partial Loads
- ○ Ratio at

50 % is 0
50 % is 0
75 % is 0

Figure A1.38: Fuel Cell System Definition Window – Methanol Fuel



System Name: Reg FC

System Type: Regenerative Fuel Cell

Rated Power (Continuous) (kW) 10

Rated Power (Peak) (kW) 10

Fuel Cell Min Load (%) 20

Generation Priority
- ● Follow Electricity Demand
- ○ Follow Heat Demand
- ○ Follow Heat and Electricity Demand

Efficiency and Consumption at

Load (%)		Fuel Cell (%)	Electrolyser (kWh/Nm^3)
25	% is	40	6
50	% is	45	5.5
75	% is	48	5.2
100	% is	50	5

Heat to Electricity Ratio for Fuel Cell

☑ Include Chp

Ratio at 100% Load is 0.8

● Estimate Ratio at Partial Loads (assuming overall efficiency (electricity + heat) remains constant)

○ Ratio at

Load (%)		Ratio
25	% is	0
50	% is	0
75	% is	0

○ Assume Constant Ratio at Partial Loads

Maximum Hydrogen Production Rate (Nm^3/hour) 40

Water Required (litres/Nm^3) 1

Energy Required to put H2 into Storage (kWh/Nm^3) 0.3

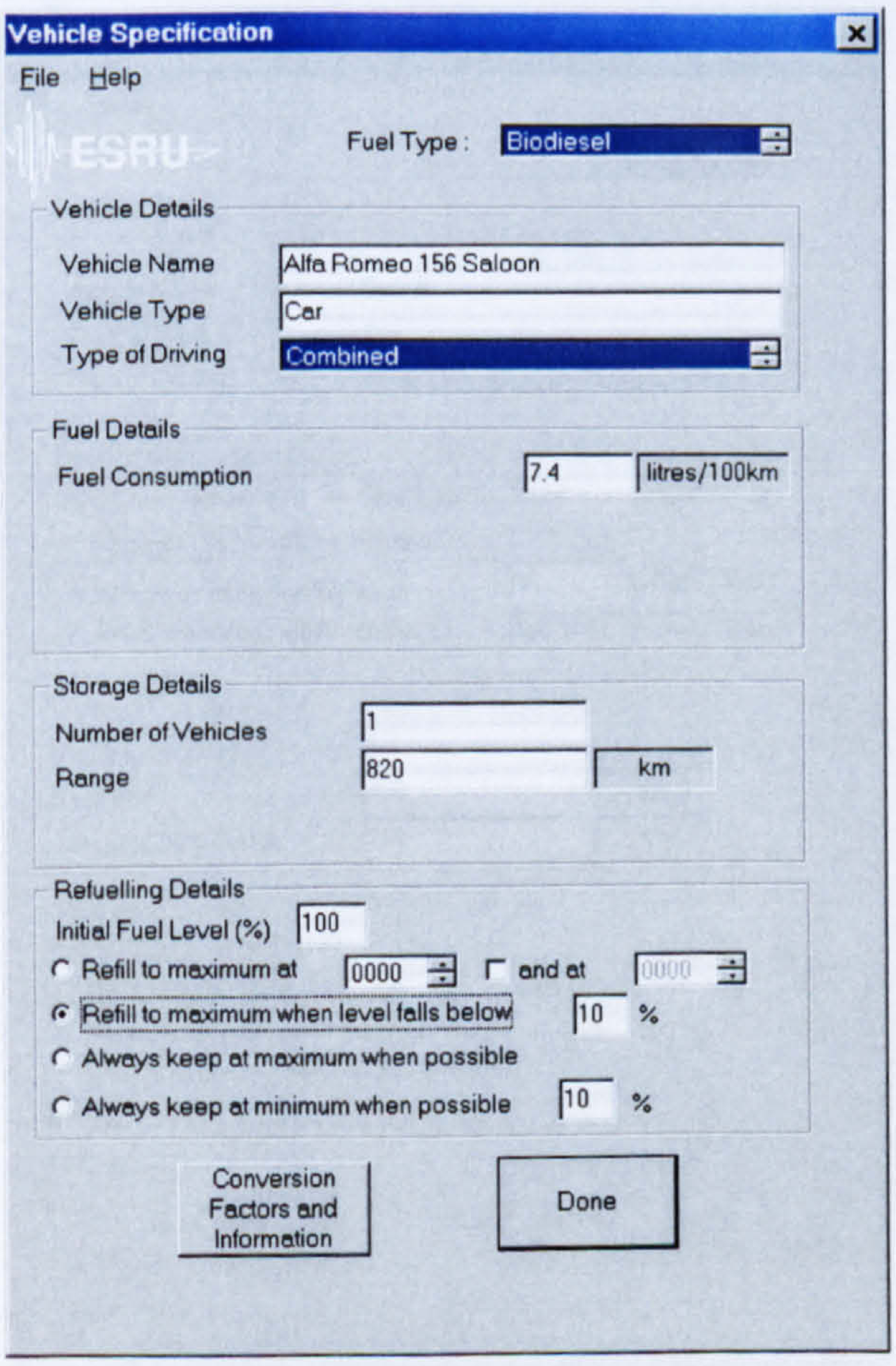
Electrolyser Min Load (%) 1

Storage Capacity (kWh) 100

Initial Storage Level (%) 50

Nm^3 = Normal m^3 of Hydrogen = 3 kWh

Figure A1.39: Regenerative Fuel Cell System Definition Window



Fuel Type : Biodiesel

Vehicle Details

Vehicle Name: Alfa Romeo 156 Saloon

Vehicle Type: Car

Type of Driving: Combined

Fuel Details

Fuel Consumption: 7.4 litres/100km

Storage Details

Number of Vehicles: 1

Range: 820 km

Refuelling Details

Initial Fuel Level (%) 100

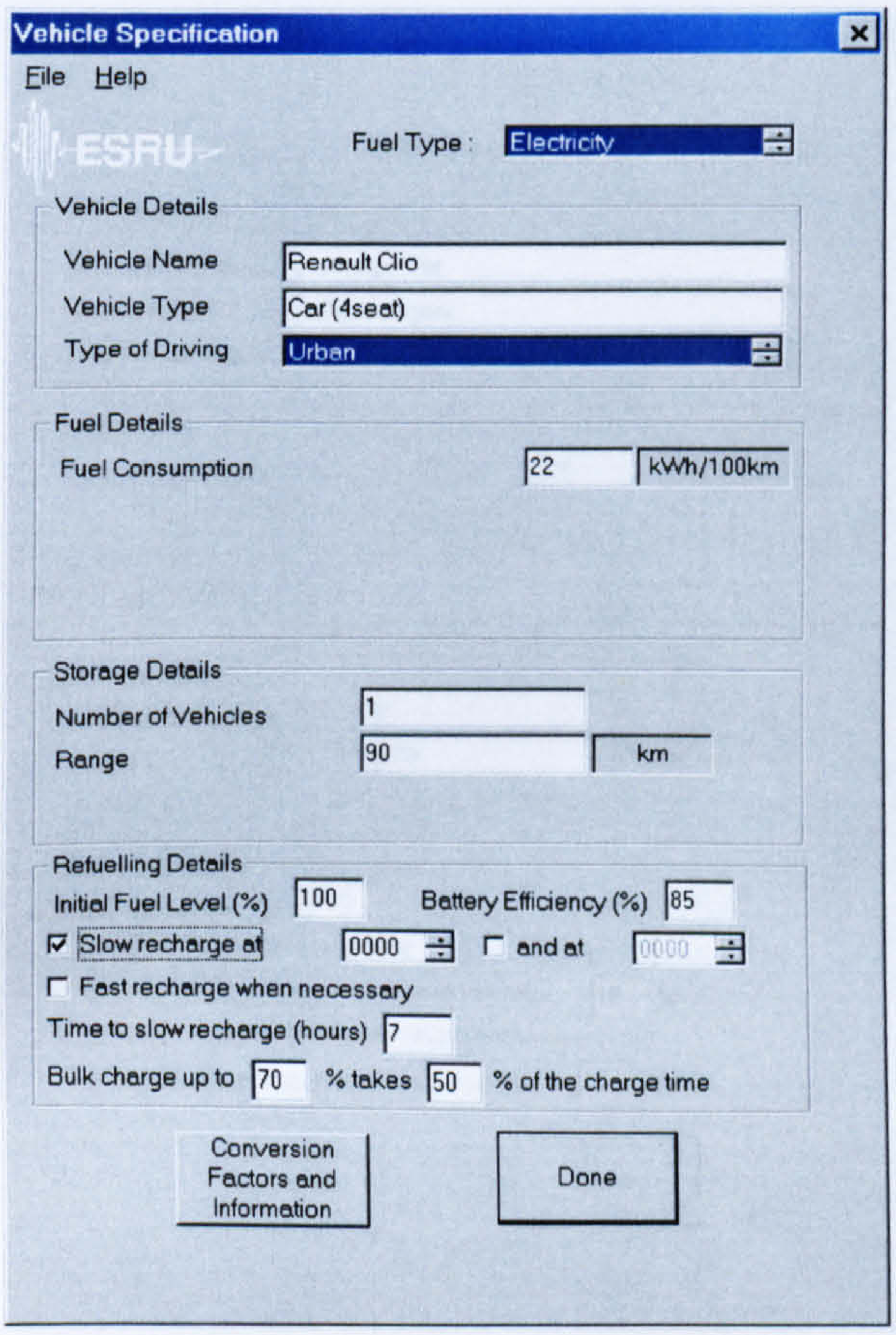
○ Refill to maximum at 0000 ☐ and at 0000

● Refill to maximum when level falls below 10 %

○ Always keep at maximum when possible

○ Always keep at minimum when possible 10 %

Figure A1.40: Vehicle System Definition Window – Biodiesel Fuel



Fuel Type : Electricity

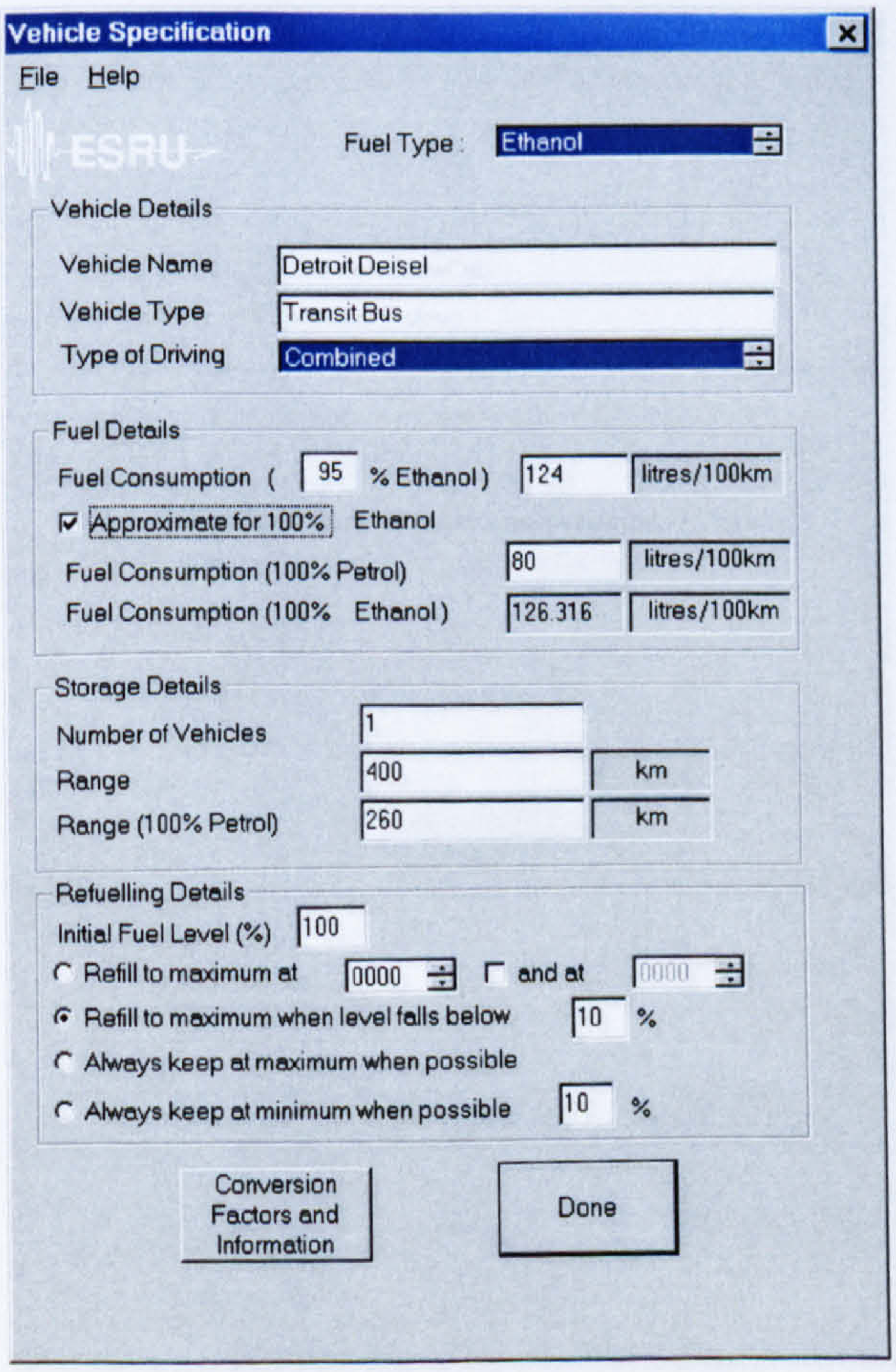
Vehicle Details
Vehicle Name: Renault Clio
Vehicle Type: Car (4seat)
Type of Driving: Urban

Fuel Details
Fuel Consumption: 22 kWh/100km

Storage Details
Number of Vehicles: 1
Range: 90 km

Refuelling Details
Initial Fuel Level (%): 100
Battery Efficiency (%): 85
☑ Slow recharge at 0000 ☐ and at 0000
☐ Fast recharge when necessary
Time to slow recharge (hours): 7
Bulk charge up to 70 % takes 50 % of the charge time

Figure A1.41: Electric Vehicle System Definition Window



Fuel Type : Ethanol

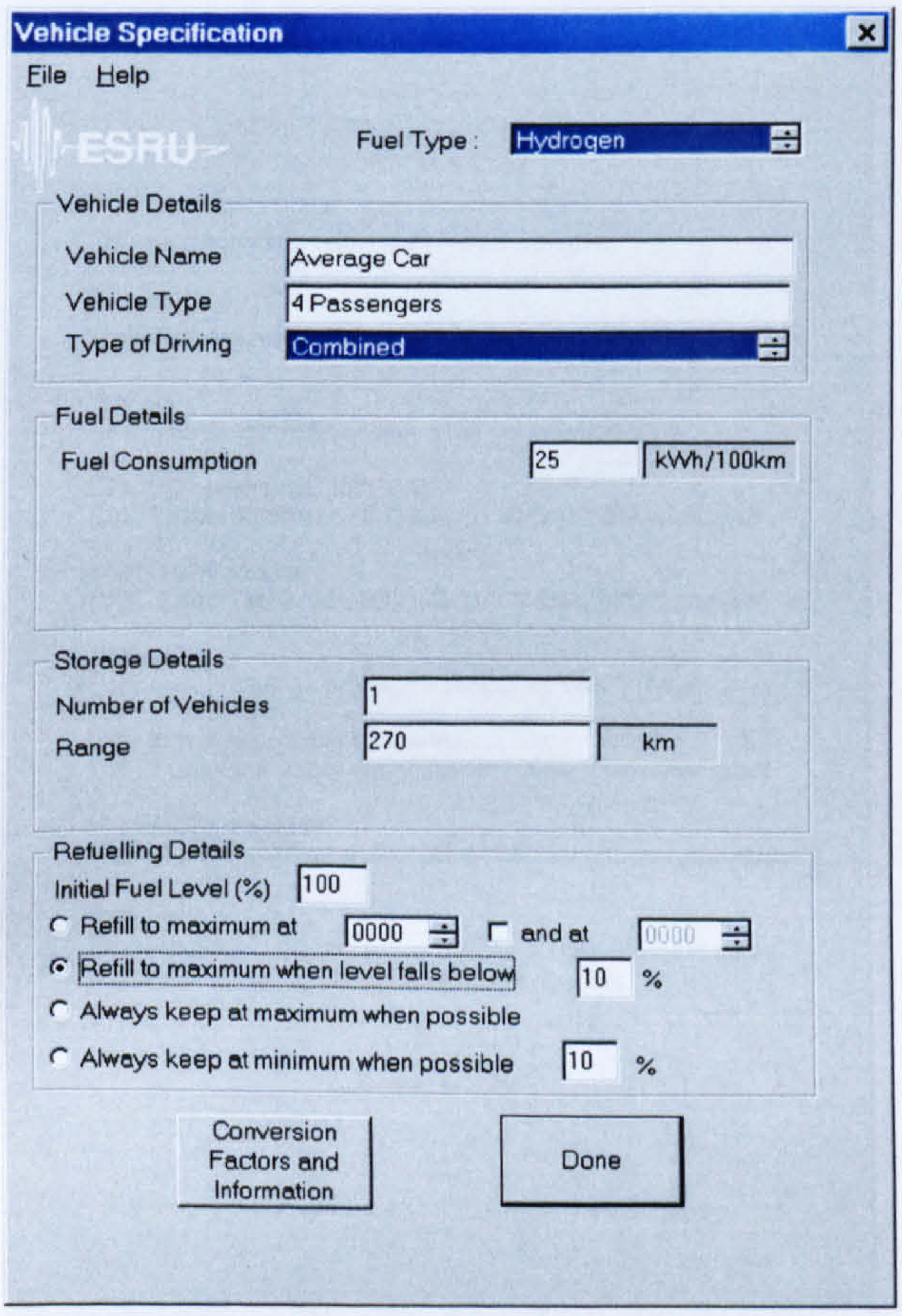
Vehicle Details
Vehicle Name: Detroit Deisel
Vehicle Type: Transit Bus
Type of Driving: Combined

Fuel Details
Fuel Consumption (95 % Ethanol) 124 litres/100km
☑ Approximate for 100% Ethanol
Fuel Consumption (100% Petrol) 80 litres/100km
Fuel Consumption (100% Ethanol) 126.316 litres/100km

Storage Details
Number of Vehicles: 1
Range: 400 km
Range (100% Petrol): 260 km

Refuelling Details
Initial Fuel Level (%): 100
○ Refill to maximum at 0000 ☐ and at 0000
● Refill to maximum when level falls below 10 %
○ Always keep at maximum when possible
○ Always keep at minimum when possible 10 %

Figure A1.42: Vehicle System Definition Window – Ethanol/Methanol Fuel



Fuel Type : Hydrogen

Vehicle Details

Vehicle Name: Average Car
Vehicle Type: 4 Passengers
Type of Driving: Combined

Fuel Details

Fuel Consumption: 25 kWh/100km

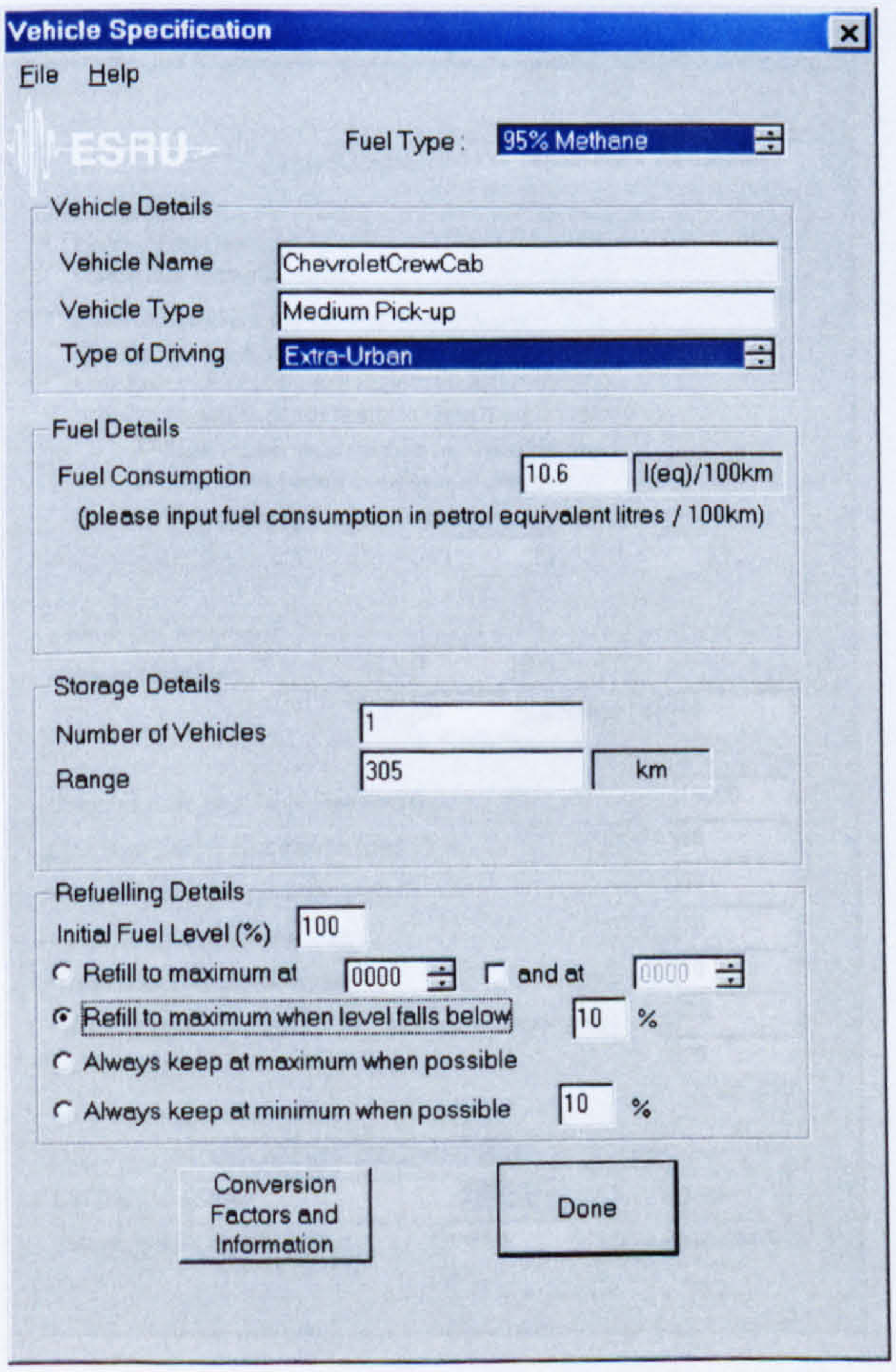
Storage Details

Number of Vehicles: 1
Range: 270 km

Refuelling Details

Initial Fuel Level (%): 100
○ Refill to maximum at 0000 ☐ and at 0000
● Refill to maximum when level falls below 10 %
○ Always keep at maximum when possible
○ Always keep at minimum when possible 10 %

Figure A1.43: Vehicle System Definition Window – Hydrogen Fuel



Fuel Type : 95% Methane

Vehicle Details

Vehicle Name: ChevroletCrewCab
Vehicle Type: Medium Pick-up
Type of Driving: Extra-Urban

Fuel Details

Fuel Consumption: 10.6 l(eq)/100km
(please input fuel consumption in petrol equivalent litres / 100km)

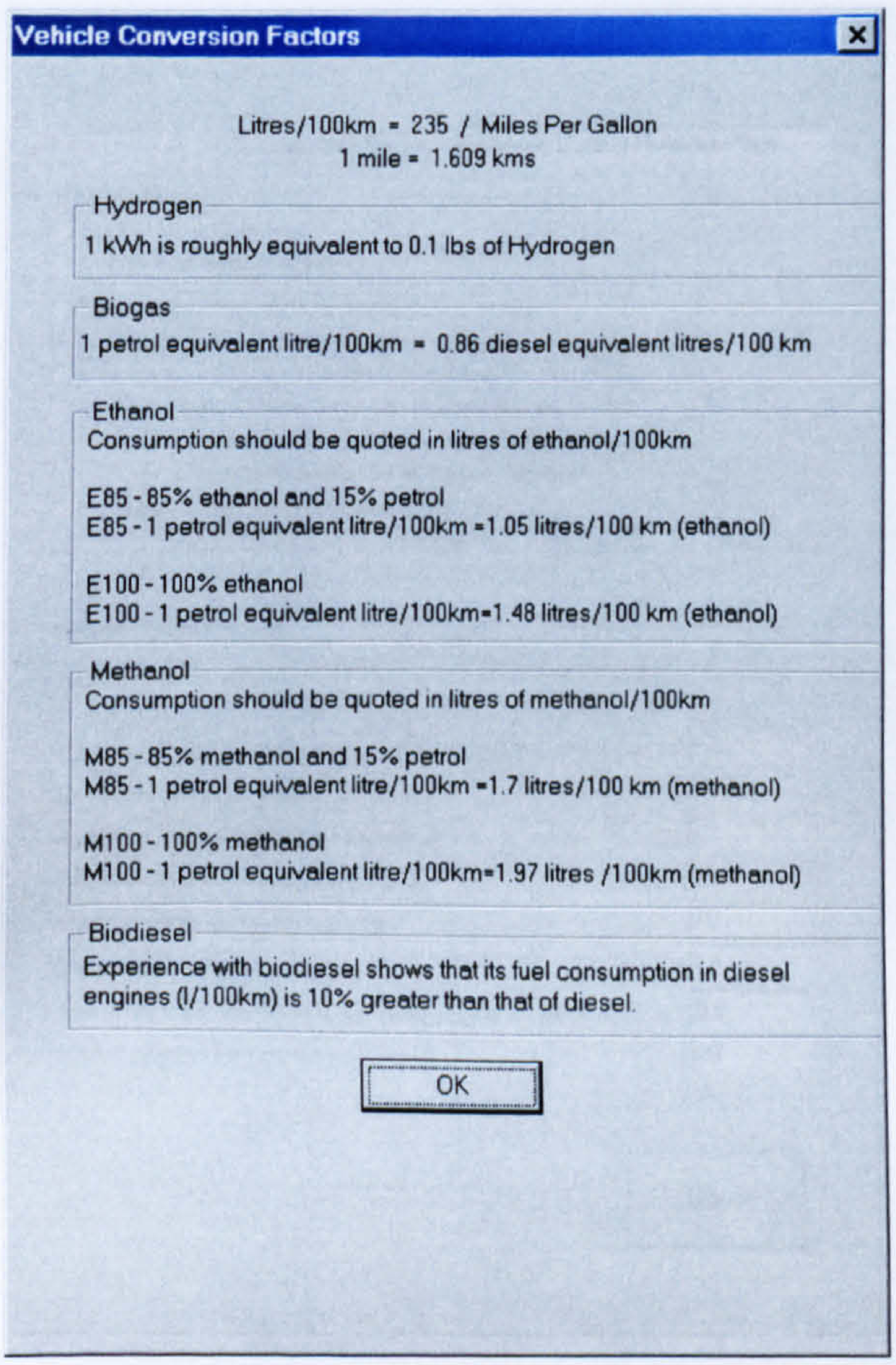
Storage Details

Number of Vehicles: 1
Range: 305 km

Refuelling Details

Initial Fuel Level (%): 100
○ Refill to maximum at 0000 ☐ and at 0000
● Refill to maximum when level falls below 10 %
○ Always keep at maximum when possible
○ Always keep at minimum when possible 10 %

Figure A1.44: Vehicle System Definition Window – 95% Methane Fuel



Litres/100km = 235 / Miles Per Gallon
1 mile = 1.609 kms

Hydrogen
1 kWh is roughly equivalent to 0.1 lbs of Hydrogen

Biogas
1 petrol equivalent litre/100km = 0.86 diesel equivalent litres/100 km

Ethanol
Consumption should be quoted in litres of ethanol/100km

E85 - 85% ethanol and 15% petrol
E85 - 1 petrol equivalent litre/100km =1.05 litres/100 km (ethanol)

E100 - 100% ethanol
E100 - 1 petrol equivalent litre/100km=1.48 litres/100 km (ethanol)

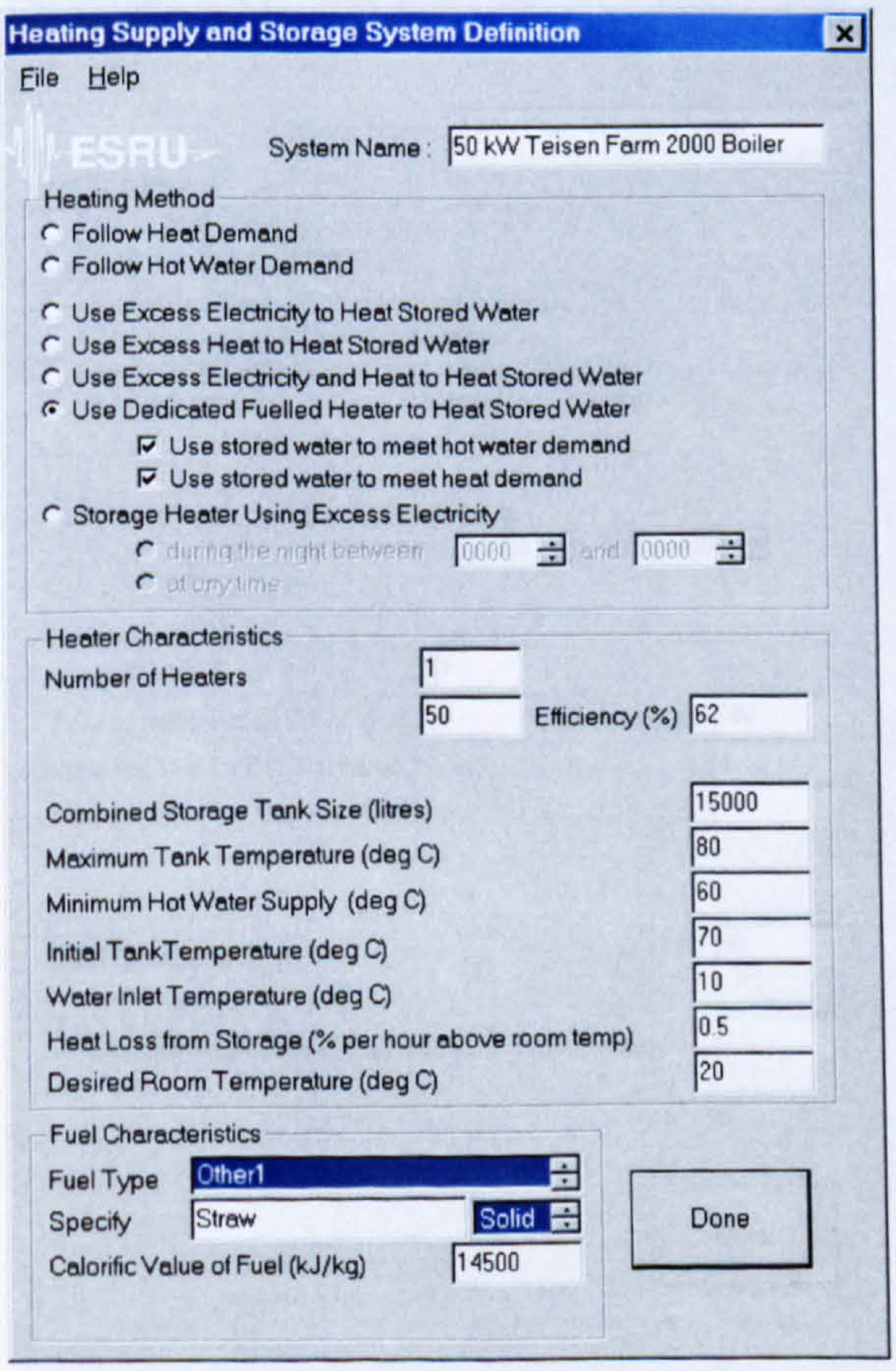
Methanol
Consumption should be quoted in litres of methanol/100km

M85 - 85% methanol and 15% petrol
M85 - 1 petrol equivalent litre/100km =1.7 litres/100 km (methanol)

M100 - 100% methanol
M100 - 1 petrol equivalent litre/100km=1.97 litres /100km (methanol)

Biodiesel
Experience with biodiesel shows that its fuel consumption in diesel engines (l/100km) is 10% greater than that of diesel.

Figure A1.45: Vehicle Conversion Factors and Information Window



System Name : 50 kW Teisen Farm 2000 Boiler

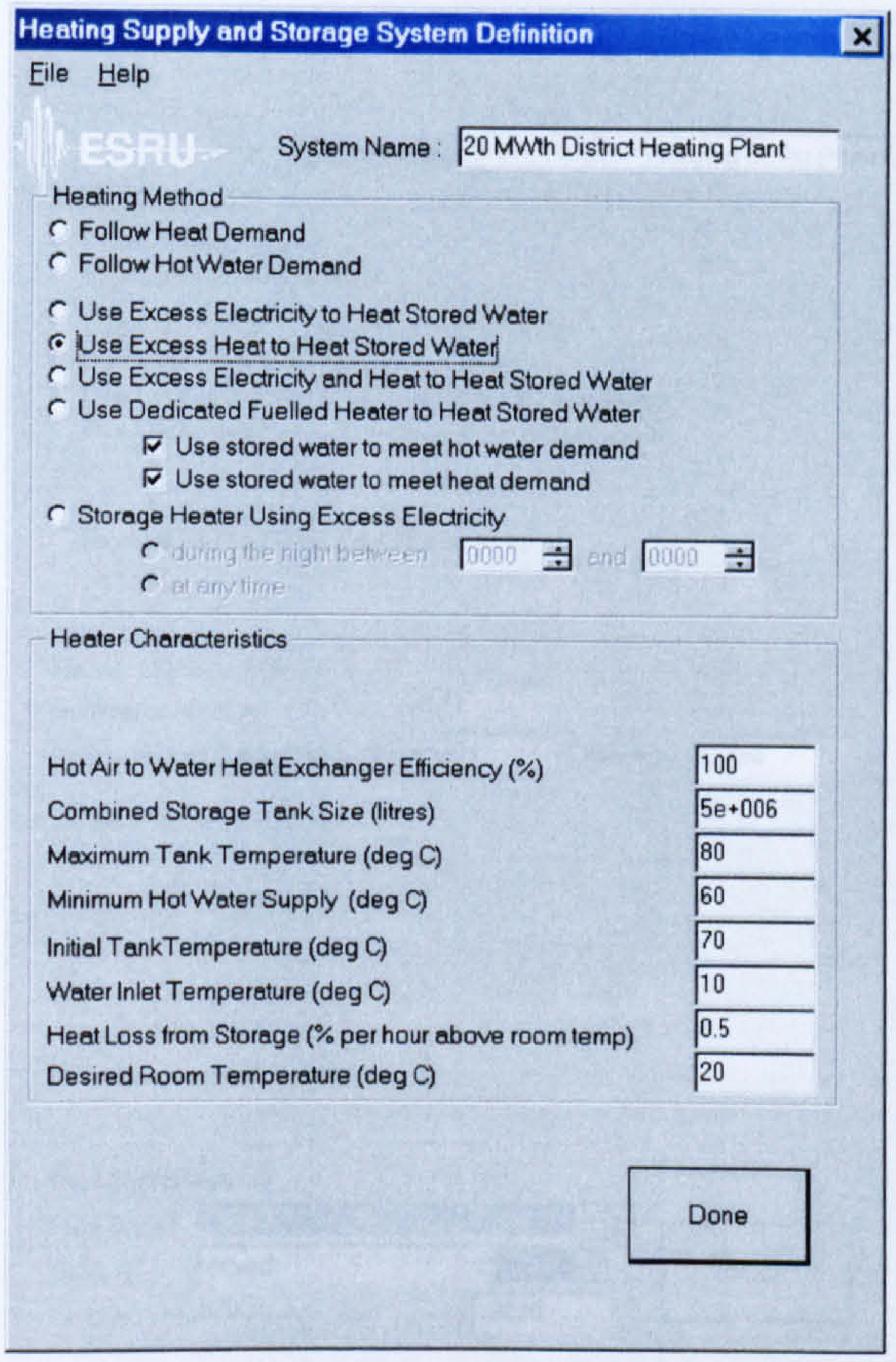
Heating Method
○ Follow Heat Demand
○ Follow Hot Water Demand
○ Use Excess Electricity to Heat Stored Water
○ Use Excess Heat to Heat Stored Water
○ Use Excess Electricity and Heat to Heat Stored Water
● Use Dedicated Fuelled Heater to Heat Stored Water
  ☑ Use stored water to meet hot water demand
  ☑ Use stored water to meet heat demand
○ Storage Heater Using Excess Electricity
  ○ during the night between 0000 and 0000
  ○ at any time

Heater Characteristics
Number of Heaters 1
50 Efficiency (%) 62

Combined Storage Tank Size (litres) 15000
Maximum Tank Temperature (deg C) 80
Minimum Hot Water Supply (deg C) 60
Initial Tank Temperature (deg C) 70
Water Inlet Temperature (deg C) 10
Heat Loss from Storage (% per hour above room temp) 0.5
Desired Room Temperature (deg C) 20

Fuel Characteristics
Fuel Type Other1
Specify Straw Solid
Calorific Value of Fuel (kJ/kg) 14500

Figure A1.46: Dedicated Boiler and Storage Heating System Definition Window



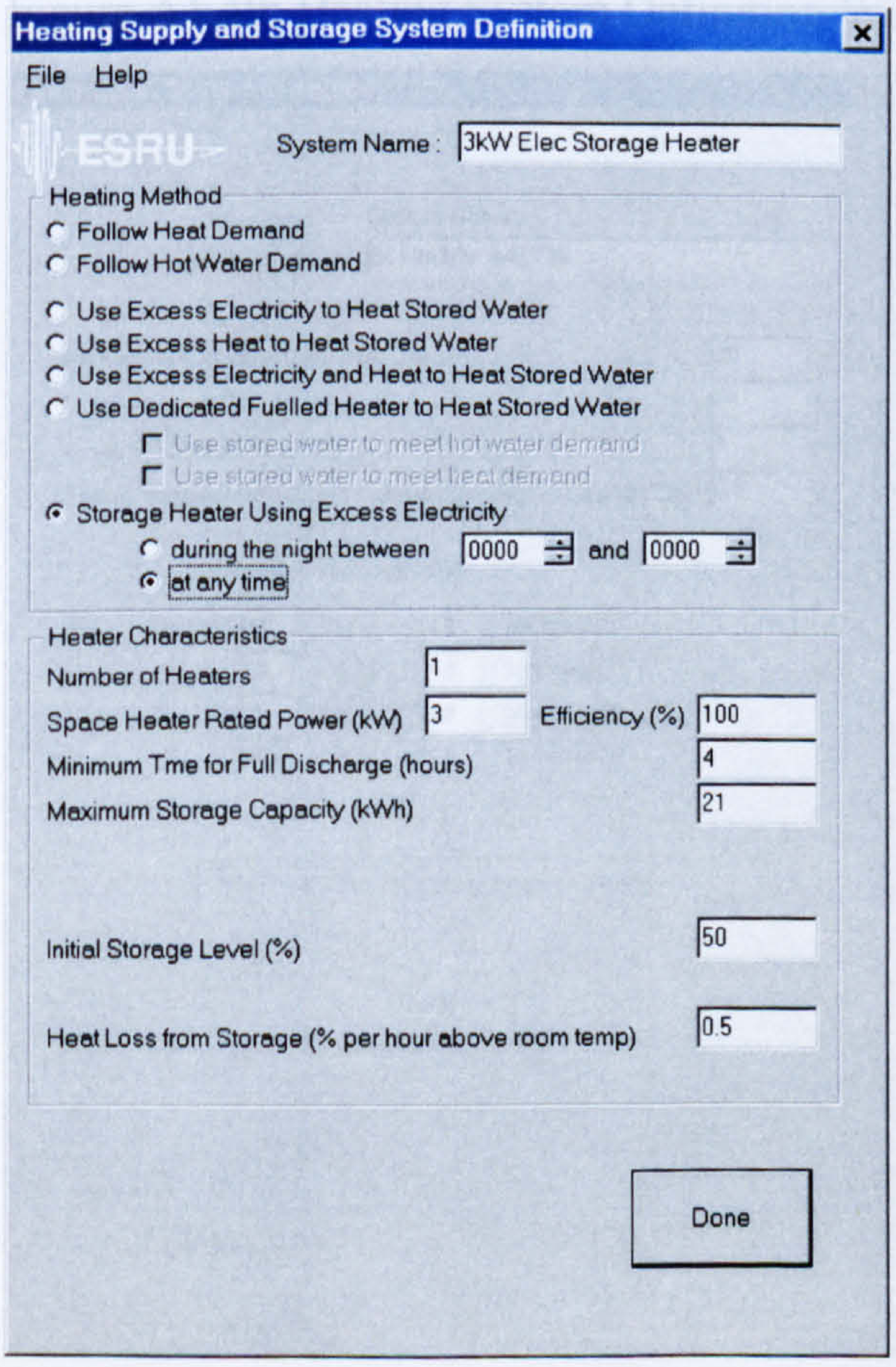
System Name : 20 MWth District Heating Plant

Heating Method
- ○ Follow Heat Demand
- ○ Follow Hot Water Demand
- ○ Use Excess Electricity to Heat Stored Water
- ● Use Excess Heat to Heat Stored Water
- ○ Use Excess Electricity and Heat to Heat Stored Water
- ○ Use Dedicated Fuelled Heater to Heat Stored Water
  - ☑ Use stored water to meet hot water demand
  - ☑ Use stored water to meet heat demand
- ○ Storage Heater Using Excess Electricity
  - ○ during the night between 0000 and 0000
  - ○ at any time

Heater Characteristics

Hot Air to Water Heat Exchanger Efficiency (%)	100
Combined Storage Tank Size (litres)	5e+006
Maximum Tank Temperature (deg C)	80
Minimum Hot Water Supply (deg C)	60
Initial Tank Temperature (deg C)	70
Water Inlet Temperature (deg C)	10
Heat Loss from Storage (% per hour above room temp)	0.5
Desired Room Temperature (deg C)	20

Figure A1.47: District Heating Storage System Definition Window



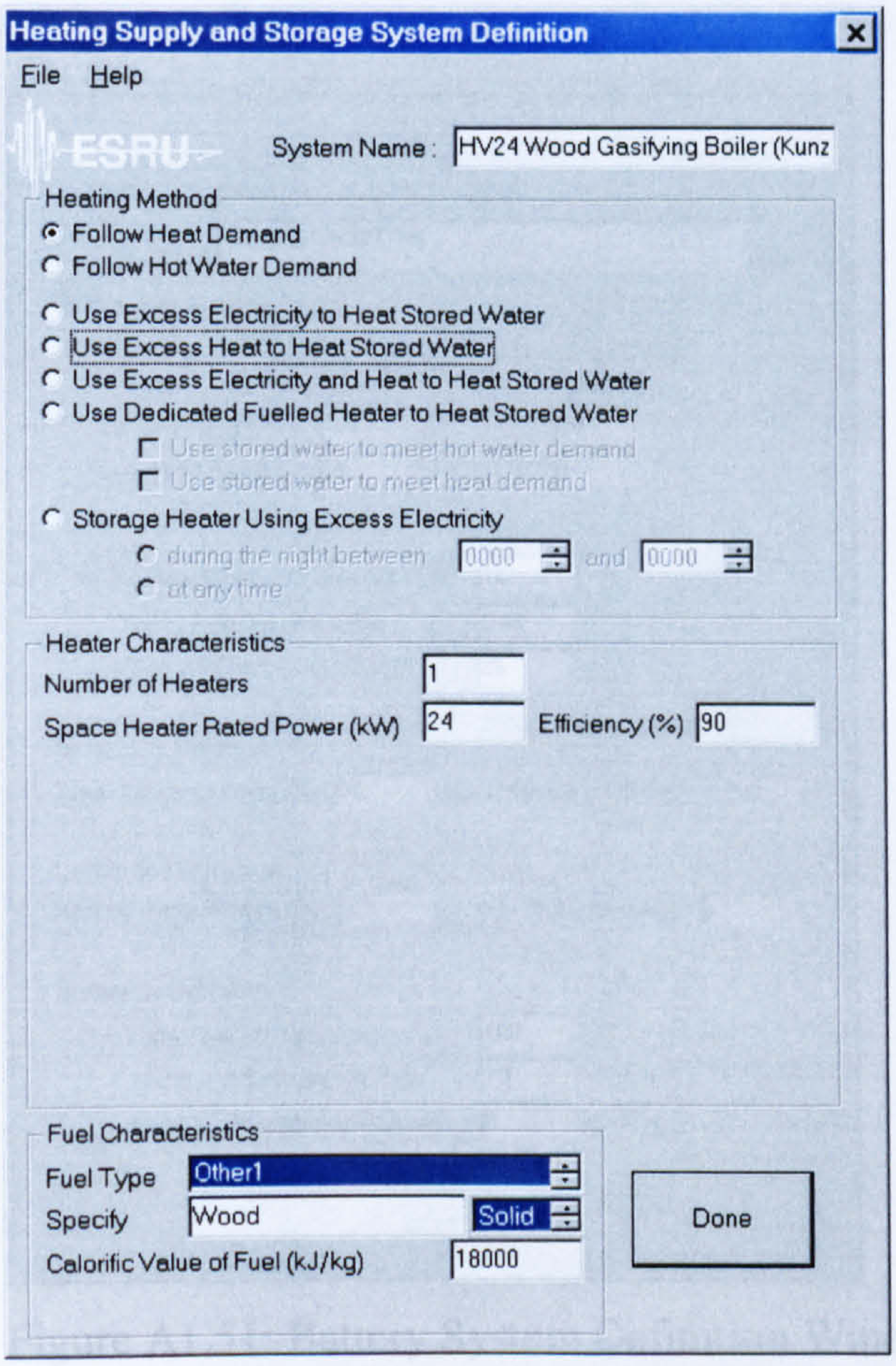
System Name : 3kW Elec Storage Heater

Heating Method
- ○ Follow Heat Demand
- ○ Follow Hot Water Demand
- ○ Use Excess Electricity to Heat Stored Water
- ○ Use Excess Heat to Heat Stored Water
- ○ Use Excess Electricity and Heat to Heat Stored Water
- ○ Use Dedicated Fuelled Heater to Heat Stored Water
  - ☐ Use stored water to meet hot water demand
  - ☐ Use stored water to meet heat demand
- ● Storage Heater Using Excess Electricity
  - ○ during the night between 0000 and 0000
  - ● at any time

Heater Characteristics

Number of Heaters	1
Space Heater Rated Power (kW)	3
Efficiency (%)	100
Minimum Tme for Full Discharge (hours)	4
Maximum Storage Capacity (kWh)	21
Initial Storage Level (%)	50
Heat Loss from Storage (% per hour above room temp)	0.5

Figure A1.48: Electric Storage Heating System Definition Window



Heating Supply and Storage System Definition

File Help

System Name : HV24 Wood Gasifying Boiler (Kunz

Heating Method

- ● Follow Heat Demand
- ○ Follow Hot Water Demand
- ○ Use Excess Electricity to Heat Stored Water
- ○ Use Excess Heat to Heat Stored Water
- ○ Use Excess Electricity and Heat to Heat Stored Water
- ○ Use Dedicated Fuelled Heater to Heat Stored Water
  - ☐ Use stored water to meet hot water demand
  - ☐ Use stored water to meet heat demand
- ○ Storage Heater Using Excess Electricity
  - ○ during the night between 0000 and 0000
  - ○ at any time

Heater Characteristics

Number of Heaters: 1

Space Heater Rated Power (kW): 24

Efficiency (%): 90

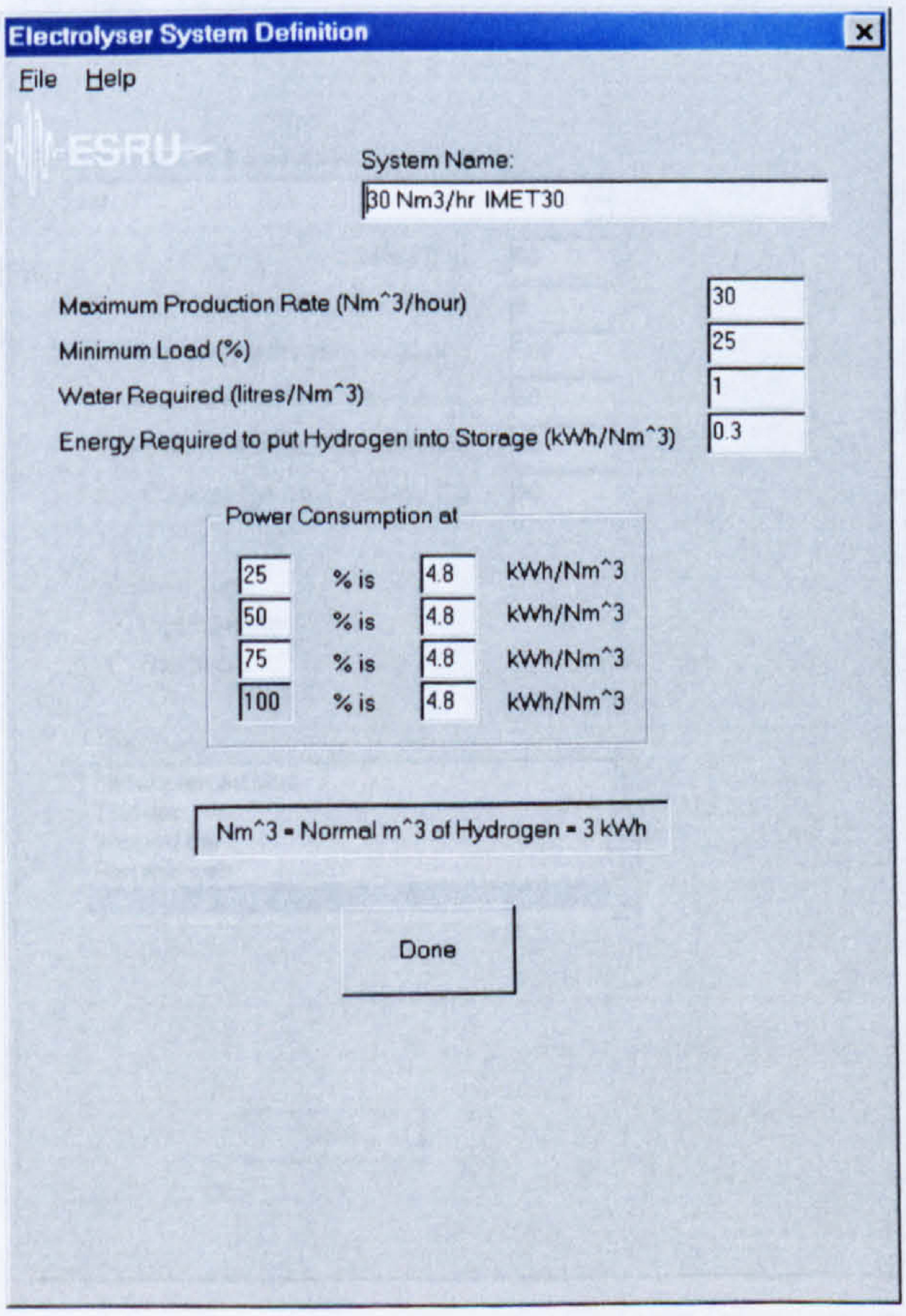
Fuel Characteristics

Fuel Type: Other1

Specify: Wood — Solid

Calorific Value of Fuel (kJ/kg): 18000

Figure A1.49: Heating System Definition Window



Electrolyser System Definition

File Help

System Name: 30 Nm3/hr IMET30

Maximum Production Rate (Nm^3/hour): 30

Minimum Load (%): 25

Water Required (litres/Nm^3): 1

Energy Required to put Hydrogen into Storage (kWh/Nm^3): 0.3

Power Consumption at

25 % is 4.8 kWh/Nm^3

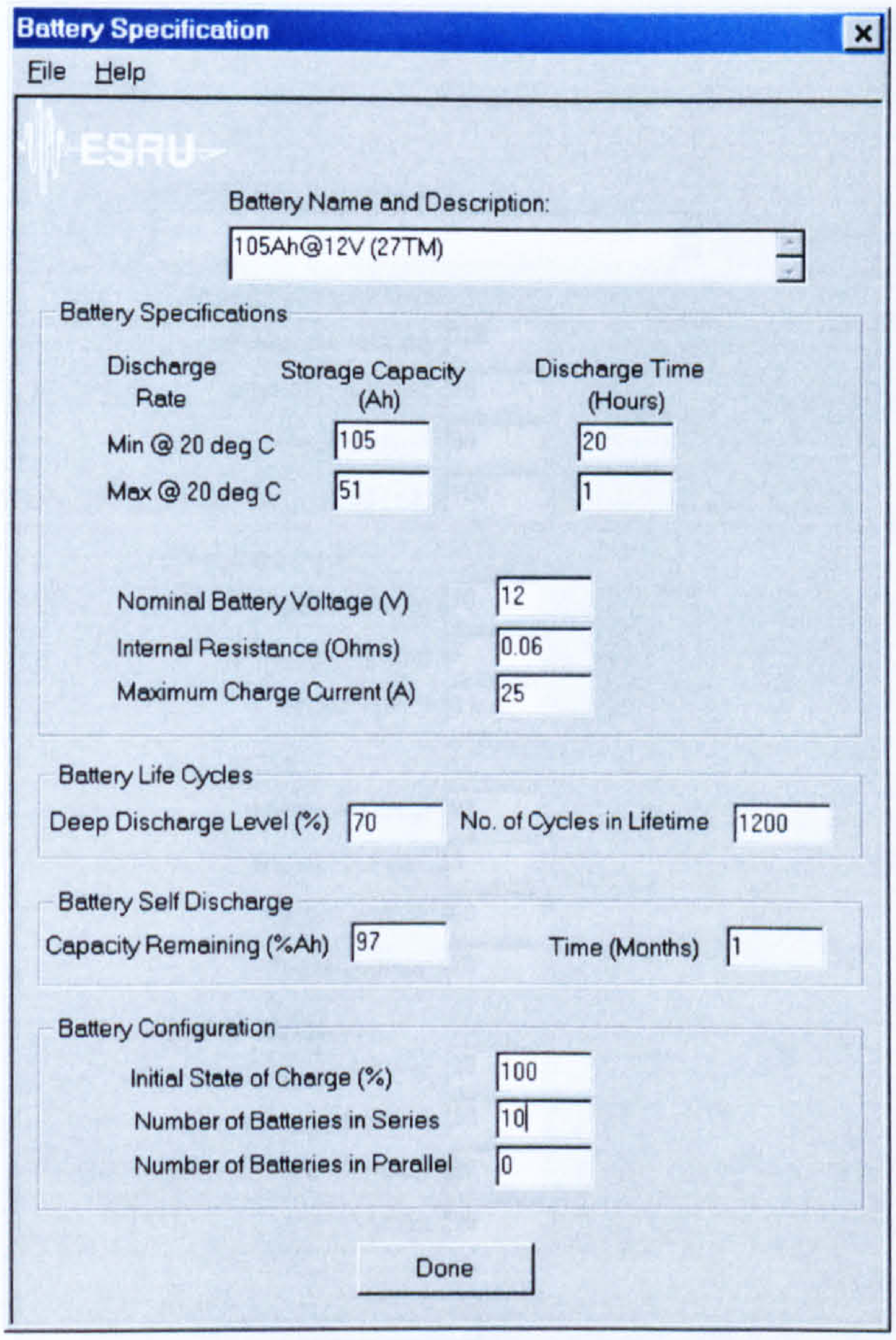
50 % is 4.8 kWh/Nm^3

75 % is 4.8 kWh/Nm^3

100 % is 4.8 kWh/Nm^3

Nm^3 = Normal m^3 of Hydrogen = 3 kWh

Figure A1.50: Electrolyser System Definition Window



Battery Name and Description: 105Ah@12V (27TM)

Battery Specifications

Discharge Rate	Storage Capacity (Ah)	Discharge Time (Hours)
Min @ 20 deg C	105	20
Max @ 20 deg C	51	1

Nominal Battery Voltage (V): 12

Internal Resistance (Ohms): 0.06

Maximum Charge Current (A): 25

Battery Life Cycles

Deep Discharge Level (%): 70

No. of Cycles in Lifetime: 1200

Battery Self Discharge

Capacity Remaining (%Ah): 97

Time (Months): 1

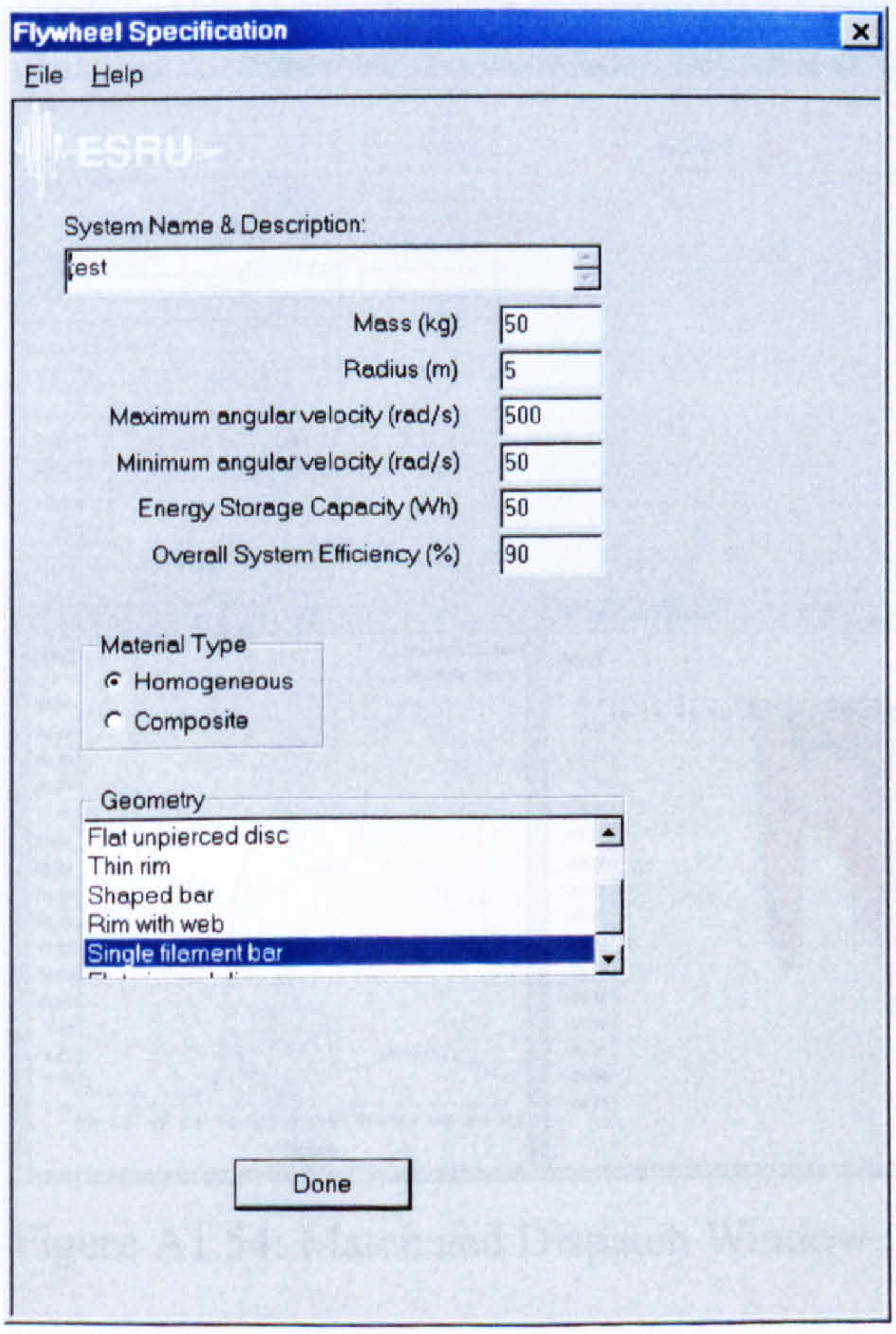
Battery Configuration

Initial State of Charge (%): 100

Number of Batteries in Series: 10

Number of Batteries in Parallel: 0

Figure A1.51: Battery System Definition Window



System Name & Description: test

Mass (kg): 50

Radius (m): 5

Maximum angular velocity (rad/s): 500

Minimum angular velocity (rad/s): 50

Energy Storage Capacity (Wh): 50

Overall System Efficiency (%): 90

Material Type

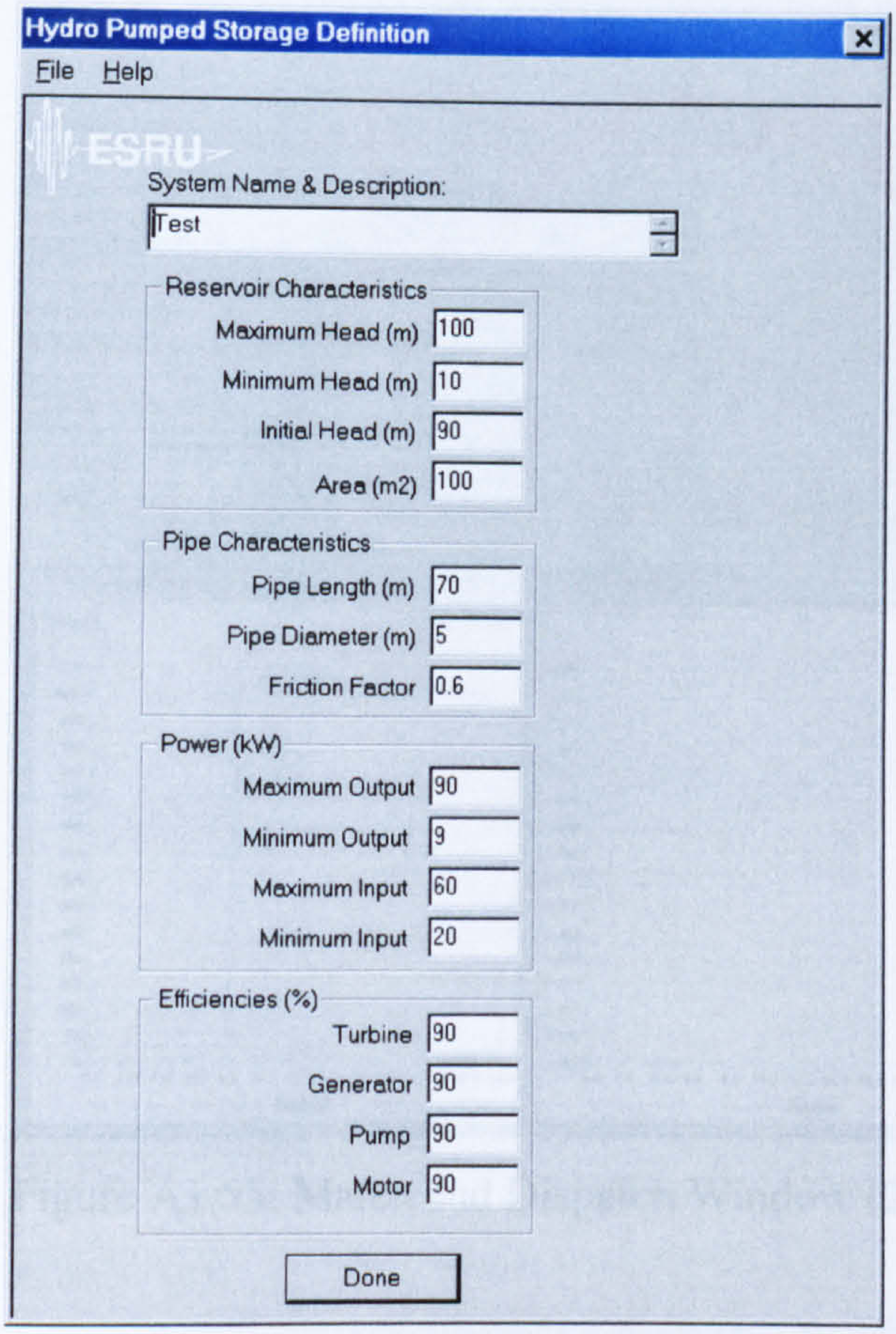
● Homogeneous

○ Composite

Geometry

- Flat unpierced disc
- Thin rim
- Shaped bar
- Rim with web
- Single filament bar

Figure A1.52: Flywheel System Definition Window



System Name & Description: Test

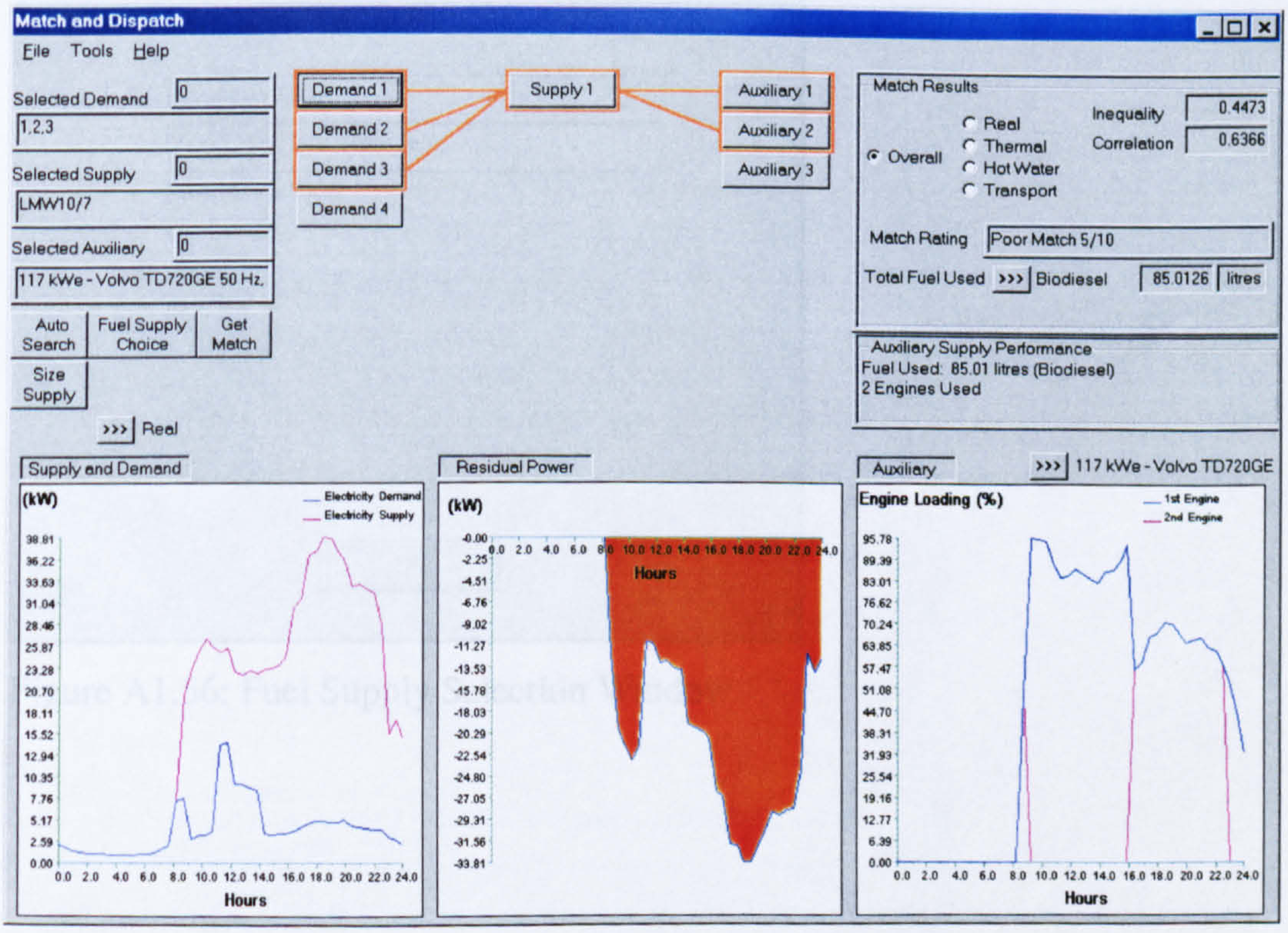
Reservoir Characteristics
Maximum Head (m): 100
Minimum Head (m): 10
Initial Head (m): 90
Area (m2): 100

Pipe Characteristics
Pipe Length (m): 70
Pipe Diameter (m): 5
Friction Factor: 0.6

Power (kW)
Maximum Output: 90
Minimum Output: 9
Maximum Input: 60
Minimum Input: 20

Efficiencies (%)
Turbine: 90
Generator: 90
Pump: 90
Motor: 90

Figure A1.53: Pumped Hydro System Definition Window



Selected Demand: 0
1,2,3

Selected Supply: 0
LMW10/7

Selected Auxiliary: 0
117 kWe - Volvo TD720GE 50 Hz.

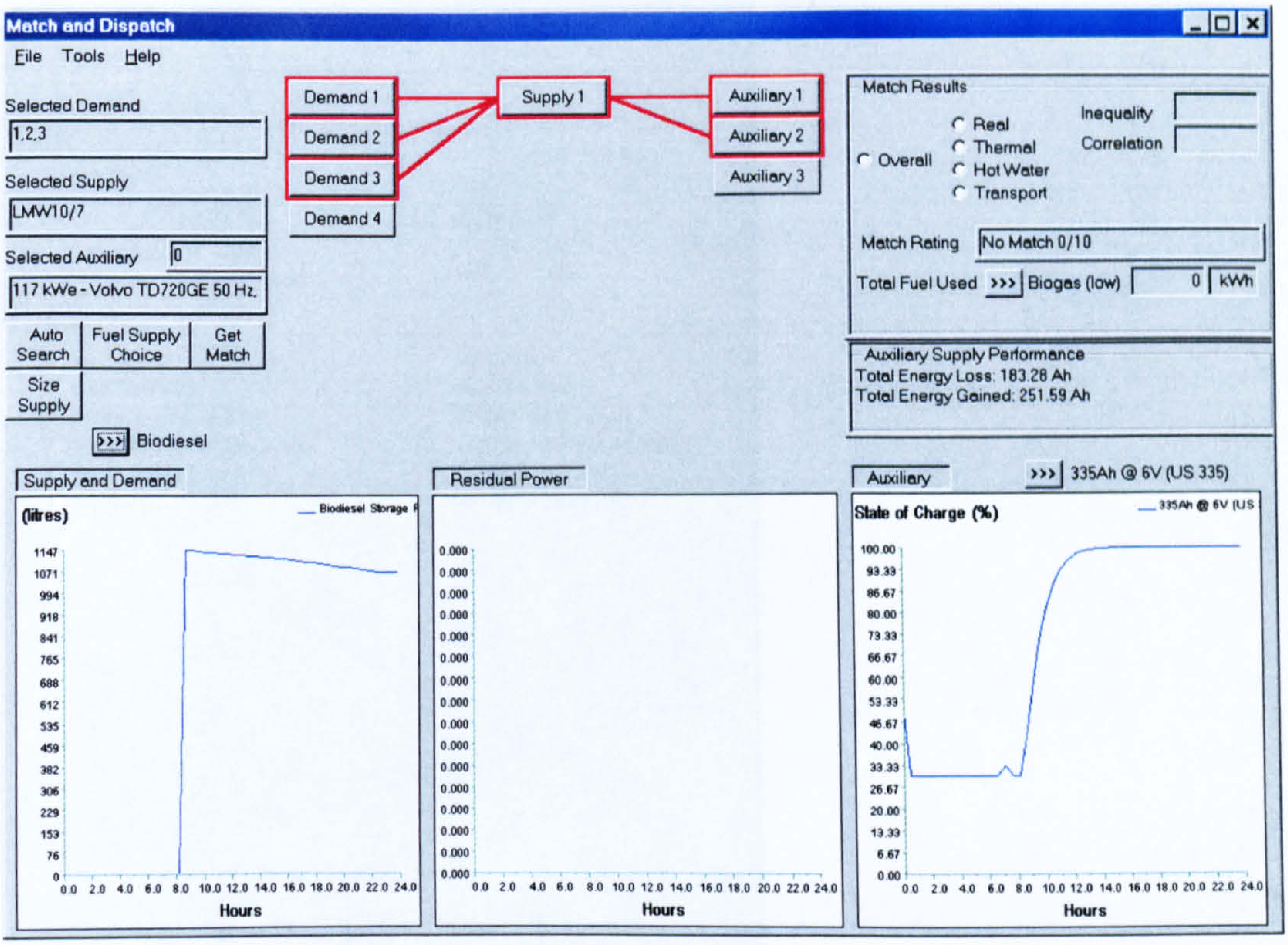
>>> Real

Match Results
● Overall
○ Real
○ Thermal
○ Hot Water
○ Transport
Inequality: 0.4473
Correlation: 0.6366
Match Rating: Poor Match 5/10
Total Fuel Used >>> Biodiesel 85.0126 litres

Auxiliary Supply Performance
Fuel Used: 85.01 litres (Biodiesel)
2 Engines Used

Auxiliary >>> 117 kWe - Volvo TD720GE

Figure A1.54: Match and Dispatch Window (1)



Selected Demand: 1,2,3

Selected Supply: LMW10/7

Selected Auxiliary: 0

117 kWe - Volvo TD720GE 50 Hz.

Biodiesel

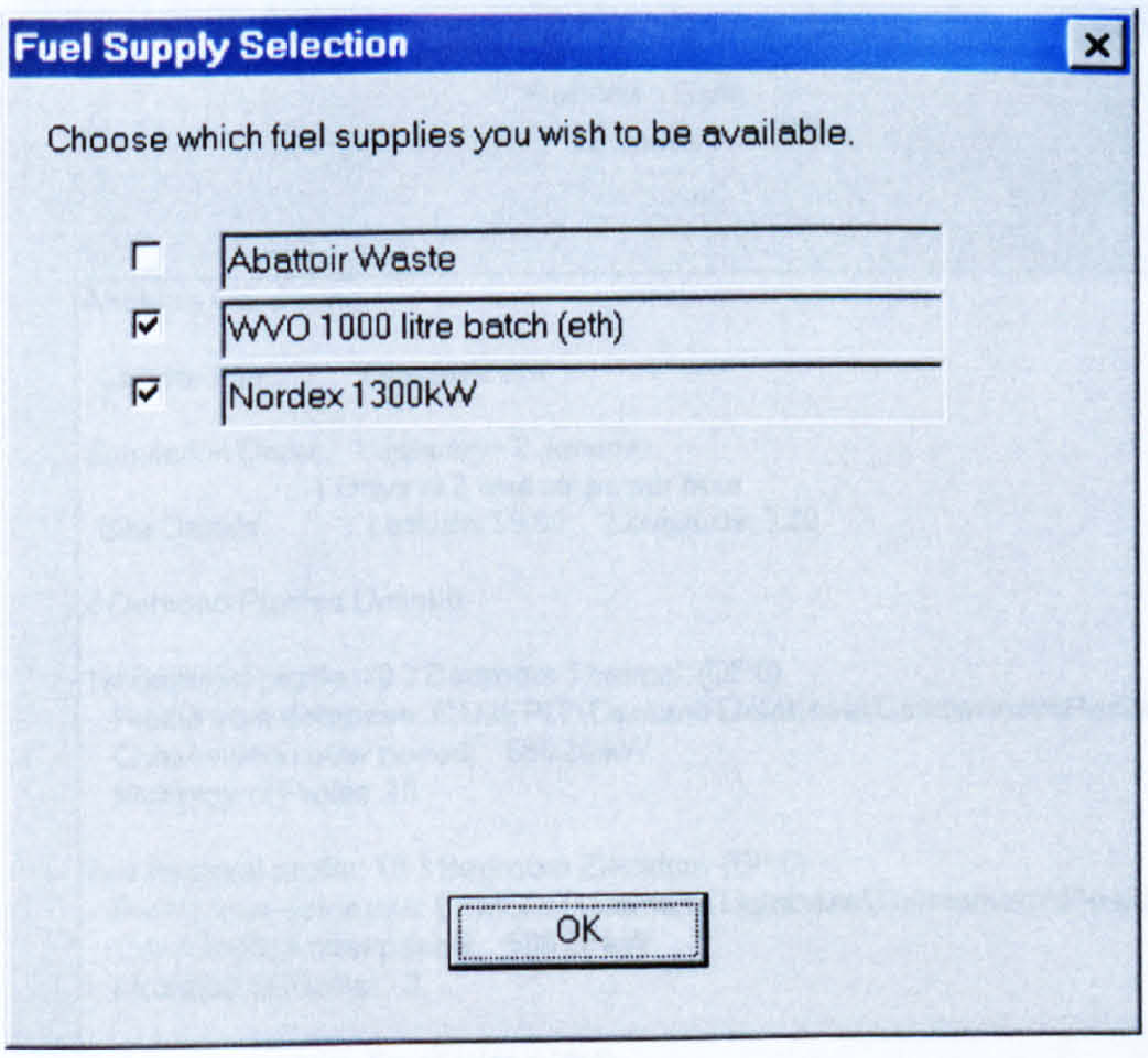
Match Rating: No Match 0/10

Total Fuel Used: Biogas (low) 0 kWh

Auxiliary Supply Performance
Total Energy Loss: 183.28 Ah
Total Energy Gained: 251.59 Ah

335Ah @ 6V (US 335)

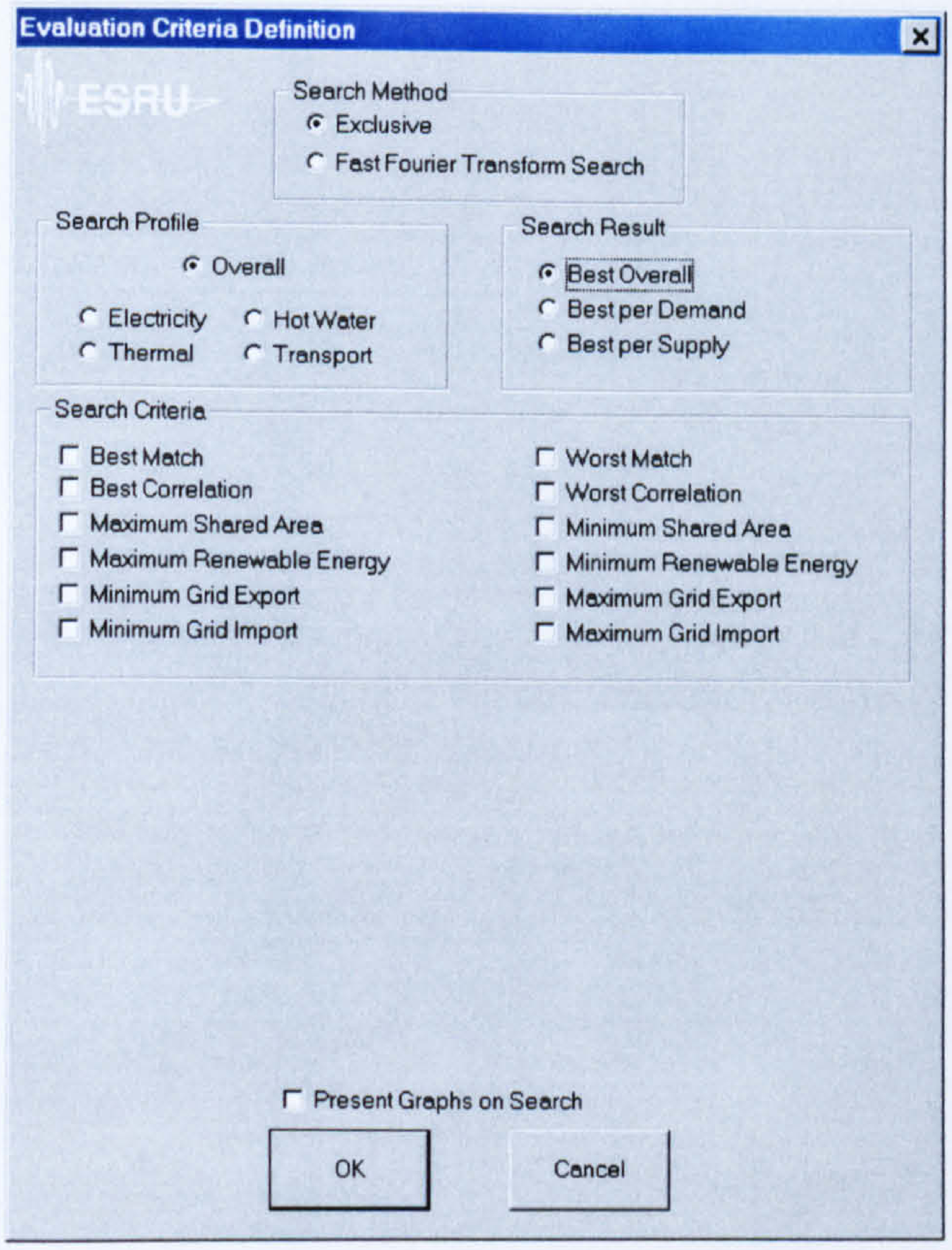
Figure A1.55: Match and Dispatch Window (2)



Choose which fuel supplies you wish to be available.

☐ Abattoir Waste
☑ WVO 1000 litre batch (eth)
☑ Nordex 1300kW

Figure A1.56: Fuel Supply Selection Window



Search Method
● Exclusive
○ Fast Fourier Transform Search

Search Profile
● Overall
○ Electricity
○ Hot Water
○ Thermal
○ Transport

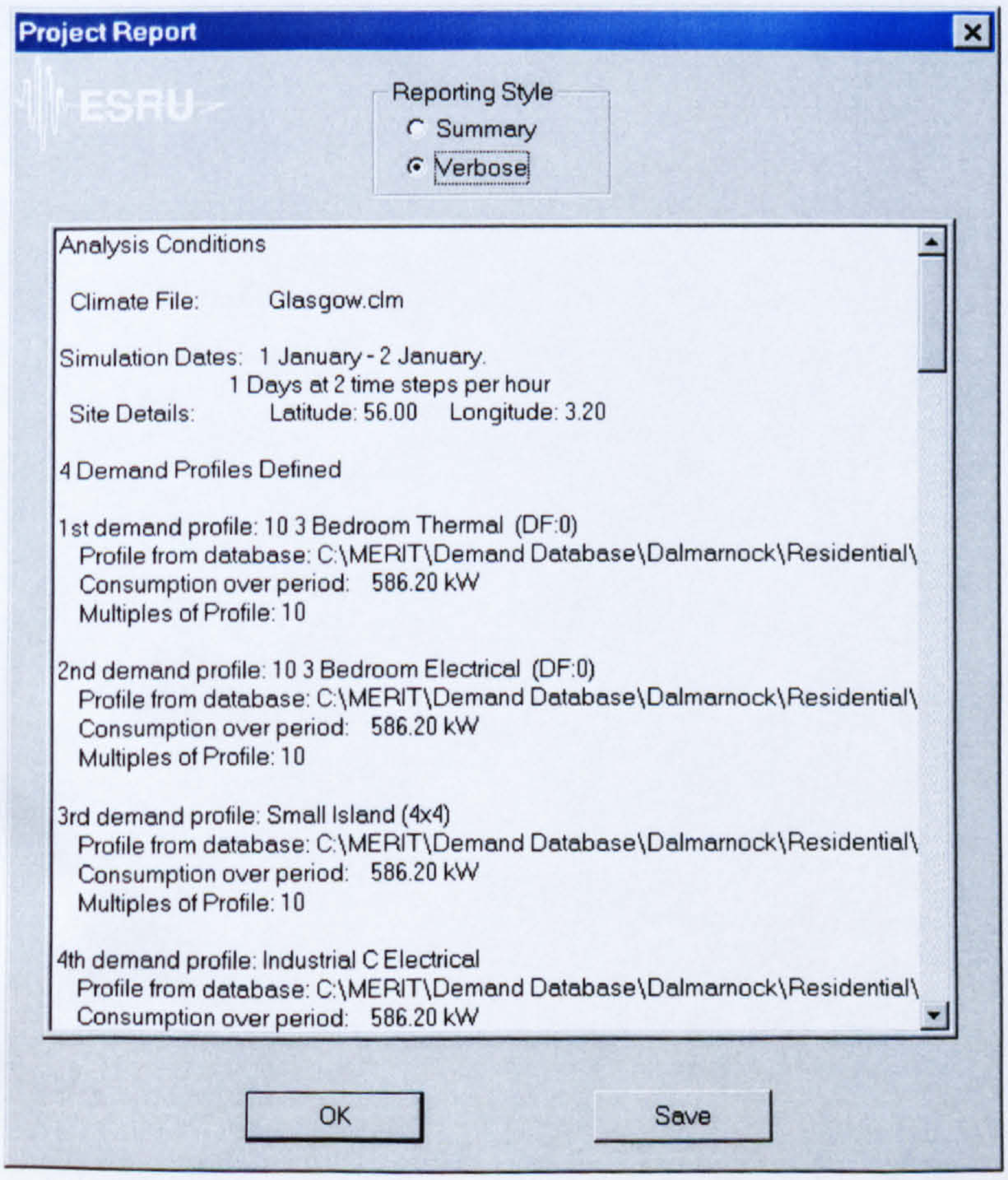
Search Result
● Best Overall
○ Best per Demand
○ Best per Supply

Search Criteria

☐ Best Match
☐ Best Correlation
☐ Maximum Shared Area
☐ Maximum Renewable Energy
☐ Minimum Grid Export
☐ Minimum Grid Import
☐ Worst Match
☐ Worst Correlation
☐ Minimum Shared Area
☐ Minimum Renewable Energy
☐ Maximum Grid Export
☐ Maximum Grid Import

☐ Present Graphs on Search

Figure A1.57: Auto Search Evaluation Criteria



Reporting Style
○ Summary
● Verbose

```
Analysis Conditions

 Climate File:         Glasgow.clm

Simulation Dates:  1 January - 2 January.
                 1 Days at 2 time steps per hour
 Site Details:         Latitude: 56.00     Longitude: 3.20

4 Demand Profiles Defined

1st demand profile: 10 3 Bedroom Thermal  (DF:0)
   Profile from database: C:\MERIT\Demand Database\Dalmarnock\Residential\
   Consumption over period:   586.20 kW
   Multiples of Profile: 10

2nd demand profile: 10 3 Bedroom Electrical  (DF:0)
   Profile from database: C:\MERIT\Demand Database\Dalmarnock\Residential\
   Consumption over period:   586.20 kW
   Multiples of Profile: 10

3rd demand profile: Small Island (4x4)
   Profile from database: C:\MERIT\Demand Database\Dalmarnock\Residential\
   Consumption over period:   586.20 kW
   Multiples of Profile: 10

4th demand profile: Industrial C Electrical
   Profile from database: C:\MERIT\Demand Database\Dalmarnock\Residential\
   Consumption over period:   586.20 kW
```

Figure A1.58: Project Report Window