DEVELOPMENT OF AN ANALYTICAL COMPUTER TOOL FOR BUILDING INTEGRATED RENEWABLE ENERGY AND CHP

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Abstract

This thesis describes a computer tool that was developed to compare different combinations of photovoltaic (PV) panels, solar thermal collectors and combined heat and power (CHP) technologies for building applications in order to find the option with the lowest cost of emissions reduction.

The novelty of this computer tool is that it addresses the uncertainty of building energy load profiles in the sizing of renewable energy and CHP technologies by applying the Monte Carlo Method. A database of historical building energy load profiles was collated for this purpose. However, little domestic hot water load profiles were found in the literature. Therefore, as part of this study, a survey was also carried out to collect some domestic hot water load profile data.

The domestic hot water demand survey consisted of a questionnaire and monitoring study. The questionnaire consisted of two parts: a general questionnaire about the dwelling and a diary study. The questionnaire collected general information about the dwelling, enabling the load profiles collected to be classified into different building type categories. In the diary study the hot water consumption patterns were recorded. The hot water energy consumption data was also obtained from direct monitoring using temperature sensors attached to the hot water pipes of the different appliances to record when and from which appliance hot water was used throughout the day in the dwellings. Load profiles were formed using this data and the data from the diary study in the questionnaire, together with typical hot water usage of different appliances. These were calculated from hot water usage times and typical flow rates of the different appliances that were recorded by a clamp-on flow meter. The load

profile data collected from the survey and the literature was loaded into the computer tool database.

The tool was developed in two Excel files each combining a different renewable energy technology (Photovoltaics and Solar Thermal) with CHP and the tool was programmed using Visual Basic for Applications (VBA) in Excel. The computer tool codes are executed in the following order:

1) Process building loads and load profiles
2) Size renewable and CHP technologies
3) Carry out economic and environmental analysis
4) Apply Monte Carlo method to determine the most probable outputs of each technology combination (only carried out if building energy load profiles are not known by the user)
5) Compare and analyse technologies or combination of technologies to facilitate the selection of the appropriate option.

The outputs consist of a technical analysis, economic analysis and environmental analysis and a price tag on the emissions savings (£/kgCO_2 saved). The computer tool can therefore be used to compare several combinations of renewable energy/CHP technologies and provide project energy managers with required technical, economical and environmental data to facilitate making vital long term investment decisions.

To test the computer tool and its accuracy, a case study was used to run the tool and was compared to sample manual calculations of the tools calculation procedures. The example building with a total floor area of 1750m^2 consisted of three clusters of 5 two-bedroom flats of 100m^2 each, 15 one-bedroom flats of 50m^2 each, and 500m^2 of office space with occupancy capacity of 50 people. Three main technologies were considered in different combinations: combined heat and power, solar thermal collectors for hot water and photovoltaic panels for electricity generation.

Depending on the overriding objectives of a project, usually two scenarios are presented: a) maximising return on investment (i.e., short payback period) or b) reducing CO_2 emission at the expense of higher capital cost and longer payback period. Hence, it was concluded that if the project is driven by the cost of energy generation, then using Combined Heat and Power in combination with a back up boiler and grid electricity would make the best investment returns. If the reduction of CO_2 emissions is more important, then the option of incorporating renewables with or without CHP would be a more attractive proposition. However, the option of incorporating renewables and CHP would offer the better solutions if both cost of energy generation and CO_2 emissions are important.

Acknowledgements

I dedicate this thesis to my daughter Yasmeen.

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Nomenclature

A_{sc}	Collector area (m^2)
A_f	Floor area (m^2)
$CC_{current}$	Current capital cost (£)
CCHP	Combined cooling heat and power
CCL	Climate Change Levy
CC_{NPV}	NPV capital cost (£)
$CC_{NPVreplacement}$	NPV replacement cost (£)
CHP	Combined heat and power
$C_{NPVtotal}$	Total NPV cost (£)
CO_2	Carbon dioxide
c_p	specific heat capacity (J/gK)
$DC_{current}$	Current disposal cost (£)
DCF	Discounted cash flow
DC_{NPV}	NPV Disposal cost (£)
D_e	Electricity demand (kWh)
D_{ep}	Pump electricity consumption (kWh)
D_g	Gas demand (kWh)
D_h	Heat demand (kWh),
$D_{H,p}$	Peak heat demand (kW)
DR	Discount rate (%)
EC_{boiler}	Boiler system energy cost (p/kWh)
EC_{EGrid}	Electricity grid energy cost (p/kWh)
E_{CO2}	CO_2 Emissions (kg CO_2)
EC_{system}	System energy cost (p/kWh)
EETS	European Emissions Trading Scheme
EF_e	Electricity emission factor (kg CO_2/kWh)
EF_g	Gas emission factor (kg CO_2/kWh)
EGrid	National electricity grid
EPBD	European Energy Performance of Buildings Directive
ESC	System cost per emissions saved (£/kg CO_2 saved)

F	Factor related to the effectiveness of the heat transfer from the collector plate to the heat removal fluid
f	monthly factor to take into account the varying demand throughout the year
f_E	CO_2 emissions factor ($kgCO_2/kWh$)
$FC_{current}$	Current annual fuel cost (£)
FC_{NPV}	NPV Fuel cost (£)
FI	Annual fuel input (kWh)
H	Number of operating hours (hours)
I_s	Incident solar radiation normal to the collector (kWh/m^2)
kW	Kilowatt
kWh	Kilowatt hour
kW_{th}	Kilowatt thermal
l	litres
(1- L)	efficiency of the power conditioner, transformer, interconnection (%)
m^2	square meters
$MC_{current}$	Current annual maintenance cost (£)
MC_{NPV}	NPV Maintenance cost (£)
n	Project lifetime (years)
NPV	Net present value
O	Output (kWh)
O_A	Annual output (kWh)
O_L	Lifetime output (kWh)
O_{NPV}	NPV output (kWh)
P_p	Pump power rating (kW)
PV	Photovoltaics
Q	Useful heat collected per unit area (W/m^2)
Q_E	Energy (J)
Q_{sc}	Collector output rating (kWh)
RET	Renewable energy technologies
ROC	Renewables Obligation Certificate
RoT	Rules of thumb
S_b	Boiler size (kW)
S_{PV}	PV size (m_2)

ST	Solar thermal system
T_a	Ambient temperature (°C)
T_m	Average collector temperature (°C)
U	Heat loss coefficient (W/m^2K)
VBA	Visual Basic for Application
WD	Weekday
WE	Weekend day
ΔT	Temperature difference (K)
η_b	Gross boiler efficiency (%)
η_{PV}	Efficiency of the PV cells (%)
η_{sc}	Collector efficiency (%)
$(\tau\alpha)$	Transmittance-absorptance product

Chapter 1:

Introduction

The use of renewable energy technologies and CHP in the built environment is becoming increasingly more important. However the initial design of renewable energy (RE) and CHP systems tends to be more complicated and time consuming than the design of traditional energy systems. As opposed to “conventional” fossil fuelled energy systems, the sizing of renewable energy and CHP systems energy requires building energy load profiles, which however are not easily predicted.

The main objectives of this study are:

- To develop a computer tool to enable suitable combinations of renewable energy technologies and combined heat and power (CHP) systems to be selected for a building. The tool optimises the integration of the combined technologies for the supply of electricity, space heating and hot water to different building types and helps in the selection of the more appropriate technologies. The Monte Carlo Method (MCM) is used to take into account the uncertainty of load profiles in the computer tool to give most probable sizes and costs of different technology combinations.
- To conduct a survey to collect domestic hot water demand profiles for residential buildings.

Chapter 2 describes the background and literature review to this PhD study. CHP and solar thermal and PV technologies are discussed, along with their sizing procedures and the relevant policies for CHP and RETs. Analysis tools and the decision making process in selecting appropriate technologies are also reviewed in this chapter. The review shows that there is not a tool currently available that selects suitable combinations of CHP and RETs for a project, taking into account the uncertainty of building energy load profiles using the MCM.

Chapters 3 discusses the importance of building energy load profiles for the sizing of RETs and CHP technologies; and the Monte Carlo Method is presented as a method to take into account the uncertainties of load profiles. Load profile data was collected to form a database to be used in the computer tool and a hot water demand survey was carried out to collect profile data for residential buildings.

Chapter 4 describes the methodology and the outline of the tool developed in this PhD study. The tool is being programmed using Visual Basic for Applications in Excel. Excel was selected, because it is widely available for designers and used with most Windows based applications.

Chapter 5: The developed computer tool is tested by carrying out a sample calculation and using the tool to simulate a number of possible scenarios of CHP/ RET integration for an example mixed office and residential use building. The results from this example are analysed and the tool's advantages and limitations are discussed.

Chapter 6 presents the conclusions of the study and recommendations for further work.

Chapter 2:

Literature Review

2.1 BACKGROUND

"The nature and pattern of our built environment both shapes and is shaped by energy issues" (RICS Foundation 2004)

Buildings have energy demands in the form of electrical power, heat, and cooling. Traditionally, these are provided separately by the national electricity grid, boilers and air-conditioning systems respectively which are predominantly fuelled by fossil fuels. Fossil fuels constitute the main part of the UK primary energy supply and their overall consumption has increased over the years as shown in Figure 2.1. It can also be seen that there is a marked decrease in the use of coal and an increase of energy produced by natural gas and oil over this same period as a result of the UK government's policy on climate change and pollution control.

The increasing demand for fossil fuels worldwide not only has the effect of releasing CO_2 and other emissions in large quantities, which result in environmental pollution and global warming, but also accelerates the depletion rate of these resources (IPCC 2001). There is a strong consensus among energy producers and researchers that fossil fuel supplies could be peaking, with the likelihood of a shortage of supplies in the near future (Salameh 2003). This has been demonstrated recently by a substantial increase in the prices of oil and gas with negative effect on the world economy (see Figure 2.2).

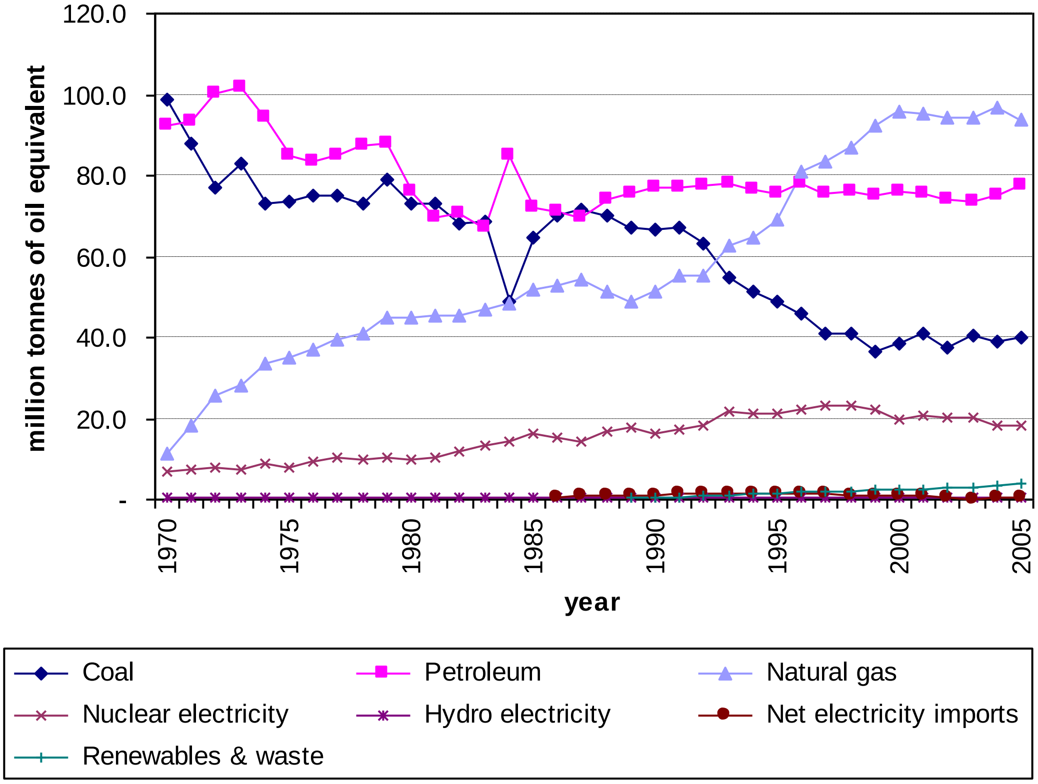


Figure 2.1 UK Final Energy Consumption, by Fuel, 1970 to 2005 (BERR 2007)

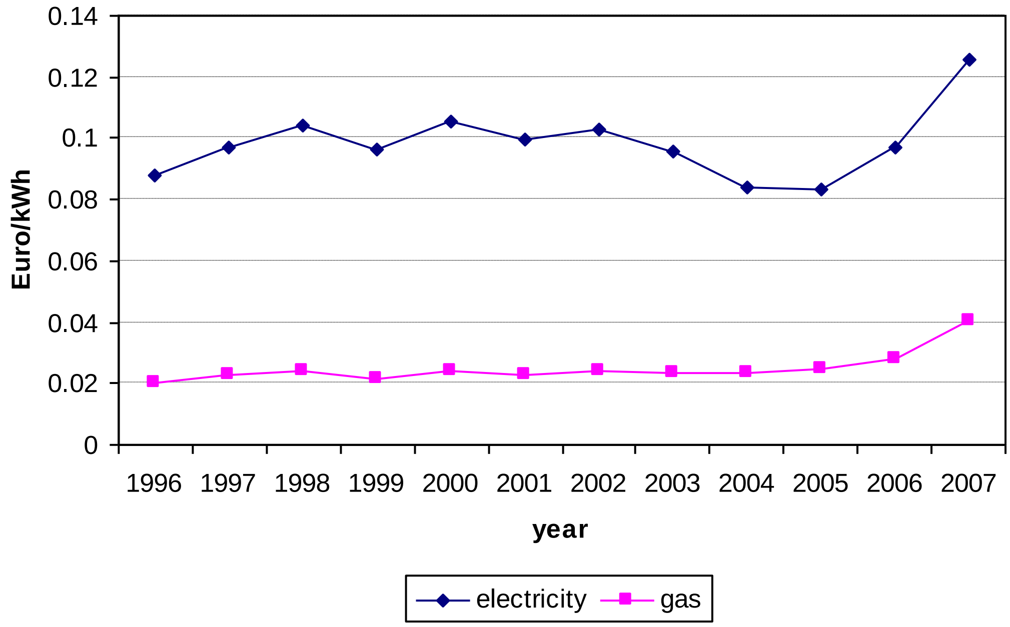


Figure 2.2 UK energy prices (Eurostat 2007)

Alternative energy sources will therefore need to be developed to satisfy future energy demand. Renewable energy sources could be exploited directly by converting solar radiation or water power into electrical power or indirectly through the use of hydrogen as fuel. Figure 2.3 summarises some of the different energy sources available.

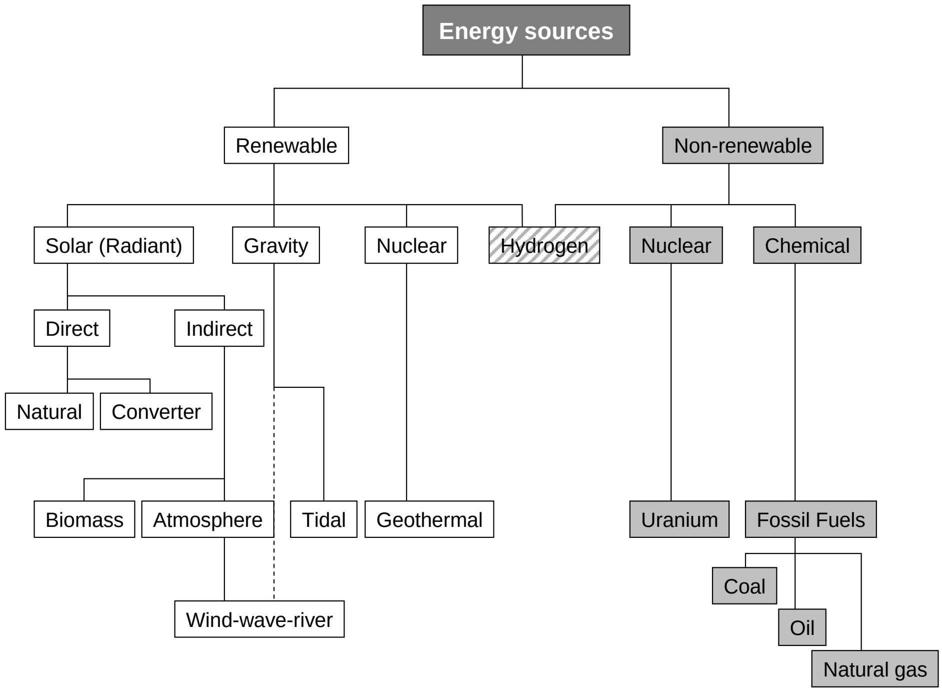


Figure 2.3 Energy Sources [adapted from Chapman (1989)]

Although the cost of generating power from renewables is currently higher than generating power from fossil fuels (see Figure 2.4), the increase in fossil fuels cost could play a major incentive in the push to developing more sustainable processes and technologies. However, government policies and mechanisms encouraged by agreements such as the Kyoto Protocol (UNFCCC 1997) are the key to achieving this transition.

Figure 2.5 shows that domestic buildings are the second biggest energy users in the UK after the transport sector, with 29% and 37% respectively. The need to reduce

CO_2 emissions from buildings is therefore essential if the UK is to meet its target outlined in its Energy White Paper to reduce CO_2 emissions by 60% below the 1990 level of 584 million tonnes by the year 2050 (DTI 2003, Office for National Statistics 2007).

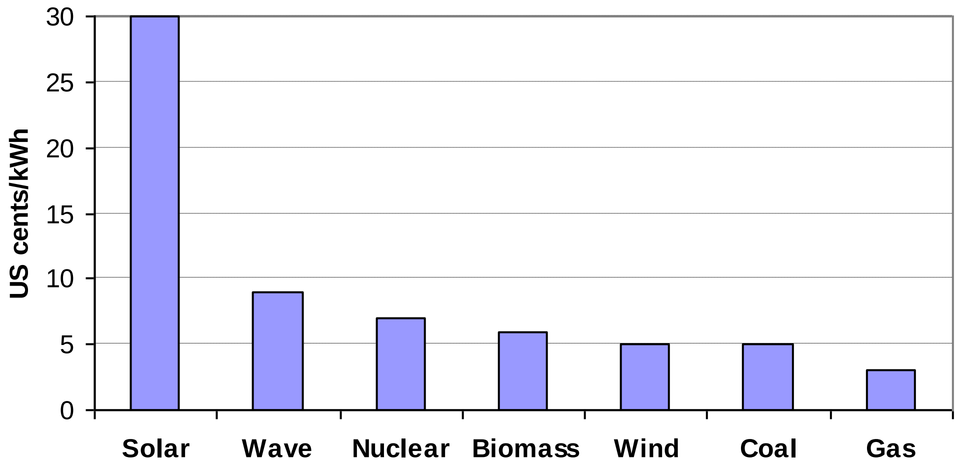


Figure 2.4 Typical costs for electricity generation (Gross et. al. 2003)

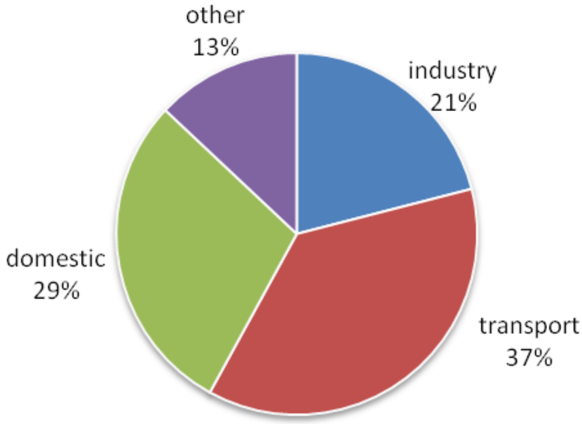


Figure 2.5 UK Use of Fuels in 2006 (BERR 2007)

The reduction of CO_2 emissions of buildings can be achieved by using energy efficient appliances, management of energy demand side, and introducing higher building regulation standards such as air tightness, level of thermal insulation, on-site renewable energy generation, etc...(Chwieduk 2003).

The efficient use of fossil fuels and renewable energy systems should be a prime concern in the supply of energy to buildings. The UK produced the largest amount of energy in Europe after Norway in 2005 which is a result of oil exploration from the North Sea (Figure 2.6). It can also be seen from Figure 2.6 that the share of renewables remains relatively small in most countries of the European Union (EU).

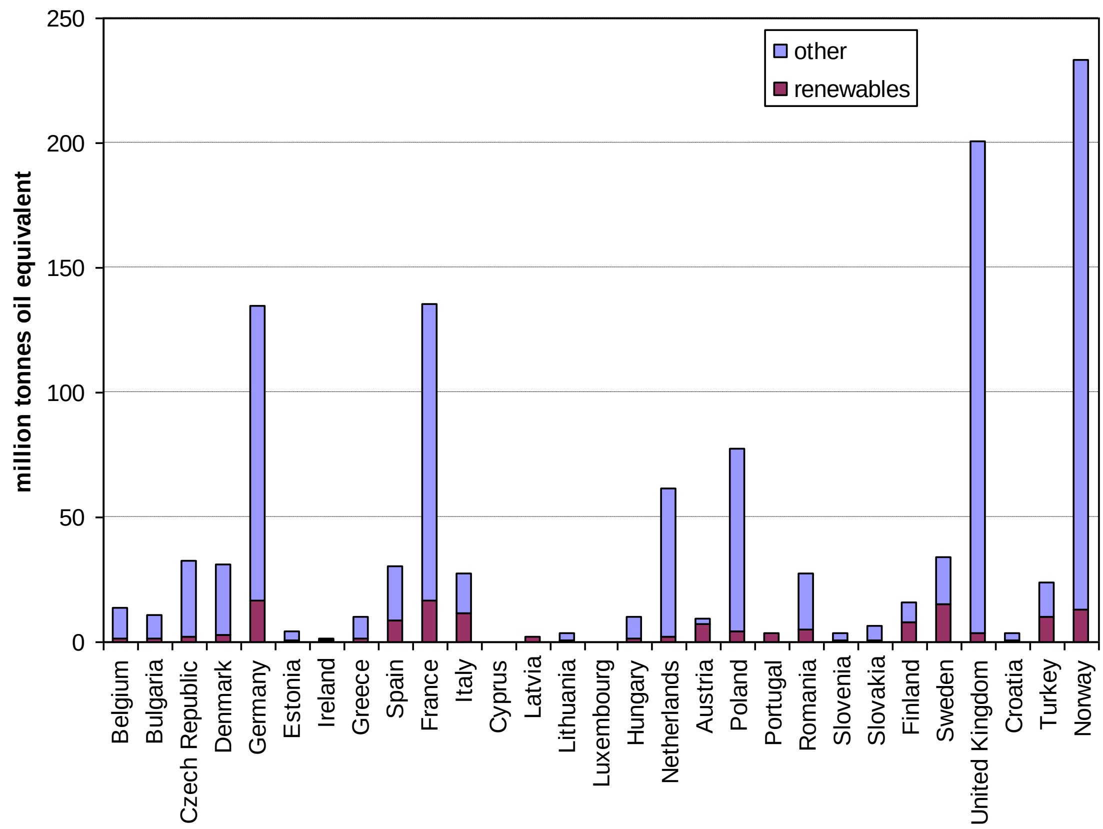


Figure 2.6 European primary energy production in 2005 (Eurostat 2007)

Figure 2.7 shows that not all the energy consumed was also produced in the same country. With the exception of Norway all other EU countries are net importers of energy, mainly oil and gas.

Figure 2.8 shows that there is a substantial effort being made to generate power from renewables in all EU countries. Although the UK is one of the largest energy producers and consumers in the EU, its share of energy production from renewable sources was one of the lowest. Germany, France and Sweden have the highest proportion of energy produced from renewable sources. Figure 2.8 also suggests that most of the renewable energy produced in each country tends to be used nationally.

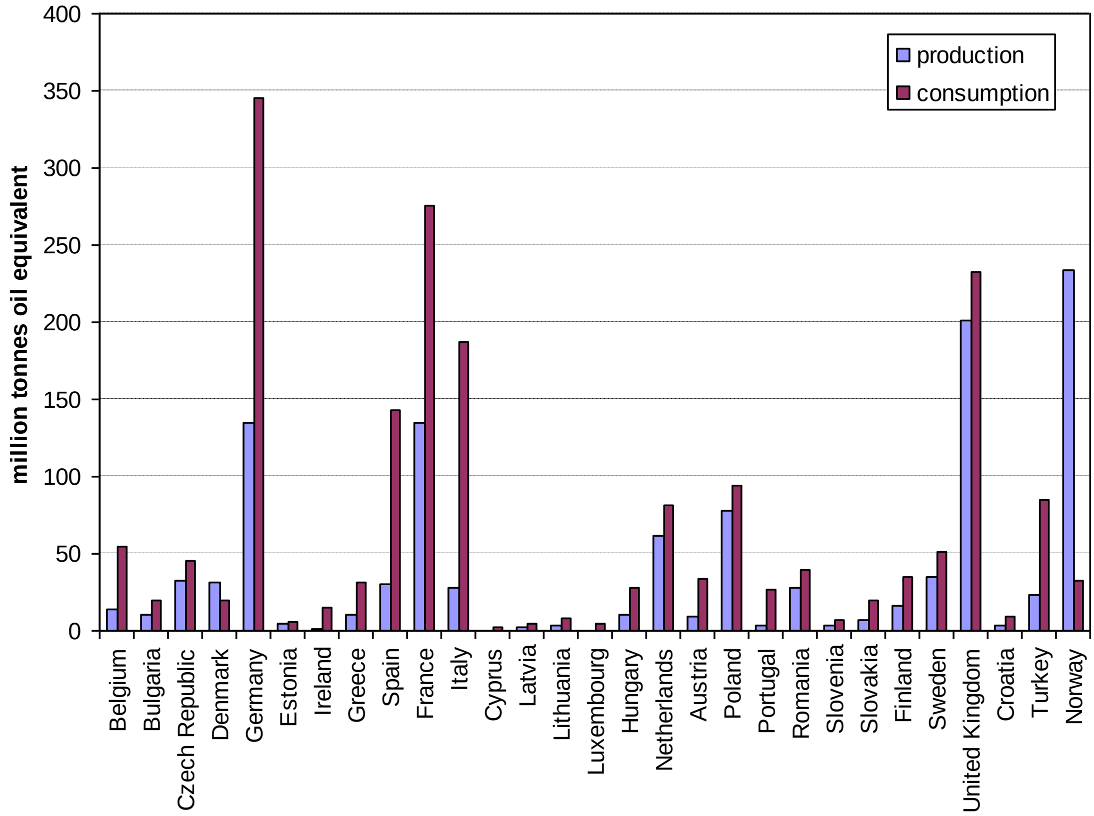


Figure 2.7 European energy production and consumption in 2005 (Eurostat 2007)

Sims et. al. (2003) compared the carbon emissions and mitigation costs from electricity generation and showed that there were alternative ways of generating electricity cost-effectively combined with carbon emission reduction. The comparison was made between standard gas or coal fired power stations and more efficient power generation from fossil fuels, the use of renewable energy or nuclear power and the capture and disposal of CO_2. Figure 2.9 shows the average cost of carbon reduction ($/t Carbon avoided) of some of these technologies. However the choice of technologies in terms of cost savings and carbon emission reductions is site and application specific. Sims et. al. (2003) stated that through the application of some of these technologies the global energy sector has the potential to reduce carbon emissions by 8.7-18.7% by 2020 compared to 27 136 Mt of CO_2 emissions in 2003 (IEA 2007).

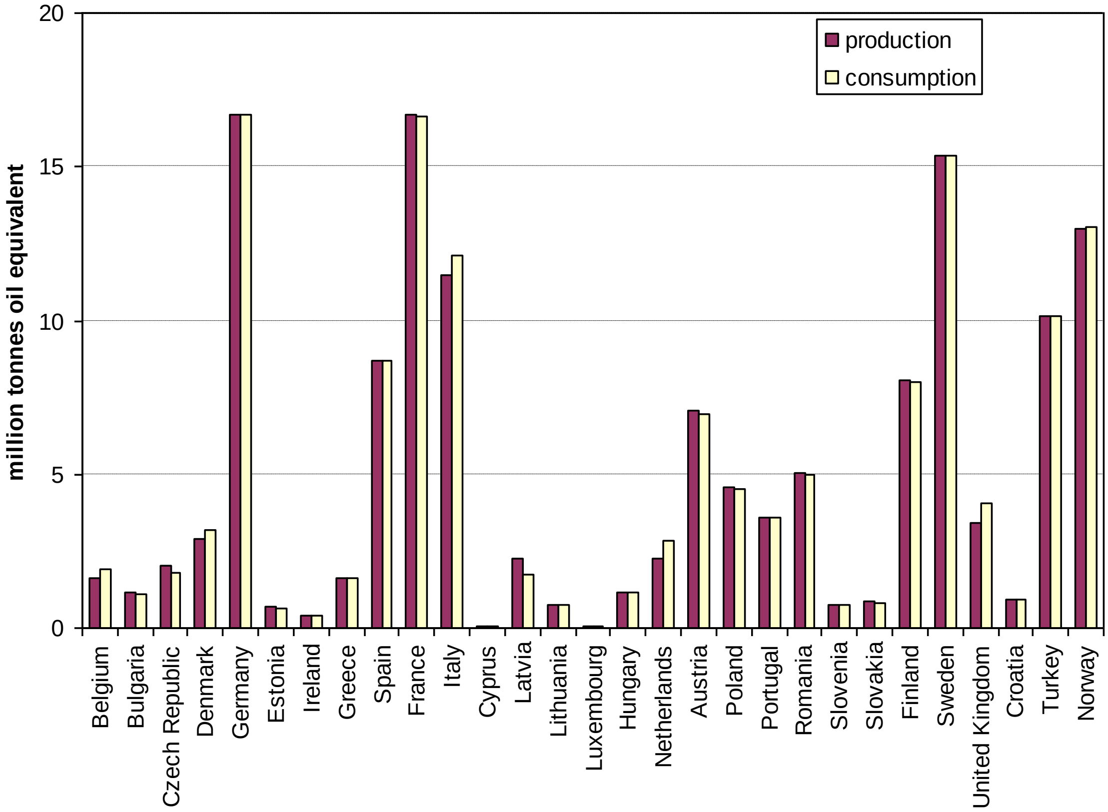


Figure 2.8 European renewable energy production and consumption in 2005 (Eurostat 2007)

Sims (2004) considers how placing a value on carbon emissions could help the adoption of renewable energy technologies to reduce the effect of climate change. External costs (the associated cost to the environment and health) are not usually taken into account when comparing the costs of energy systems. However if taxes are enforced to take into account external costs, renewable energy technologies are likely to become economically more viable.

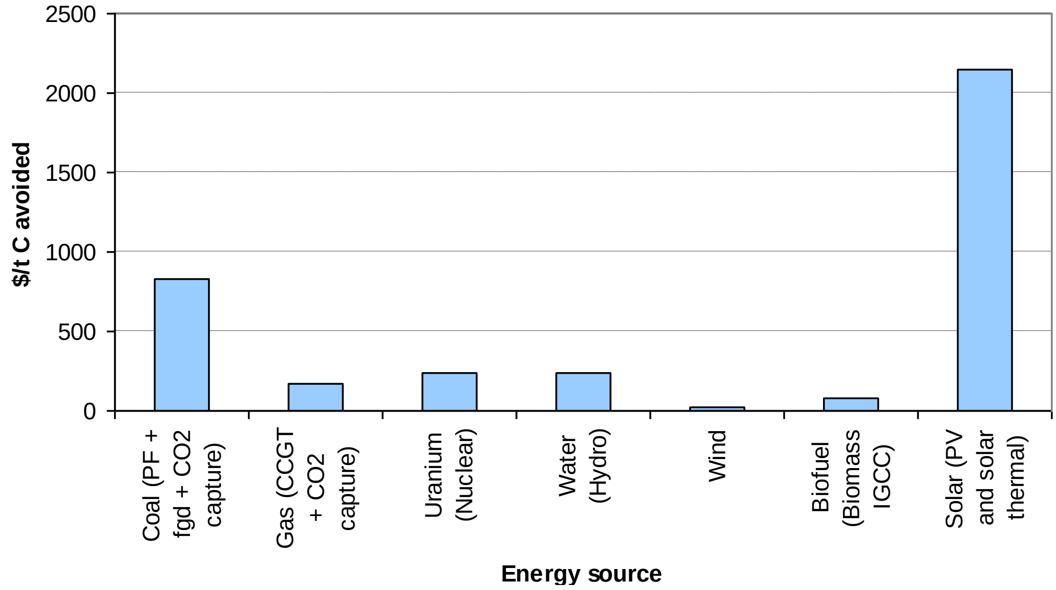


Figure 2.9 Cost of carbon reduction of mitigation technologies in the power generation sector compared to gas-fired power stations (Sims et. al. 2003)

Given that a large proportion of energy consumption is in buildings, Figure 2.10 shows methods of integration of energy technologies in buildings, either direct as stand alone systems, through community grids or via the national grid.

Integrated into buildings, renewable energy and combined heat and power (CHP) technologies could be used to reduce the CO_2 emissions of buildings. Watson (2004) discusses that payback periods for micro-generation are usually too long for most energy companies. However, payback periods could be more acceptable to consumers having to replace their existing energy technology, such as replacing a faulty boiler with a micro-CHP system for example. This research work focuses on the direct integration of renewables and CHP with buildings with any surplus electricity production being exported to the national electricity grid. However large scale electricity export to the national electricity grid results in a variety of issues that require careful consideration.

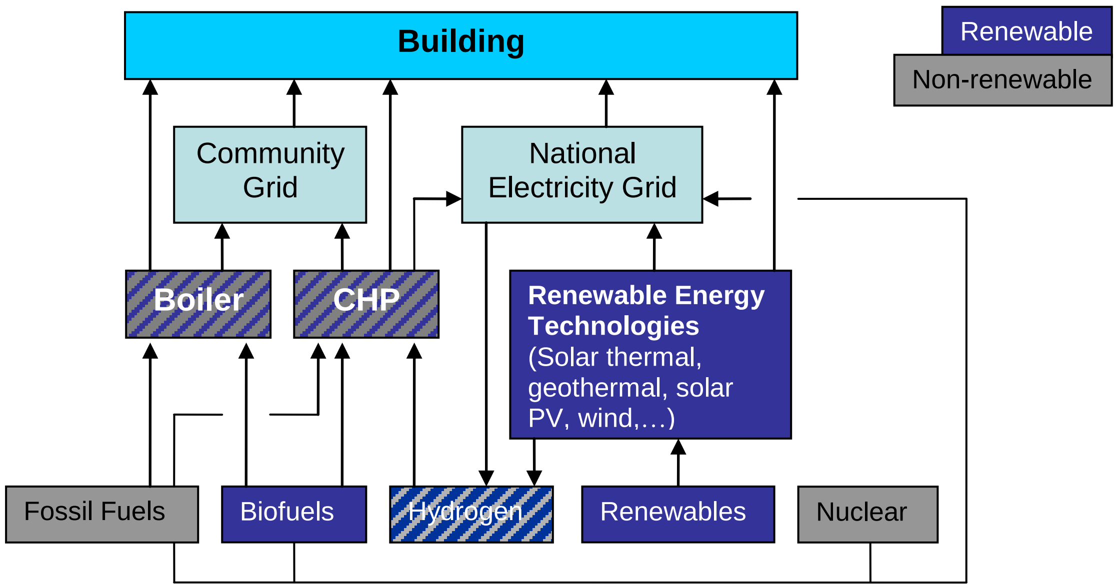


Figure 2.10 Integrating Energy Technologies with Buildings

Renewables and CHP can make a contribution to the security of electricity supply by diversifying the electricity mix (DTI 2007). Wu et. al. (2004) investigated the impact of CHP and renewables on the UK transmission network, distribution network, central generating system and regulatory policy. The conclusion was that the UK national electricity grid could accommodate the Government's targets of 10% renewables and 10GWe CHP by 2010. However in order to achieve this, modifications to the distribution grid and to the regulatory framework would be required.

Currently, large "central power stations" feed directly into the national high voltage grid. In the case of smaller systems, electricity system operators need to consider intermittency, decentralisation of generation, and remoteness of some generation options associated with renewables. Most renewable generation is intermittent and relatively unpredictable. As more renewable energy is utilised intermittency becomes more of an issue. Additional storage and upgrading of transmission lines would be required as renewables generation increases. However, others have undertaken studies to investigate various options that could be applied to enable the smooth integration and increased uptake of renewables and CHP into the national energy supply system (Wu et. al. 2004).

Decentralised energy systems are usually in close proximity to the demand, supplying power directly to local distribution networks and therefore requiring careful management of local networks. Decentralised energy systems require a strong local grid and centralised energy systems require a strong national (transmission) grid. Since national transmission grids are of higher voltages than local grids, the use of decentralised energy systems could therefore avoid large losses associated with transmission grids (Lund et. al. 2000) as well as avoiding reinforcements of the existing national transmission grid.

Abu-Sharkh et. al. (2005) investigated the viability of microgrids consisting of Micro-CHP and PV in the UK. They concluded such microgrids could avoid the need to replace coal and nuclear power stations and reduce the demand on the transmission and distribution network by being independent of the national electricity grid. This conclusion was also reported by Voorspools et al (2002) who investigated small CHP for residential applications. They concluded that careful planning of such systems can reduce the need to expand the national electricity grid.

This PhD study considers the application of building integrated CHP and renewable energy systems. The immediate proximity of the energy source to the energy demand avoids transmission losses and the on site use of energy avoids major reinforcements of the national grid. However, decentralised micro energy systems such as micro-CHP and renewables could result in increased variations of the national grid load profile which might as previously discussed, result in a need to upgrade existing transmission lines. This could compromise overall carbon savings if not integrated in national energy policies (Peacock et. al. 2006).

2.2 UK AND EU POLICIES

2.2.1 Policies on Renewables

Christiansen (2002) showed the important link between public policies and the development of new and renewable energy systems. EREC (2004) considered how different policies can lead to the consideration of different renewable energy scenarios. Both studies showed that a minimal employment of renewable energy was mainly the result of weak demand-side policies, changes in public priorities and low electricity prices.

Goldemberg et. al. (2004) examined how adequate policies can be used to encourage the introduction of renewables, taking Brazil as a case study. Cosmi et. al. (2003) advised the use of suitable price mechanisms, regulatory instruments and informative campaigns to promote technology innovation and a larger use of renewable energy. Meyer (2003) argued that in European countries at present, free trade is emphasised and this hinders the long term planning of sustainable energy development. Morthorst (2003) investigated national environmental targets and international emission reduction instruments for the introduction of renewable energy. He concluded that a closely coordinated combination of an international tradable permit market and a green certificate market could achieve national greenhouse gas reduction targets. Options to support the development of renewable energy include:

public funding for R&D and dissemination programmes, public procurement, direct state subsidy, fiscal incentives, and statutory obligations on electricity suppliers (Gross et. al. 2003).

Kwant (2003) investigated the policies and instruments in The Netherlands, and concluded that renewable energy trading in a European market requires European harmonisation of energy policies. The European Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market (EC 2001) was developed as a basis for creating such a Community framework. The Commission's overall target is 22% of electricity from renewables by 2010. Under this directive each country is required to commit to an individual target for renewable energy. The UK's target is 10% of electricity from renewables by 2010. In conjunction with the target, guarantees of origin are issued to ensure the electricity is generated from eligible renewable energy sources. In the UK the 2003 Electricity Regulations have implemented the renewable energy guarantees of origin (REGOs) that are issued by Ofgem (electricity and gas markets regulators in the UK).

The UK government Energy White Paper (DTI (2007) outlines a long term energy strategy for the UK. Four objectives are outlined:

i) A target of 60% CO_2 reduction by 2050 from 1990 figures, with real progress by 2020
ii) Maintaining energy supplies reliability
iii) Promoting competitive markets and improving productivity
iv) Ensuring every home is adequately and affordably heated.

Programmes and mechanisms introduced in the UK, in conjunction with EU programmes for funding the development of low carbon energy technologies, include: direct government expenditure (such as R&D grants), legislative requirements for energy supply companies, allowances against mainstream taxation (such as enhanced capital allowances), and measures associated with the UK climate change levy (including the Emissions Trading Scheme). DTI (2004) reports the current UK renewables policy as consisting of the following four elements:

i) The Renewables Obligation binds all electricity suppliers in the UK to supply a specific proportion of electricity produced by renewable sources. The aim is to increase this proportion to 10% by 2010 and to 15% by 2015.
ii) Exemption from the Climate Change Levy (CCL) for electricity produced from renewables.
iii) Expansion of the support programmes for new and renewable energy including capital grants and an expanded R&D programme.
iv) Initiation of a regional strategic approach to planning and targets for renewables development.

Under the EU Climate Change Agreements the European Council agreed binding targets of 20% renewable energies in overall EU consumption and 20% reduction of greenhouse gas emissions by 2020 (DTI 2007). There has been an increase in the use of renewables in the UK (see Section 2.4), however the 10% target outlined in the Renewables Obligation has yet to be achieved (Figure 2.11). The Renewables Obligation can be met by suppliers by acquiring Renewable Obligation Certificates (ROCs), paying a buy out price of £34.30 per MWh (DTI 2007), or a combination of both.

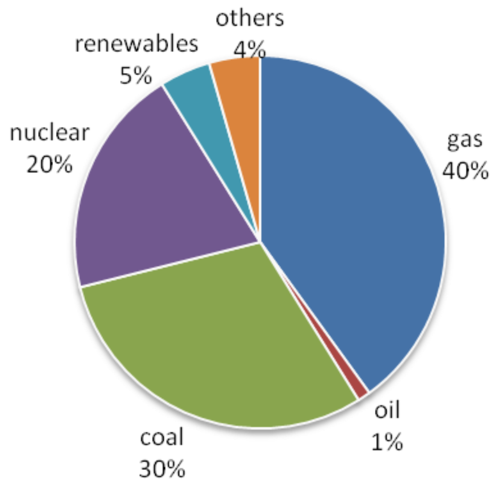


Figure 2.11 UK electricity mix in 2006 (DTI 2007)

The CCL is a tax on the use of non-renewable energy in industry, commerce and the public sector. Renewable energy is therefore exempt from this tax.

The UK government launched its Microgeneration Strategy in 2006 to encourage microgeneration and make it a realistic option for households, communities and small businesses. The Strategy includes planning procedures adapted to encourage microgeneration, an accreditation scheme for installers and products and the Low Carbon Buildings Programme which provides grants for microgeneration technologies (IEA 2007). Total funding for new and renewable energy from 2002 to 2008 is £500 million. Grants for research and development are given under the Technology Programme and BERR's Grant for Research and Development to help businesses and individuals develop technologically innovative products and processes. This includes funding for new and renewable energy. Capital grants are available to fund demonstration projects to help reduce their costs and risks. The Capital Grants Scheme includes the Low Carbon Buildings Programme which provides grants for micro-generation technologies (BERR 2007).

Regional renewable energy targets are being set according to the regions' renewable energy potential and are to be reflected in the regional planning policies. The 'Merton Rule' sets a target of the use of onsite renewable energy to reduce annual CO_2 emissions for all new major developments by 10% and was first implemented in the London Borough of Merton (Merton Rule 2008). Other local authorities have followed and/or are expected to follow Merton's lead.

Anderson et. al. (2003), however, points out a lack of clarification of targets and mechanisms for implementing the UK government's strategies and a lack of sufficient detail on which policies would achieve the targets set in the 2003 Government White Paper. Other points noted were that the time-frame for change was limited, the impact of economic growth on energy consumption was not examined, and improvements in energy-efficiency and renewables uptake would not necessarily lead to reductions in energy demands and use of fossil fuels. Also, the national statistics of energy consumption, on which the Energy White Paper is based, did not account for emissions associated with imported goods, and there is a need for regulations to be set that require all sectors to achieve absolute emissions reductions. Anderson et. al. (2003) also suggested that other issues in the White Paper were open for discussion and therefore inhibit the momentum of change. For example, although the White Paper announced a tightening of building regulations, this does not include energy efficiency improvements on existing building stock, which account for a large amount of emissions.

Wordsworth et. al. (2003) carried out an analysis on the UK government energy-efficiency programmes and concluded that although most programmes were cost effective, supply side measures were reliant on future cost reduction of technologies.

However, the study also reported that as most programmes had not been in place for long it was therefore too early to fully assess their effectiveness.

Shackley (2007) outlined other policies that could encourage the use of renewable and CHP in the UK. As well as the government policies outlined above they included the EU Emissions Trading Scheme, a target for installation of 10GWe CHP capacity by 2010, the Energy Efficiency Commitment, the Carbon Abatement Technologies Strategy, and increased RD&D into low- and zero-carbon technologies.

2.2.2 Policies on CHP

The European Directive 2004/8/EC (EC 2004) and the UK governments Carbon Emission Reduction Target 2008-11 aim to promote and develop Good Quality CHP in the European internal energy market, taking into account national climatic and economic circumstances. Member states are advised to support and encourage CHP along with other energy saving measures. Cogeneration units should be developed to match economically justifiable demands for useful heat output and barriers to the increase of cogeneration should be reduced. The EU Cogeneration Directive that came into force in 2004 aims to ensure grid access to small generators, and the removal of barriers to co-generation. The UK government developed their strategy for CHP (DEFRA 2004) and in 2000, a target of 10,000MWe of CHP capacity by 2010 was announced which was reaffirmed in the UK government Energy White Paper. The government’s support for CHP includes fiscal incentives, grant support, and regulatory framework (DEFRA 2004). However, no clear policy instrument or mechanism was put in place to achieve the target (Shackley 2007) and in 2006 total CHP capacity was still at 5,549 MWe (BERR 2007).

Current UK Government incentives for Good Quality CHP are: Climate Change Levy Exemption, Enhanced Capital Allowances, reduction or exemption from Business Rating charges, and VAT reductions for domestic CHP. Langdon (2004) points out that regulatory policies that could increase the use of CHP include: CHP evaluation studies to be submitted with building planning applications, enforcement of the European Energy Performance of Buildings Directive (EPBD), and enforcing the European Emissions Trading Scheme (EETS). Evaluation studies are already required to be submitted along with planning applications by some local authority planning departments. Building regulations encourage low carbon technologies such as CHP. Under the EPBD, CHP systems and decentralised energy supply systems need to be considered for new buildings and refurbishments with floor areas in excess of $1000m^2$. The EETS is intended to reduce carbon emissions from EU industry. This should encourage the use of CHP in industry and benefits could be passed down to customers, as decentralised systems become more viable.

2.3 COMBINED HEAT AND POWER (CHP)

"Combined Heat and Power (CHP), also known as cogeneration, is the name applied to processes which from a single stream of fuel simultaneously generate heat and power." (CIBSE 1999)

Haworth et. al. (2004) described the history of CHP and stated that the technology has been proven for some time. However, continual low electricity prices have hindered its widespread adoption. As electricity prices increase, CHP will become more financially viable.

CHP can offer environmental improvements, power supply security, and higher efficiencies of 70-90% compared to conventional energy systems that usually have delivered energy efficiencies of 30-45% when producing electricity (Figure 2.12). Higher efficiencies result in reduced overall primary energy consumption and carbon emissions (Hargreaves 2004).

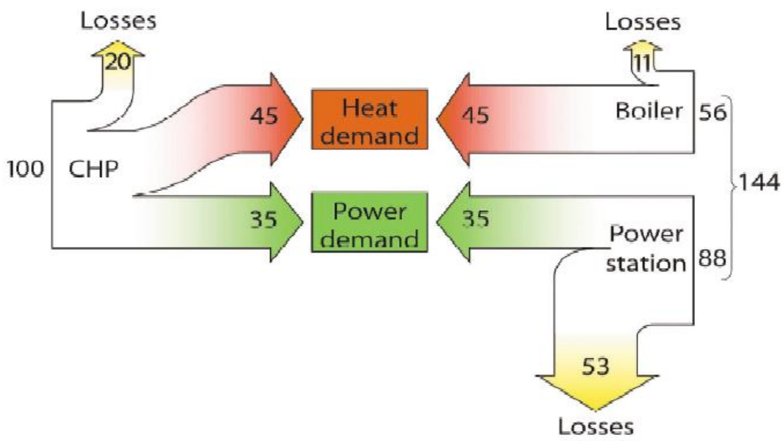


Figure 2.12 Energy flow diagram – CHP vs conventional system (Carbon Trust 2004)

Jacket water cooling and engine cooling systems can recover approximately 50% of the energy content of the fuel in CHP systems. This results in an overall system efficiency of 70-80%. Using a condensing heat exchanger, a further 10% can be recovered from the exhaust gases and therefore increase efficiencies to around 90% (Langdon 2004).

Martens (1998) discusses that CHP efficiencies, especially thermal efficiencies are influenced by the application of the system and in some applications separate heat and power production can have a higher overall efficiency than a CHP system. For example, electricity production by combined cycle plants (efficiency > 50%) and heat production by high efficiency boilers (efficiency > 90%) could lead to higher overall efficiencies than some CHP installations.

2.3.1 CHP technologies

The range of CHP that is available is shown in Figure 2.13. Hargreaves (2004) describes the different CHP technologies.

CHP types	•Fuel Cells (Solid Oxide) •Fuel Cells (Proton Exchange Membrane) •Internal Combustion Engines	•Spark Ignition Engines •Micro-Turbines •Small Scale Gas Turbines	•Large Reciprocating Engines •Large Gas Turbines
	Micro CHP (up to 5 kWe)	**Small scale CHP** (below 2 MWe)	**Large scale CHP** (above 2 MWe)
Application areas	•small groups of •dwellings •small commercial buildings •individual domestic buildings	•hospitals •hotels •leisure centres •universities •residential buildings.	•community heating schemes •large sites comprising of several buildings

Figure 2.13 CHP range

Traditional prime movers of CHP units are reciprocating engines or gas turbines. Small-scale CHP usually are packaged units with a spark ignition reciprocating engine driving a synchronous electric generator.

Large scale CHP are usually gas turbines that run on either gas or light oil. The rotation of the turbine drives the generator. High exhaust temperatures make this type of CHP especially applicable for high grade heat supply.

Packaged Stirling engine micro-CHP units, such as the Microgen unit now commercially available in the UK, are an alternative to reciprocating engine CHP and are more suited to domestic applications. EST (2001) claim that micro-CHP can achieve energy savings of 30% in a domestic application and that installed micro-CHP capacity could be of 15-20 GW in the UK.

In the UK, fuel cells for CHP are currently at the demonstration stage. However these systems are showing considerable potential, since they have higher electrical efficiencies, reduced CO_2 emissions and they operate without combustion (Langdon 2004). An example of research in this area is a co-generation system with direct internal reforming-molten carbonate fuel cell for residential use developed by Sugiura et. al. (2002).

2.3.2 CHP fuels

Natural gas is the most common fuel used for CHP in the UK (Figure 2.14). However, renewable energy sources and other fuel sources, such as biomass and hydrogen, are much "cleaner" forms of energy to power CHP systems.

"Biofuels" such as wood burned for heating were the first fuels used by mankind. They are still the most commonly used form of renewable energy in the world (Figure 2.18) and can also be used to power CHP systems.

Biomass powered CHP is a well established technology in countries such as Finland, Denmark and Sweden (OPET 2004). In the UK, a tree cuttings fuelled biomass CHP plant is installed at 'BedZED', a zero emissions mixed-housing development in Beddington (Van der Horst 2005).

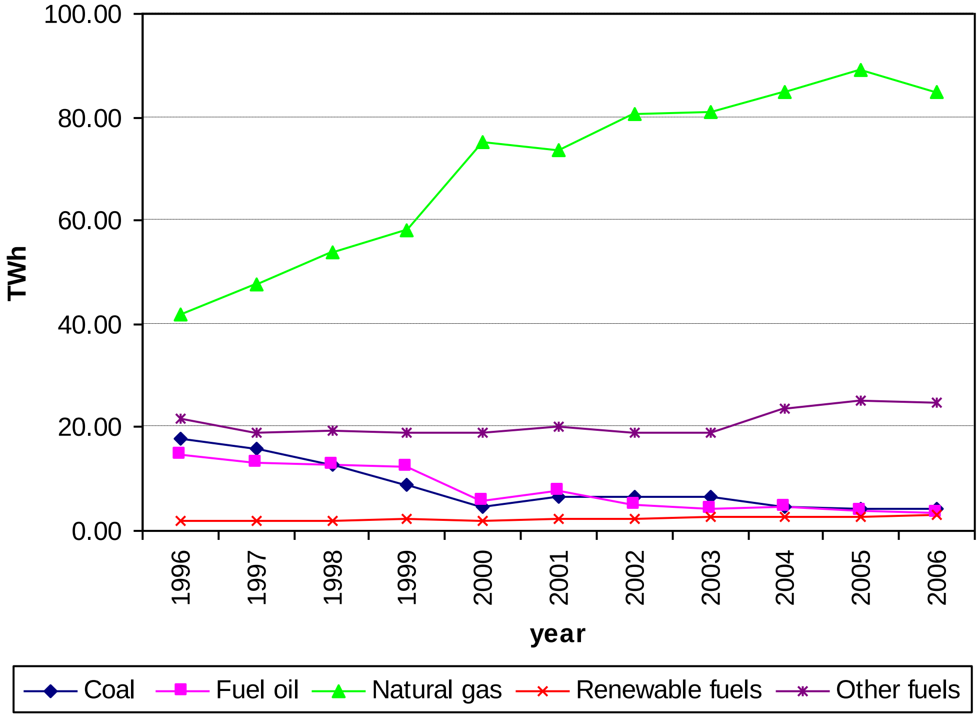


Figure 2.14 CHP use of Fuels in the UK (BERR 2007)

Arbon (2002) discussed that the replacement of fossil fuels with biomass is to be encouraged and the UK is focussing on biomass as one of the areas for intensive R&D studies in the near future. Van der Horst (2005) however argues that the biomass energy sector has not been supported to its fullest potential in the UK.

Hydrogen is considered an 'energy carrier' and could be used to store renewable energy (Boyle 2004). Hydrogen can also be used in fuel cell CHP systems that convert chemical energy into electrical energy with no emissions associated with it (Sugiura 2002).

Elam et. al. (2003) described the International Energy Agency's efforts to advance hydrogen energy technologies, with a vision of hydrogen playing a key role in all sectors of the economy. Winter (2003) discussed this build-up of the hydrogen-based energy market in the industrial North Rhine-Wesfalen region of Germany, where in

2003, 13 stationary fuel cells were in place. These were supported by their 3-year fuel cell programme 2001-03, which aimed at developing hydrogen production, storage, transport, and utilisation technologies.

Wallmark et al (2003) investigated the application of a stand-alone PEFC for buildings in Sweden. However, they concluded that the fuel cell system is not currently economically viable. Mc Ilveen-Wright et al (2003) came to a similar conclusion in their investigation of wood-fired fuel cell applications in a hospital, a leisure centre, a multi-residential community and a university hall of residence. They concluded that expectant capital costs would not make the systems viable for general use. However they could be more cost effective in rural applications where transport cost for other fuels are high and there is no electricity grid.

2.3.3 CHP Sizing

CHP is not applicable to all situations and its suitability to a project needs to be checked. For example, Boait et. al. (2006) concluded that micro-CHP in residential applications is generally best suited to dwellings with higher heating loads such as a large detached house. Hawkes at al (2005) investigated the application of a solid oxide fuel cell CHP system for different UK dwelling sizes and also concluded that the system would be viable for large dwellings only. The applicability of CHP systems however is dependant on occupancy patterns and behaviours and can therefore vary from building to building.

A CHP system should operate for at least 5000 hours per year to be economically viable (Carbon Trust 2004) and is therefore not appropriate for every application. If this condition is met, the CHP system can be sized to match the electricity and/or heat demands. For building applications, CHP usually replaces a boiler system and would therefore be sized on the base heat demand of the building, as this is generally the limiting factor (BRECSU 1996), with the electricity grid supplying any additional electricity to the building.

BRECSU (1997) outlined a simple financial appraisal tool, in the form of a spreadsheet, for potential CHP applications. It determines the suitability of a CHP system by calculating the payback period of the system using readily available information on energy use, fuel costs and operating conditions. A better method would be the discounted cash flow (DCF) method of financial appraisal to determine the net present value (NPV) of the project (Northcott 2002).

Optimum sizing and operation strategies are important to achieve maximum economic and environmental merits of the CHP system (Beihong et. al. 2006). Different methods are used to size CHP, some of which are described below.

Voorspools (2006) compared different CHP sizing strategies. The usual sizing method, maximising the output of a cogeneration unit for a given heat demand profile is compared to the options of 1- reduced-scale sizing: using a smaller CHP unit with higher usage and 2- partial-heat-usage sizing: using the same size CHP unit with increased usage (i.e. not using part of the heat). They found that both the reduced-scale sizing and the partial-heat-usage sizing methods could result in higher fuel and emission savings.

Hawkes (2007) investigates “heat-led”, “electricity-led” and “least-cost” operating strategies for Stirling engine, gas engine and solid oxide fuel cell micro-CHP technologies. It was shown that the commonly used heat-led strategy may not always provide the minimum cost to meet the energy demand. The fuel cell system achieved minimum operating cost and minimum CO_2 emissions when following the least-cost operating strategy. For the Stirling and the gas engines, minimum CO_2 emissions did not coincide with least-cost, but where achieved with the heat-led operating strategy. The least-cost operating strategy is dependant on electricity buy-back prices. As buy-back prices increase, electricity-led operating strategies will become less important, as surplus electricity can be viably exported to the grid.

Utilisation time can be increased by using some of the heat from the CHP to power an absorption refrigeration system providing cooling for example for the refrigeration cabinets in a supermarket (Maidment et. al. 2002).

Seasonal storage can also increase the utilisation efficiency of a CHP system, by storing heat or coolth during periods of low utilisation for use during peak-demand periods. Tanaka et. al. (2000) simulated a district heating and cooling system with seasonal water thermal storage and found that when heating and cooling demands were well balanced the energy performance of the overall system was improved. Maidment et. al. (2000) described the viability of CHP in a typical cold storage application and presented a number of CHP configurations. They concluded that by using the heat produced from the CHP for absorption chillers to provide cooling to the chill store, the utilisation period was maximised. This made CHP economically attractive with a potential payback of around 4.5 years.

Cardona et. al. (2003) described a methodology for sizing trigeneration plants in hotels. Two management philosophies were compared in the paper: the thermal demand management and the primary energy saving management. The latter being the preferred method in the paper. This method achieves maximum energy savings during the life cycle of the plant using a criterion based on previously obtained consumption data. The optimum size of the plant was found for the highest energetic and environmental benefits. However, this analysis did not include an economic assessment, which is often the main deciding factor for projects.

Silveira et. al. (2003) presented a thermo-economic analysis of cogeneration plants. This methodology analyses and improves the design of CHP, aiming for a minimum exergetic production cost.

Dentice d'Accadia et. al. (2003) carried out an analysis of a micro CHP system when used with household appliances and determined the optimum operation mode to match the user's electricity and thermal demands. The heat output is used fully in order to optimise the micro-CHP system and maximise the efficiency of the CHP system. Therefore the CHP was not only linked to the appliances, but also supplied heat to warm the ambient air or heat the domestic hot water.

One of the main deciding factors when sizing CHP is the economic viability of the system. Langdon (2004) summarises the variables determining the capital and operating costs of a CHP system:

i) CHP should operate for at least 5000 hours per year to be economic (Carbon Trust 2004).
ii) Energy demand profiles determine the size of the CHP unit and therefore the expected energy savings and associated cost savings can be determined.
iii) Using the CHP for part or all of the standby capacity can reduce capital costs.
iv) Government incentives and regulations can also affect the cost of the CHP system.

v) The fuel import/export and maintenance costs will affect the operating costs of the system.

vi) Potential costs of the requirement for a new or larger gas or electricity infrastructure should not be underestimated and could make a CHP system uneconomical.

vii) Additional potential costs associated with additional plant space and exhaust flue for the system and the cost of integrating the system with any existing heating and electrical systems should also be taken into account.

The Net Present Value (see section 4.3) is often used for the economic aspect of CHP optimisation (Kalina et. al. 2004) and takes into account the time value of money.

CHP is not only selected for projects for financial reasons. But the increased efficiency of CHP compared to “conventional” energy systems can also mean that CHP is selected for environmental reasons. CHP can therefore also be sized to have the lowest emissions associated with it.

In the computer tool developed in this study, CHP is sized in terms of both costs and emissions to achieve the lowest cost of emission savings in £/kg CO_2 saved. When sizing CHP, as is the case with other renewables, it is important to know when the energy will be required ie. building energy load profiles are considered. However, as discussed in chapter 3, these are sometimes difficult to predict. The tool developed in this study takes into account the uncertainty of load profiles in the sizing procedure of technologies.

Other tools that are available to size CHP systems are summarised in section 2.5.

CHP rarely covers the total heat and electricity demand in which case other technologies are required to cover the peak loads. Traditionally, back-up boilers would be used to meet the difference in heat demand and the national electricity grid would supply the additional electrical power required. However, the use of renewable energy technologies would be a better option for reducing emissions and fossil fuel demand. The tool developed in this research investigates this option.

2.3.4 Current status of CHP in the UK

In the UK, CHP capacity has increased over the years (Figure 2.15) with the majority of installations being small/medium scale (Figure 2.16). However Figure 2.17 shows that there is a large potential for the increased use of micro-CHP systems especially in domestic buildings in the UK. Burer et. al. (2003) argued that advanced integrated energy solutions such as CHP could be economically and environmentally viable in the near future, especially with high electricity prices. Their adoption however would depend on the technology, the way the technology is used and the tariffs for exporting electricity (Newborough 2004). As well as having the potential to achieve energy, emissions and cost savings for domestic users, micro-CHP can reduce the load placed on the national electricity grid and Newborough (2004) states the importance of micro-CHP application in the UK being integrated with national energy policy.

Section 2.2 discussed the aspects of the policies and regulations that aim to encourage the adoption of CHP in the UK. Policies and regulations making CHP attractive for industrial businesses have led to an increase in the output of large scale CHP (Figure 2.15). King (2004), however, argued the need for increasing current efforts in adopting CHP and for the UK to catch up with other leading European countries such as Denmark.

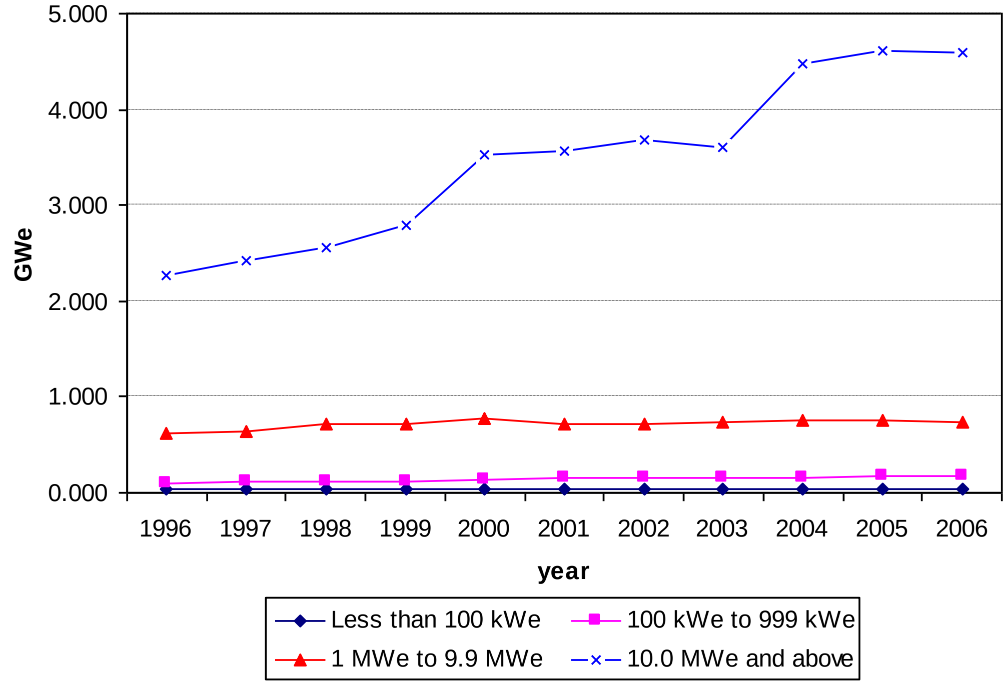


Figure 2.15 CHP capacity in the UK (BERR 2007)

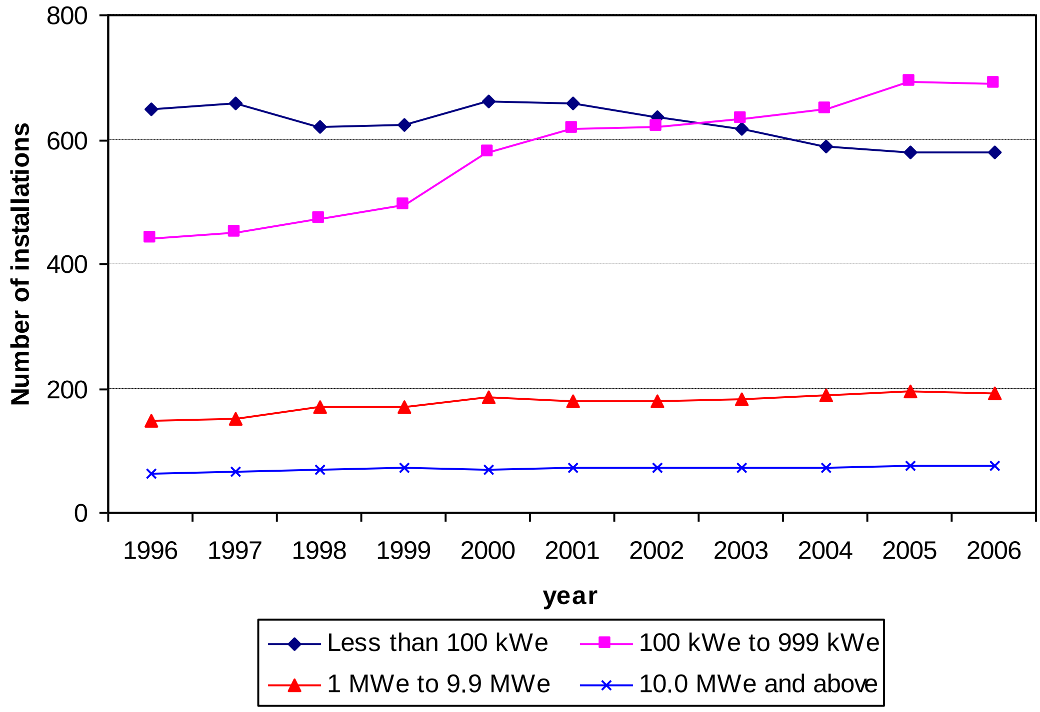


Figure 2.16 Number of CHP installations in the UK (BERR 2007)

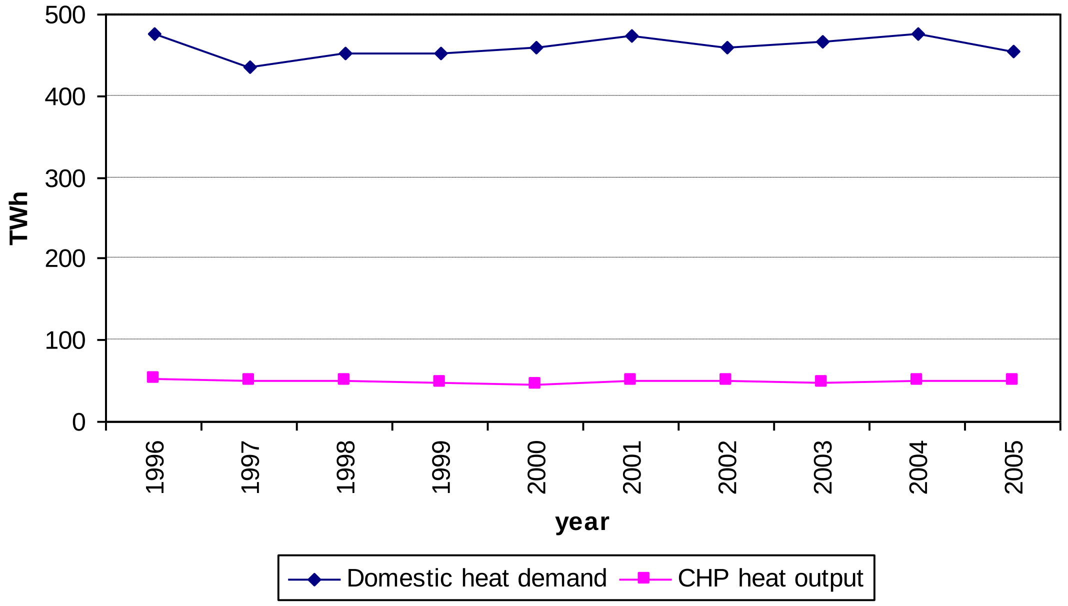


Figure 2.17 UK heat demand vs total UK CHP output (BERR 2007)

2.3.6 Application examples of CHP

Some CHP case studies installed in the UK are listed in table 2.1.

"Conventional" CHP is not often combined with renewables. However fuel cells are and can use hydrogen produced by renewables to produce energy when needed.

Hedstroem et. al. (2004) and Sigma Elektroteknik (2001) described a solar-hydrogen-biogas-fuel cell system installed in GlashusEtt in Stockholm, Sweden. The system consisted of a fuel cell system, PV array, electrolyser, hydrogen storage, and a separate control system. The proton exchange membrane fuel cell system had a maximum rated electrical output of 4 kWe and a maximum thermal output of 6.5 kWth. The evaluation showed that the system can work on both biogas and hydrogen (produced by electrolysis of water) and efficiencies were reported to be close to the rated efficiencies of the components.

Table 2.1 CHP case studies (Carbon Trust 2004, Van der Horst 2005)

Case Study	**Year of installation**	**CHP size (kWe)**	**CHP type**
'BedZed', Beddington	2002	130	Biomass CHP, spark ignition
York University, York	1995	1030	Reciprocating engine
Queens Medical Centre, Nottingham	1998	4900	Gas turbine
Southbury Leisure centre, Enfield	2002	80	Micro turbine
Woking Park, Woking	2001	200	Fuel cell
Coventry University, Coventry	1994	2 x 300	Reciprocating engines
Freeman Hospital, Newcastle upon Tyne	1997	2 x 1350	Spark ignition engines
Southampton City Council	1998	5700	
Northampton General Hospital, Northampton	1995, 1997, 2001	220 + 450 85	Reciprocating engines Micro-turbine
Elizabeth House, Rochester	2002	2 x 5	Reciprocating engines
Arnold Leisure Centre, Gelding	1992	75	Reciprocating engine

2.4 RENEWABLE ENERGY

Renewable energy can be defined as follows:

"Energy flows derived from natural forces that are continuously at work in the earth's environment, and which are not depleted by being used. " (Energy Efficiency Best Practice in Housing 2004)

Figure 2.18 shows the trend in use of different renewable energy sources since 1996. Apart from biofuels, the contribution from renewable energy has not changed appreciably. This is due to large scale hydro schemes not being very popular with the public, as they have an impact on its environment (Boyle 2004), wave energy use has not been explored fully yet, and wind energy technology, although being well established, has not been widely used in the UK as public opposition makes its application difficult. The use of biofuels however has dramatically increased since 1996 and Figure 2.19 shows that biofuel is currently the most widely used source of renewable energy in the UK both for the production of electricity and heat as seen in Figure 2.20. This large increase of biofuel use in electricity production is due to the increased use of landfill gas and municipal solid waste, which are classified as biofuels. Geothermal and solar energy have a high potential to be used on building applications to provide heat and electricity to buildings.

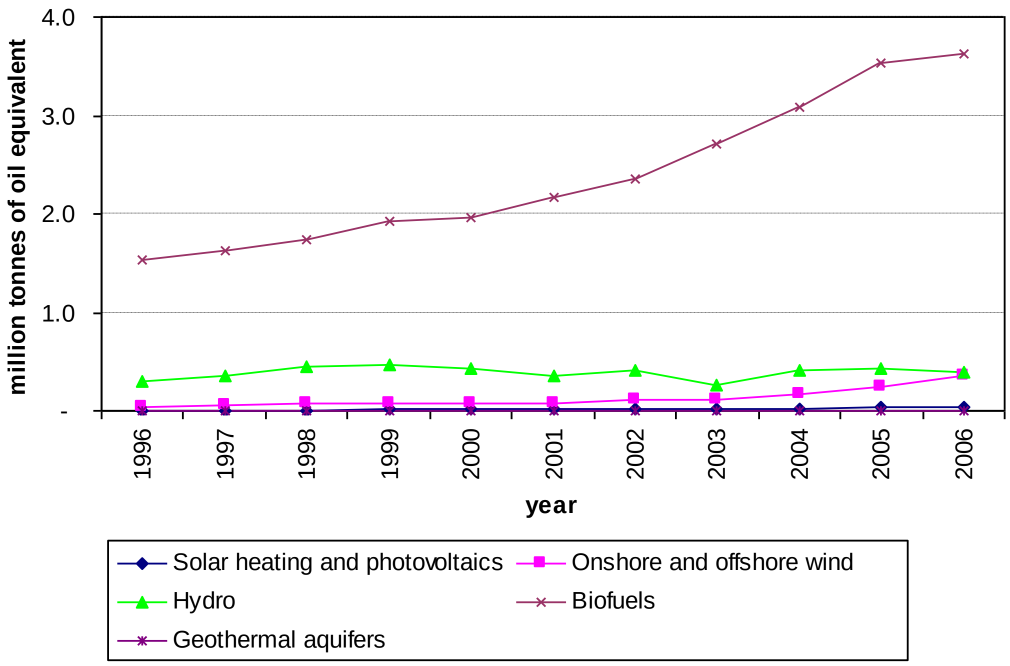


Figure 2.18 Renewable sources used to generate electricity and heat in the UK (BERR 2007)

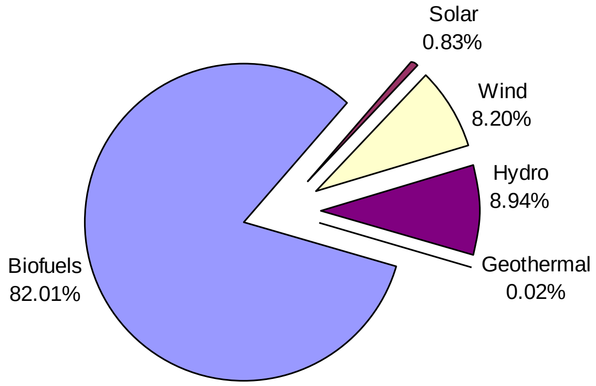


Figure 2.19 Use of renewable sources in 2006 in the UK (BERR 2007)

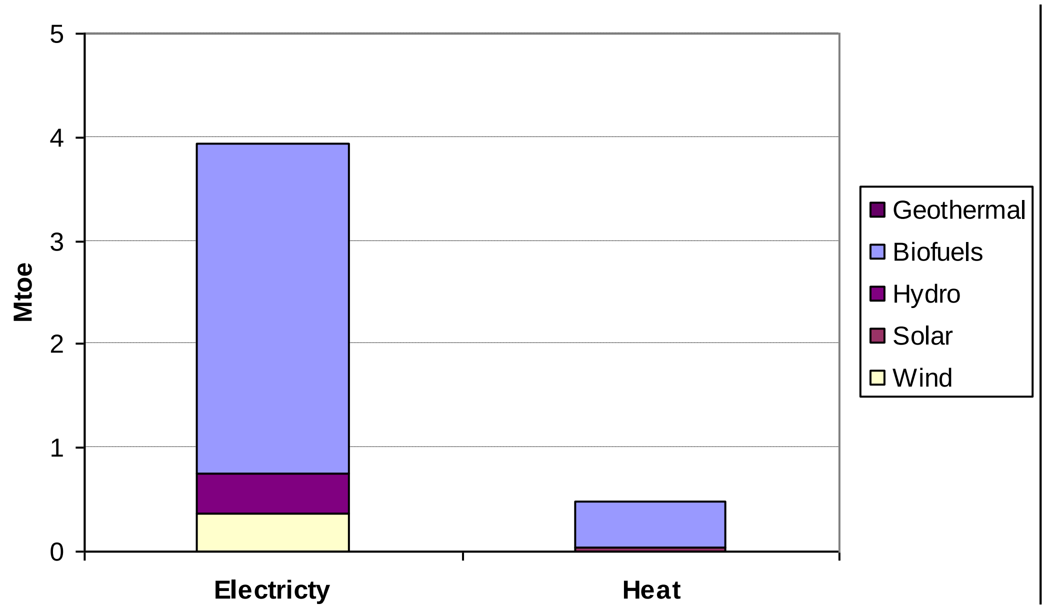


Figure 2.20 Use of renewables to generate electricity and heat in 2006 in the UK (BERR 2007)

There is a high potential for the production of energy from renewables across the World. According to EREC (2004) renewables could supply almost 50% of the total energy demand in the World by 2040 (Figure 2.21), however Table 2.2 shows that current use of renewable energy compared to its potential is slim (Table 2.2).

The barriers to the development of renewable energy technologies need to be addressed for their widespread adoption. Duffin (2000) states that supportive policies are essential for the success of renewable energy technologies. Cost is also a barrier to most renewable energy technologies (see Figure 2.4). However, this barrier can also be overcome by the implementation of adequate policies. Policies related to renewable energy in the UK are described in section 2.2.1.

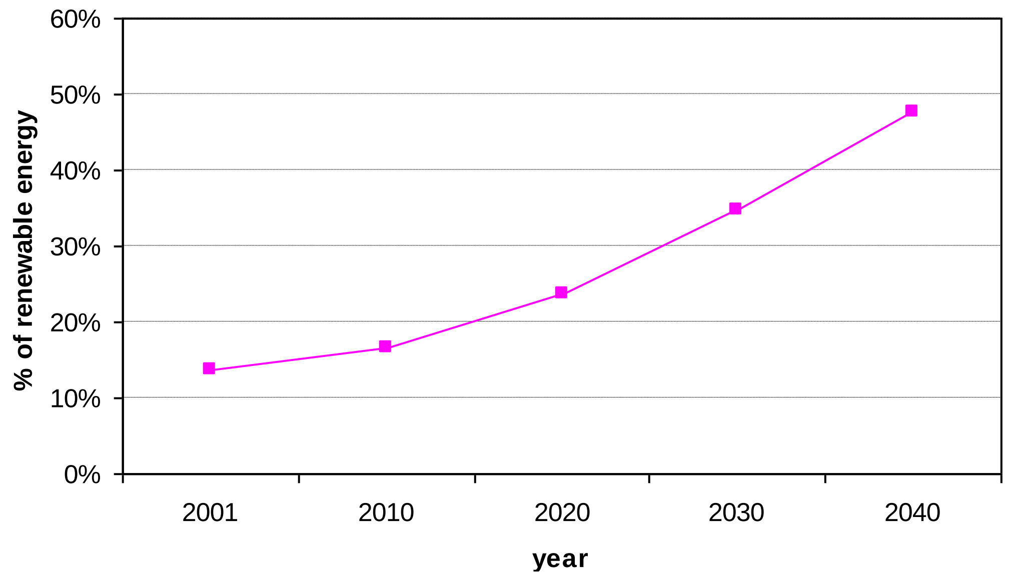


Figure 2.21 Prediction of renewable energy contribution to the World energy supply (EREC 2004)

Table 2.2: Global renewable energy resources and output of installed renewables (Gross et. al. 2003)

Resource	Scale of technical potential (useful energy output) (TWh/year)	Output of installed renewables (TWh/year)
Direct solar	12,000 - 40,000	1.2
Wind	20,000 - 40,000	50
Tidal	>3500	-
Geothermal	4,000 - 40,000	44
Biomass	8,000 – 25,000	185

The Energy Efficiency Best Practice in Housing (2004) advises on renewable energy technologies when designing or refurbishing urban housing, and highlights the importance of the consideration of energy efficiency before considering the installation of energy systems. It is also important to consider the indirect emissions associated with the production and transportation of the renewable technologies as shown in Table 2.3.

Table 2.3: Environmental impact of renewable energy technologies (Ackermann et. al. 2002)

Technology	**Energy pay back time in months**	**SO2 (kg/GWh)**	**NOx (kg/GWh)**	**CO2 (t/GWh)**	**CO2 and CO2 equiv. for methane (t/GWh)**
Coal fired (pit)	1.0- 1.1	630 – 1370	630 – 1560	830 – 920	1240
Nuclear	N.A.	N.A.	N.A.	N.A.	28 – 54
Gas	0.4	45 – 140	650 – 810	370 – 420	450
Hydro:					
Large hydro	5 – 6	18 – 21	34 – 40	7 – 8	5
Microhydro	9 – 11	38 – 46	71 – 86	16 – 20	N.A.
Smallhydro	8 – 9	24 – 29	46 – 56	10 – 12	2
Wind turbines:					
4.5m/s	6 – 20	18 – 32	26 – 43	19 – 34	N.A.
5.5m/s	4 – 13	13 – 20	18 – 27	13 – 22	N.A.
6.5m/s	2 – 8	10 – 16	14 – 22	10 – 17	11
PV:					
Monocrystalline	72 – 93	230 – 295	270 – 340	200 – 260	N.A.
Multicrystalline	58 – 74	260 – 330	250 – 310	190 – 250	228
Amorphous	51 – 66	135 – 175	160 – 200	170 – 220	N.A.
Geothermal	N.A.	N.A.	N.A.	N.A.	50 – 70
Tidal	N.A.	N.A.	N.A	N.A.	2

This study concentrates on solar thermal and PV, combined with CHP technologies as solar thermal and PV technologies are commonly integrated into buildings. Ground source heat pump (GSHP) and wind technologies, although they are also well suited to building integration, are not currently included in the computer modelling tool however could be included in further research. The tool will not incorporate hydro, wave, river, or tidal energy technologies as these are not commonly integrated into buildings and the integration of these resources with buildings are highly dependant on the location.

2.4.1 Solar thermal energy

Boyle (2004) describes different ways in which solar radiation in the form of heat can be colleted and used in buildings:

- Building orientation: designing a building with a large south facing façade could allow for passive solar heating and natural lighting.
- Active solar thermal collectors: a solar collector is used to harvest incident solar radiation. The low temperature heat collected is usually used for hot water heating. This is the method considered in this section.
- Centralised power stations using concentrating solar technologies: these are large scale power generation schemes in the order of MW power ratings and usually function according to the Rankine cycle whereby a steam turbine is used to convert high pressure working fluid vapour into shaft power. This option is not integrated with buildings and is therefore not considered in this research.

a) Building design

The use of passive solar heating in buildings can be optimised by insulating the building to reduce heat losses, installing an efficient heating system, orientating the building south facing, avoiding over shading and having "thermally massive" walls.

b) Solar radiation

The sun radiates energy from its high temperature surface (approximately 6000°C). Radiation reaching the earth surface consists of direct and diffuse radiation (Boyle 2004). Figure 2.23 shows the mean direct and diffuse irradiation on a horizontal surface in the London area. In the UK, the total irradiation consists of about 50% direct and 50% diffuse irradiation (Boyle 2004) and the total radiation varies throughout the year, being the highest in June and lowest in December (Figure 2.22).

A south-facing surface receives the most radiation in the northern hemisphere (CIBSE 2006). The optimum tilt of the surface depends on the time of year most energy is required. Best performance of a collector in spring and autumn is achieved with a tilt equal to the latitude of the location. Optimum tilt in the summer requires a more horizontal tilt and in winter a more vertical tilt is better. The optimum tilt for year round radiation in London is 30° (Boyle 2004). However, a collector orientation between south-east and south-west is acceptable for most solar heating applications, which makes solar hot water applications suitable to most buildings (Boyle 2004).

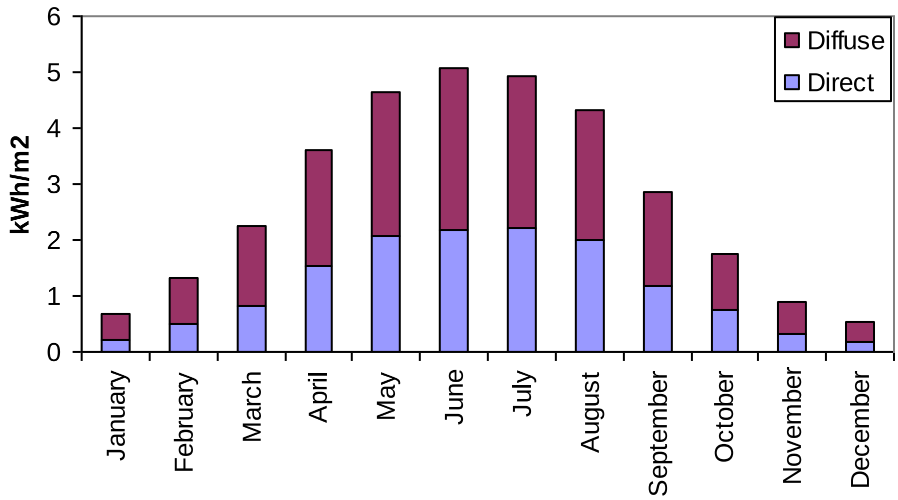


Figure 2.22 Mean solar irradiation on a horizontal surface – London area
(CIBSE 2006)

Using a solar system for space heating in the UK is not usually viable as most of the solar radiation is available during the summer, when space heating is not required, and during the winter when the space heating demand is greatest, the solar radiation available is lowest (Figure 2.22). A solar collector system could however be used for cooling in building applications. Florides et al (2002) reviews different solar and low energy cooling techniques for buildings. Thermal energy storage such as underground heat stores and aquifer stores can also be used to increase solar energy utilisation throughout the year (IEA 2002).

Theoretical efficiencies of solar thermal systems do not always correspond to their actual efficiencies and it is therefore important to gain more insight into installed systems. Solar water heating installations have been analysed and monitored to gain information on their performance and problems encountered (ETSU 2001, Lloyd 2001). ETSU (2001) monitored four systems in different sites to gain information on hot water usage, delivery temperature, useful energy delivered and the proportion of the demand satisfied by the system, which could be useful for future studies.

c) Rooftop solar water heater

The rooftop solar water heater is the most common form of solar collector. This system can be a pumped system or a thermosyphon system.

In northern Europe, where freezing usually occurs in winter, pumped systems are usually used. A pumped system consists of a collector panel (which consists of three layers: glazing, absorber plate and insulation), a storage tank, and a pumped circulation system (containing anti-freeze in cold climates). In the UK this type of system for a typical dwelling with 3-5m^2 of collectors would typically supply 40-50% of hot water requirements (Boyle 2004).

A thermosyphon system is a simpler installation not requiring a pump. Natural convection of the hot water rising from the collector carries heat to the storage tank situated above the collector. This system is not suited for climates where frost occurs as the hot water tank is usually situated outdoors.

Different types of solar thermal collectors available on the market are: collectors without glass cover (usually used for swimming pool applications), flat plate collectors with glass cover, and vacuum tube absorber tubes (Boyle 2004). Concentrating collectors are another form of collectors (Kalogirou 2004). Collectors can be stationary or sun-tracking. In this study collectors for building applications are considered. These are usually stationary flat plate and vacuum tube collectors as described below. Kalogirou (2004) and SEA (2004) describe these two collector types:

i) Flat plate collectors

Flat plate solar collectors consist of an absorber, a transparent cover and insulation in a frame. The absorber plate absorbs the solar heat and transfers it to the transport medium in tubes. Flat plate collectors are the most used collector type and are mainly used for hot water production. They are less expensive (£2000 - £3000 for a typical domestic installation (EST 2005)) however also less efficient compared to evacuated tube collectors.

ii) Evacuated tube collectors

There are two main types of evacuated tubes:

The full flow evacuated tubes work in a similar way to flat plate collectors. They have an absorbing plate with tubes where a fluid absorbs the heat. However with evacuated tube collectors, all this is encased in a vacuum tube and several tubes connected to a manifold form a collector.

The heat pipe evacuated tube collectors consist of a heat pipe inside an evacuated tube. The vacuum reduces convection and conduction losses making evacuated tubes able to operate at higher temperatures than flat plate collectors. The heat pipe is a sealed copper pipe containing a fluid that undergoes an evaporating-condensing cycle: Solar heat evaporates the liquid and the vapour travels to the heat pipe condenser situated in the manifold where the fluid condenses transferring heat to the fluid in the manifold, the fluid returns back to the heat pipe and the process is repeated. Several tubes are connected to the manifold to make up a solar collector.

Evacuated tube collectors work efficiently with low radiation and with high absorber temperatures and higher temperatures may also be obtained. The heat pipe in evacuated tube collectors also protects the collector from overheating or freezing. Costs for a typical evacuated tube domestic installation are £3500 - £5000 (EST 2005).

Solar thermal systems can be direct or indirect systems. In direct systems the water is directly heated by the collectors i.e. the water to be heated passes through the collector panels. In indirect systems a heat exchanger is used to transfer the heat from the collector circuit to the water in the storage tank. This type of system is especially used in climates where freezing occurs as anti-freeze can be used in the collector circuit to avoid the water from freezing. Figure 2.23 shows a diagram of an indirect system. The hot water storage tank in a solar thermal system has two heating coils one for the solar system and one for the auxiliary system (usually a boiler or an electric heater). In order for the solar system to be used primarily, the coil for the solar system is usually situated at the bottom of the tank (the colder part). The pump is controlled by the controller which is linked to sensors on the collectors and storage tank. (SEA 2004)

A solar thermal system can either be a pressurised circuit or a drain-back circuit. A pressurised system is a closed loop circuit with anti-freeze and requires an expansion vessel for temperature variations. A drain-back system is drained when the pump isn't working (for example when the temperature is below freezing) and therefore requires a tank inside the building for the water to drain into.

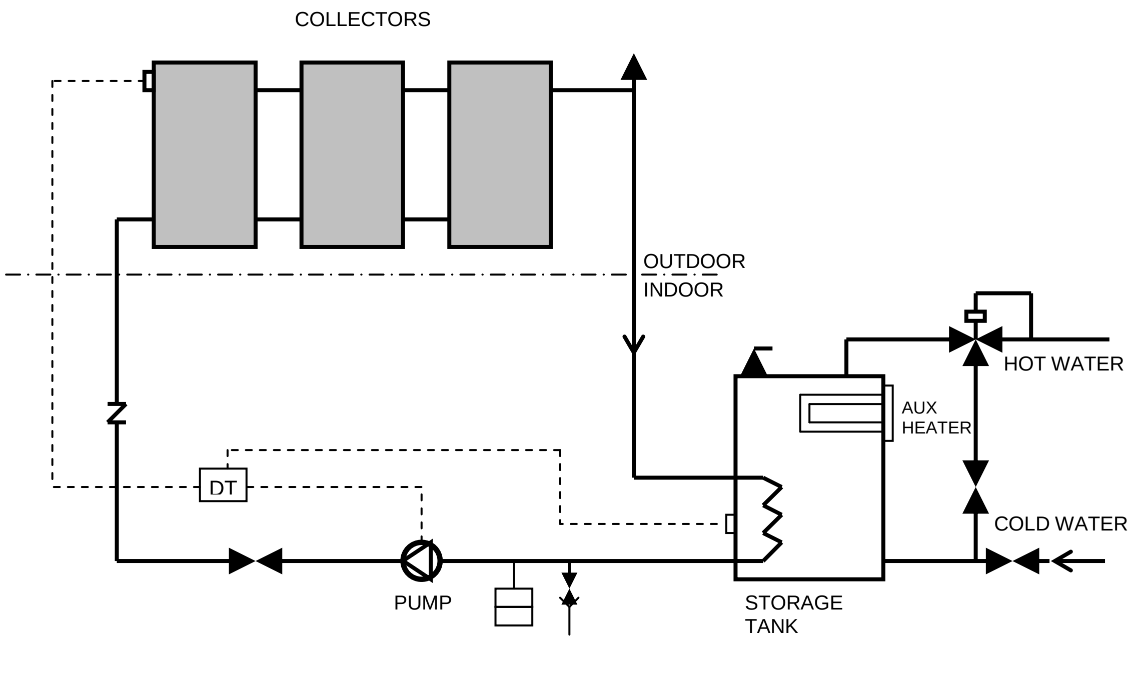


Figure 2.23 Indirect water heating system (Kalogirou 2004)

d) Solar thermal collector sizing

Design and sizing of solar thermal collectors are often achieved using Hottel-Whillier-Bliss equation. The equation expresses the useful heat collected, Q, per unit area, in terms of two operating variables, the incident solar radiation normal to the collector plate, I_s, and the temperature difference between the mean temperature of the heat removal fluid in the collector, T_m, and the surrounding air temperature, T_a.“ (McVeigh 1977). This is given as:

$$Q = F\{(\tau\alpha)I_s - U(T_m - T_a)\} \qquad \text{Equation 2.1}$$

where, F is a factor related to the effectiveness of the heat transfer from the collector plate to the heat removal fluid, $(\tau\alpha)$ is the transmittance-absorptance product and U is the heat loss coefficient (W/m^2K).

The useful energy output of a solar collector can be expressed as follows (Duffie 1991):

$$Q_{sc} = A_{sc} \times I_s \times \eta_{sc} \qquad \text{Equation 2.2}$$

where, A_{sc} is the total Collector area, I_s is the incident solar radiation normal to the collector and η_{sc} is the collector efficiency.

Therefore, using equation 2.1 and 2.2 a solar thermal collector instantaneous efficiency can be given by (Duffie 1991):

$$\eta_{sc} = F(\tau\alpha) - FU(T_m - T_a) / I_s \qquad \text{Equation 2.3}$$

Atmaca (2003) quotes typical values of $F(\tau\alpha) = 0.75$ and $FU = 6.5$ for double-glazed flat plate collectors, and $F(\tau\alpha) = 0.7$ and $FU = 3.3$ for evacuated tube collectors. A more detailed calculation of solar collector sizing is given in Chapter 4 as part of the computer modelling tool developed for this research.

Sizing of the components of solar thermal systems is complex and includes predictable components such as collector performance characteristics, and unpredictable components such as weather data. Simulation and modelling software packages are used for a detailed investigation and sizing of solar thermal systems (Kalogirou 2004). Many simulation methods have been developed over the years. The *f*-chart correlation method is one of the simple methods. It is a method to estimate the fraction of energy that will be supplied by solar energy for a given solar heating system (Beckman et al 1977). Other simulation packages such as SOLCOST (Win 1980), TRYNSYS (University of Wisconsin 1990), WATSUN (University of Waterloo 1994), Polysun (Polysun 2000), EUROSOL (Lund 1995) and RETscreen (RETscreen International 2004) are more detailed simulation methods. See Section 2.5 for more computer tools.

Although simulations can be valuable methods of investigating solar thermal systems, not all aspects affecting the performance of the systems can be considered and modelled. Mistakes can also easily be made in the process as a high skill level is required to make the correct judgements and produce accurate results. The tool developed in this study uses a basic sizing procedure not requiring many input parameters. It might not deliver a detailed simulation, however the sizing does not require “expert” knowledge of solar thermal systems in order to operate the tool.

e) Hot water storage tank sizing

Matrawy et al (1996) developed a graphical method for the optimisation of solar thermal water heating systems. The optimum collector and storage sizes were found for a given solar fraction. Bojić et al (2002) concluded from their solar thermal system simulation that systems with larger storage volumes yielded higher solar fractions. However an economical analysis should be carried out in addition to find the optimum storage volume for a system. In the tool developed in this study, the hot water storage volume is assumed to be 1/3 of the daily hot water demand, as for a hot water storage for a typical boiler system (Institute of Plumbing and Heating Engineering 2002).

Lund (2005) investigated the sizing of solar thermal combi-systems (supplying both hot water and space heating) with short-term heat storage. Over-sizing a solar thermal system to provide some space heating proved to be advantageous for less efficient buildings, where there was a space heating demand in some of the summer months. However for newer, more efficient buildings, this sizing strategy leads to a negative economic outcome. Sizing the solar thermal system to supply some space heating is therefore not economically advantageous in all cases. In the tool the solar thermal system is sized only to supply hot water and does not consider the heating demand in the sizing procedure.zx

f) Current status of solar thermal energy

As part of the EU target of 20% renewable energy by 2020, solar thermal technologies are encouraged (ESTIF 2007). The country with the largest share of the solar thermal market in the EU is Germany with 50% (Figure 2.24). However, although solar energy is currently not used extensively in the UK (Figure 2.20), and the UK has one of the smallest amounts of collectors in operation (Figure 2.25), the UK has had the highest market growth in 2005/2006 with 93% (Figure 2.26) and is now in 8th place in the EU solar thermal market (ESTIF 2007).

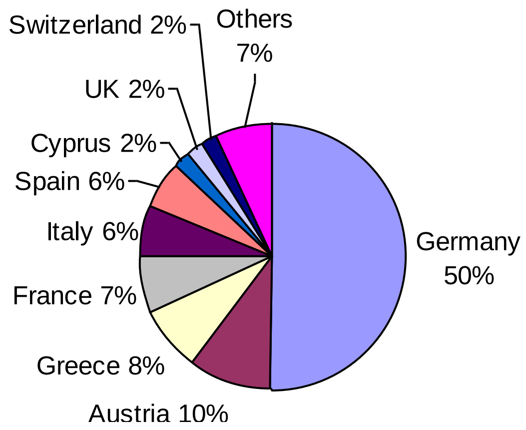


Figure 2.24 Shares of the European solar thermal market (ESTIF 2007)

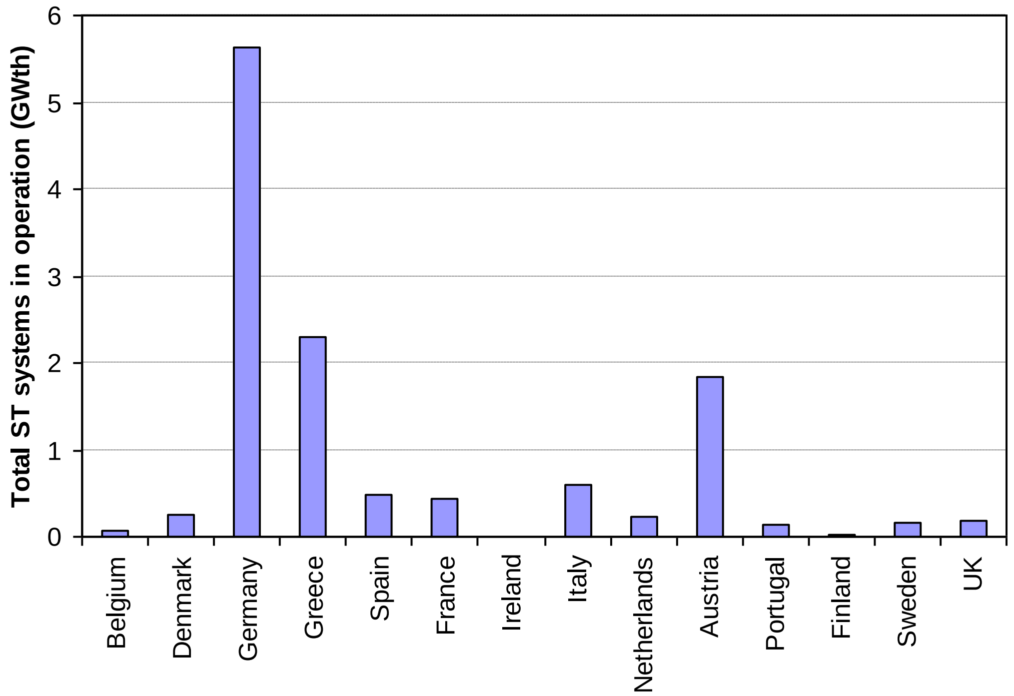


Figure 2.25 Total solar thermal collectors in operation in 2006 (ESTIF 2007)

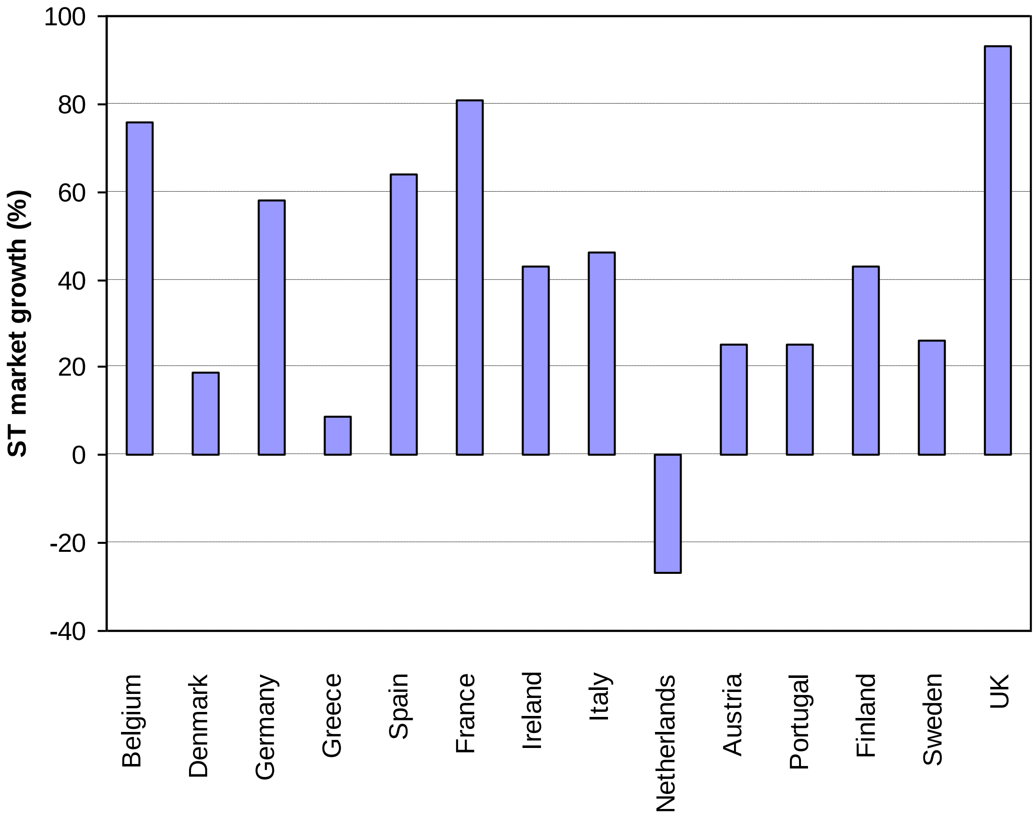


Figure 2.26 Solar thermal system market growth 2005/2006 (ESTIF 2007)

Per capita statistics are a good indicator of the strength of the solar thermal market in a country. Austria for example had the largest advance in the solar thermal market with 25.2 kW_{th} per capita: twice that of Germany and about 6 times the European average in 2006. Cyprus had the largest amount of solar thermal capacity per capita in operation in 2006 with 530 kW_{th} per capita, Austria and Greece came second and third with 225 and 208 kW_{th} per capita respectively in 2006 (the European average was 27 kW_{th} per capita) (ESTIF 2007).

g) Application examples of solar thermal systems

The Energy Saving Trust publishes some case studies of solar hot water systems for buildings (EST 2008). Many solar thermal collectors are integrated in residential buildings and in certain countries are installed in most residential buildings as the primary technology supplying the hot water to the building. Other application examples are communal buildings and swimming pool applications. Some UK case studies are listed in Table 2.4.

Table 2.4: Solar thermal collector case studies [(1) ESD 2005, (2) TV Energy 2008, (3) Faber Maunsell 2003, (4) European Commission 2008, (5) EST 2003]

Case Study	Year	ST application	ST type	Other technologies
Westlea Housing Association, Calne, Wiltshire, and Swindon (1)		Domestic hot water	Flat plate	
Brill School, Buckinghamshire (2)	2003	Swimming pool	Evacuated tube	Wind turbine, PV system
SOHA Housing, Oxfordshire (2)	2004	Domestic hot water	Flat plate	PV system, GSHP
Family home, Buckinghamshire (2)	2003	Domestic hot water	Flat plate	PV system
Warden INTEGER Home, Berkshire (2)	2001	Domestic hot water	Flat plate	-
Birch Court, Sheltered elderly housing, Oxfordshire (2)	2003	Community hot water & heating	Flat plate	-
Integer Greenfields, Maidenhead (3)	1998	Domestic hot water	Flat plate	PV system
Hyde Housing Association, Greenwich (3)	1998	Domestic hot water	Flat plate	-
Phoenix House, Leicester City Council (3)	1997	Commercial building hot water	Evacuated tube	-
Josiah Wedgwood & Sons visitor centre (3)		Hot water for washrooms and café	Flat plate	-
William J. Clinton Peace Centre, Northern Ireland (4)		Hot water to Conference centre, Youth hostel, Art gallery, Café	Evacuated tube	PV system
The Fishing Village, Chatham Maritime, Kent (5)	2003	Domestic hot water	Evacuated tube	

2.4.2 Photovoltaics

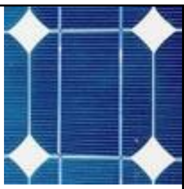
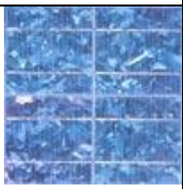
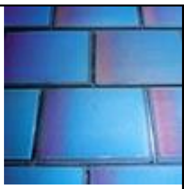
A definition of Photovoltaics is: “the conversion of solar energy directly into electricity in a solid-state device” (Boyle 2004). Photovoltaic cells (PV) consist of semi-conducting material, usually silicon, adapted to release electrons, which form the basis of electricity. Boyle (2004) describes the process in more detail.

Table 2.5 lists the main PV technologies available. Other innovative PV technologies include Multi-junction PV cells, Concentrating PV systems, Silicon spheres, Photoelectrochemical cells, and “Third generation” PV cells. Green (2000) describes the different photovoltaic technologies.

PV systems have no moving parts therefore lengthening their lifespan, have lower maintenance requirements, and do not generate noise pollution or polluting emissions. However PV production is an energy intensive process and PV technology remains expensive compared to other renewable energy technologies (Table 2.3). The cost of PV is around $6 per peak Watt, which is 6-10 times the cost of grid electricity (Gross et. al. 2003).

PV systems can be grid connected, grid support, off-grid, or hybrid systems (EPIA 2001). Grid connected systems can export excess power and import additional power. A system with grid support is connected to the grid and has battery electricity storage, which is ideal in areas with unreliable grid supply. An off-grid PV system is only connected to a battery and is ideal for remote power supply. A hybrid system is a system that can be combined with another power source to ensure constant power supply. This system can be grid connected, grid support, or off-grid. Other more efficient methods for electricity storage are being researched, such as storing energy in the form of hydrogen to be used by fuel cells (Dell 2001).

Table 2.5: PV technology (Boyle 2004, EPIA et. al. 2001)

Material	**Diagram**	**Typical efficiencies (%)**	**Advantages**	**Disadvantages**
CRYSTALLINE PV				
Monocrystalline silicon		12-15	High efficiency	Labour intensive Expensive
Polycrystalline silicon		11-14	Easier to produce	Less efficient
THIN FILM PV				
Amorphous silicon		5-7	Cheaper to produce than crystalline cells Less energy intensive to produce Thinner and can be deposited on a variety of materials	Less efficient than crystalline cells
Other materials suitable for thin film PV are Copper indium diselenide (CIS), Copper indium gallium diselenide (CIGS), and Cadmium telluride (CdTe).				

Building integrated PV (BIPV), such as PV roof tiles and façade cladding, can significantly reduce the cost of PV, as the cost can be offset from the alternative cladding cost. Mott Green Wall (2002) investigated the economic potential of BIPV and concluded that BIPV could make a considerable contribution towards UK renewables targets.

a) Sizing PV systems

DTI (1999) published a design guide for PV in buildings which outlines some points to consider when sizing a PV system:

i) The more energy that can be used on site the better, as exporting electricity to the grid currently is not economically interesting in the UK.
ii) The PV system is usually sized to contribute towards the total electricity load, but usually doesn't supply the total annual load.
iii) Available area for the collectors
iv) Budget

CIBSE (2000) gives some rough rules of thumb outputs of different PV systems for the UK:

- Monocrystalline or polycrystalline array: 90-110 kWh/m^2 per year
- Amorphous thin film array: 30-70 kWh/m^2 per year
- Roof-mounted, grid connected system: 700 kWh/kW_p installed per year

As for the solar thermal system sizing, the PV output can also be estimated using solar irradiation data, which is available from many sources. The solar radiation data used in the tool is from the European Commission Directorate General Joint Research Centre, PVGIS irradiance database (European Commission Directorate General Joint Research Centre 2007). Losses are assumed to be 25% (CIBSE 2000). Polycrystalline PV with a collector efficiency of 14% (CIBSE 2000) is being used in the tool as it is currently the most commonly used type of PV (IEA 2003). Roberts (1992) however outlines the limitations with many sizing procedures being the difficulty of accurately predicting the weather data and electricity loads.

Sizing procedures for PV systems with battery investigate the relationship between the sizes of the array and the battery to achieve a certain reliability of supply and usually make use of sizing curves (Markvart 2006). Roberts (1992) outlines a sizing procedure for small systems with battery storage. In this tool however it is assumed that the PV system is grid-connected and any surplus electricity generated at any one time is exported to the grid and any deficit is imported from the grid.

Equation 2.4 is the equation used to size the PV array in the computer tool.

$$S_{PV} = \frac{D_e}{I_s(1-L)\eta_{PV}}$$ Equation 2.4 (CIBSE 2000)

where, S_{PV} is the PV required area (m^2), D_e is the electricity demand (kW), I_s *is* the incident solar radiation (kW/m^2), η_{PV} is the efficiency of the PV cells, and (1- L) is the efficiency of the power conditioner (inverter, controller), transformer and interconnection.

In many cases the worst month in terms of solar radiation is used when sizing PV systems, this however does not result in the optimum in terms of techno-economics (Celik 2003). Celik (2003) suggests a method where another energy form is introduced instead of increasing the sizes of the renewable energy technologies and considers yearly radiation data. This method results in techno-economically more optimum systems. As in the method, Celik (2003) uses, in the tool developed in this study, yearly solar radiation data is used and an auxiliary energy source, in this case CHP and/or the national electricity grid, is included in the system design. The technologies are then sized to find the optimum system in terms of cost and emissions (see Chapter 4 for the tool description).

As for the ST sizing, there are tools available for sizing PV optimally that simulate the system in more detail. RETScreen (RETScreen International 2004) is one of such tools and can analyse both grid connected and battery systems.

Ulleberg et. al. (1997) simulated the performance of a stand-alone solar-hydrogen power system in Trondheim, Norway. The transient simulation program TRNSYS was used for the simulation study. The conclusion was that such a system in Trondheim would need to be quite large compared to similar systems, such as the SSSH in Freiburg, because of low insolations in Trondheim and large loads assumed. This illustrates the importance of reducing loads before designing the system.

b) Current status of PV in the UK

Although the manufacture of PV has remained small and costs high compared to other renewable energy technologies, the use of PV has steadily increased in the World since 1993 (Figure 2.27). This trend of increased use of PV has also been reflected in the UK (Figure 2.28). There is a large resource of solar energy (Table 2.2) and innovations, improvements in efficiency, and increased production, should reduce costs of the modules (Gross et. al. 2003). There therefore is a large potential for PV in the UK and the World. However, the UK is still lagging behind other European countries, such as Germany (Figure 2.29). Germany's domination in the European PV market is mainly due to the Feed-in Law introduced in 1999, making PV systems economically more viable (Jaeger-Waldau 2007).

In the UK, investment grants, subsidies for demonstration projects and 5% reduction in VAT for professional installations of PV systems are available (Hacker 2005). A 10 year Major PV Demonstration Programme was launched in 2002, providing capital grants for the installation of domestic and non-domestic PV systems in the public and private sectors (Jaeger-Waldau 2003). This however was replaced by the Low Carbon Buildings Programme which provides grants for microgeneration technologies, including PV (IEA 2007).

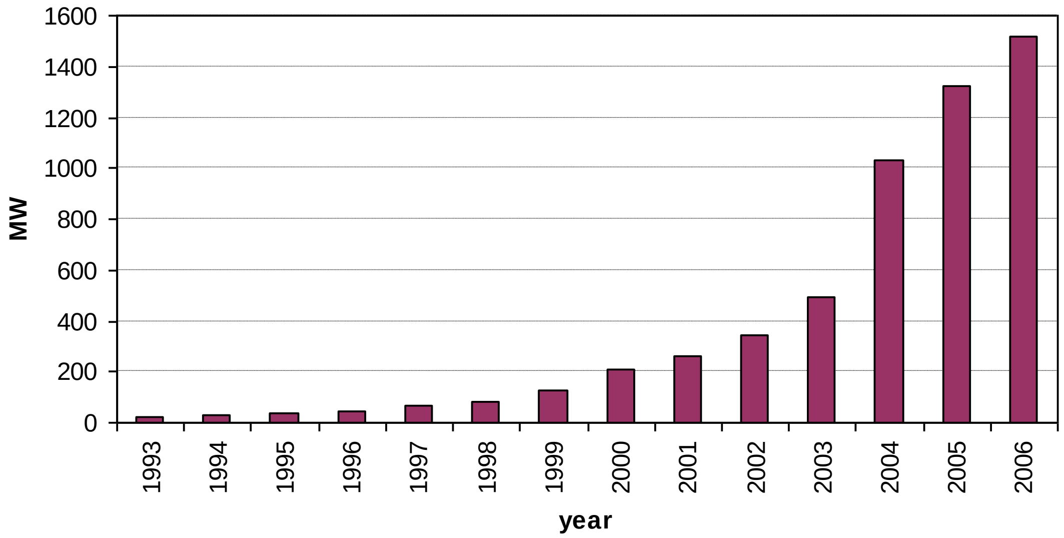


Figure 2.27 Installed PV power in the IEA PVPS reporting countries (IEA 2007)

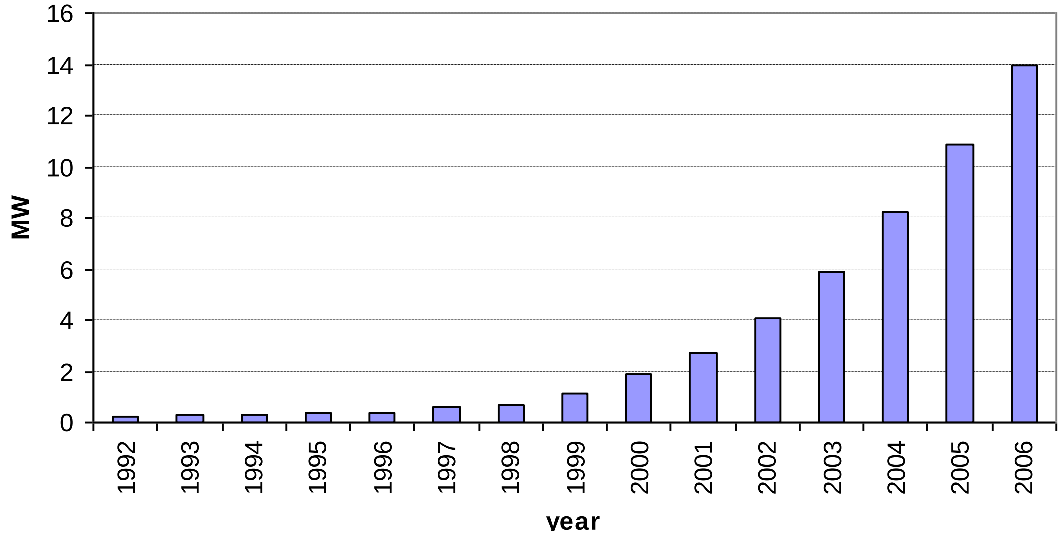


Figure 2.28 UK installed PV power (IEA 2007)

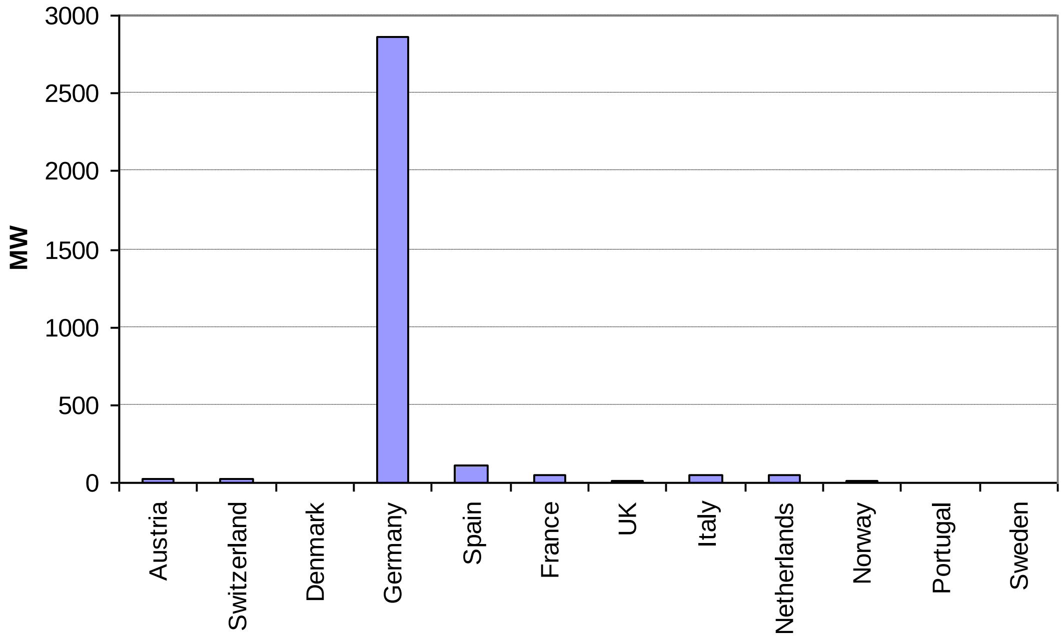


Figure 2.29 European installed PV power by country in 2006 (IEA 2007)

Export tariffs for domestic customers vary between suppliers and usually range between 6p/kWh and 8p/kWh. However a tariff of 3.5-4.5 p/kWh for total generation is also offered by suppliers (IEA 2007). There however is no Feed-in Law in the UK which has proven successful in Germany. Adequate policies encouraging the use of PV in the UK would increase the market and therefore further reduce the cost of the modules (Gross et.al. 2003).

c) Application examples of PV

PV systems can be used for homes, non-domestic buildings, large scale power plants, and satellites. Currently the most common application is in urban residential rooftop systems (Green 2000). Some application examples of PV in the UK are listed in Table 2.5. Other case studies of PV projects are listed on the British Photovoltaic Association website (British Photovoltaic Association 2004).

Table 2.6 UK Building Integrated PV case studies [(1) European Commission 2008, (2) IEA 2008, (3) EST 2003]

Case Study	**Application**	**Rated Power (kWp)**	**Year installed**	**Other technologies**
Shortenills Environmental Education Centre, Buckinghamshire (1)	Shelter	4.6	2001	-
Skegness Grammar School (1)	School demonstration project	2.5	1999	Wind turbine
Reading International Solidarity Centre (1)	Demonstration project	0.43	2002	-
Greenfields Development, Maidenhead (1)	15 social housing properties	20	2002	-
Haily Village Hall, Oxfordshire (1)	Village Hall	0.9	2002	-
Dyfi Valley Community Renewable Energy Project (1)	5 individual schemes (incl. Eco Park, Schools)	3 x 1.4 kW at Eco Park, 2 x 0.69 kW at schools	2002	Hydro, wind, solar thermal, wood heat and GSHP
Bronllys Hospital, Powys, Wales (1)	Hospital	60.62	2005	-
William J. Clinton Peace Centre, Northern Ireland (1)	Conference centre, Youth hostel, Art gallery, Café	2.4		ST hot water
BedZed, London (1)	Charging electric cars	108	2002	ST, CHP
Solar Office Doxford International (2)	Offices	73	1998	-
Jubilee Campus, Nottingham University (2)	University	53.3	1999	-
Llety Llanelli Foyer, Llanelli (3)	Social housing	28.6	2003	-
Eco House, Penrhos, Gwent (3)	House	2.1	2003	Wind turbine

Brogren et. al. (2003) presented a case study of integrated PV in buildings in Hammarby Sjöstad, an ecological Olympic village. Interviews with representatives from all involved, such as designers, contractors, and future residents were conducted and the systems were analysed and simulated. Obstacles to the integration of PV in buildings were identified as cost and lack of knowledge. It was also noted that the choice of PV technology was often based on aesthetics and a wish to appear environmentally friendly, rather than on optimal system performance.

2.4.3 Integration of PV and ST with CHP

The literature shows that in practice there is a distinct lack of combined "conventional" CHP and renewable energy technologies. Fuel cells, a form of CHP, however, are often combined with other renewable energy technologies used for the production of hydrogen.

The reasons for this trend could be:

i) "Conventional" CHP is an established technology and is not usually considered as a renewable energy technology.

ii) Although CHP is more energy efficient than other energy technologies, as discussed in section 3.4, CHP is mostly powered by natural gas, a fossil fuel, and therefore not a renewable source of energy.

iii) Fuel cell is a more recent technology, which has received a large amount of funding for its development and has consequently become quite popular for potential use as a renewable energy technology. Policies encourage the use of hydrogen, which is seen as having a large potential for future use.

iv) “Conventional” CHP is usually selected for economic reasons, rather than environmental. For projects where environmentally “friendly” solutions are specified, and where the expense is less important, other renewable energy technologies would rather be selected.

v) Using biomass to power the CHP system is another renewable solution and can be adopted easily, since biomass fuel is well established. However most biomass boilers currently are not CHP.

2.5 ANALYSIS TOOLS AND THE DECISION MAKING PROCESS

The tool developed in this research study is aimed to aid designers in the decision-making process when selecting appropriate CHP and renewable energy technologies to supply energy to a building or group of buildings. A wide range of factors affect the choice of technology combinations.

2.5.1 Decision making process

There are many different parties that should be considered in the decision-making process. Figure 2.30 shows the different parties involved, with the first party to consider being the inhabitants (in the middle of the diagram). The building inhabitants are probably the most affected by any decisions made and their views should ideally not be ignored. However the building project participants are usually the ones making the decisions, consulting other parties such as the public administration.

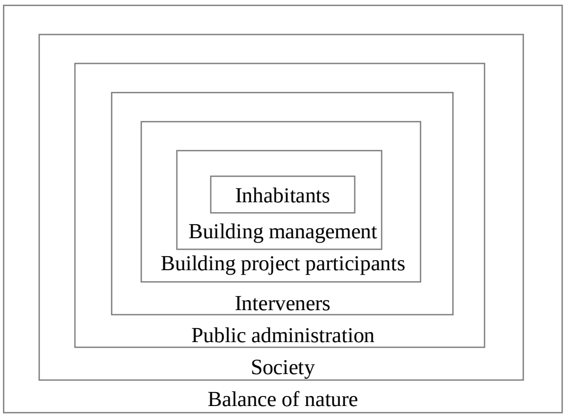


Figure 2.30 Interest groups in decision-making (Alanne 2003)

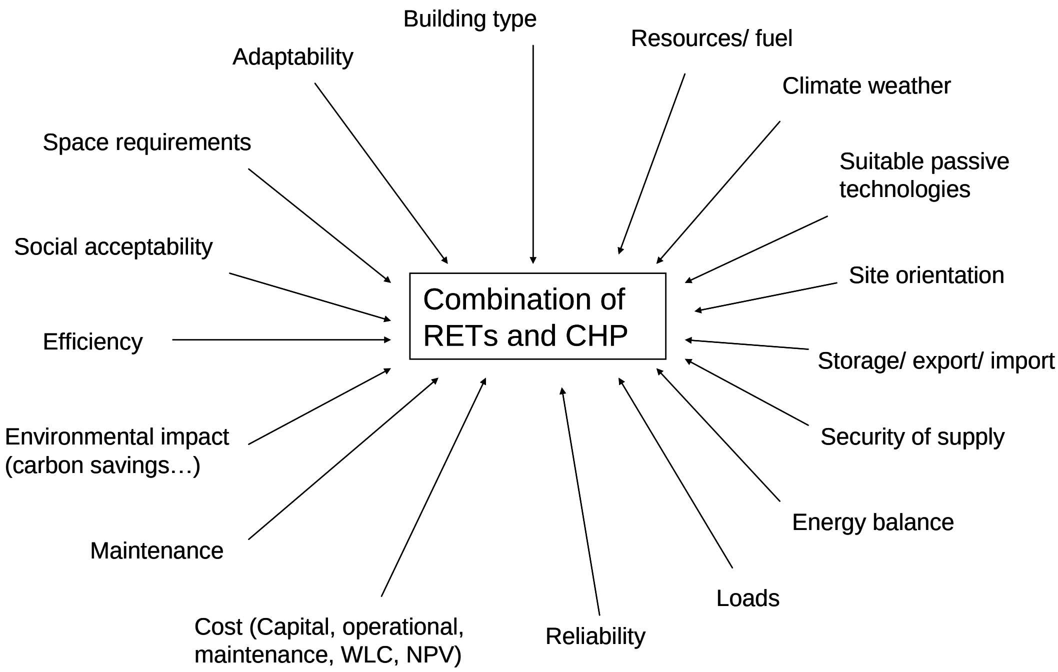


Figure 2.31 Factors to consider when choosing appropriate technologies

The choice of technologies will depend on several factors (Figure 2.31), amongst these are site dependant factors such as the climate and the resources available, the building type and associated loads, achieving a balance between energy demand, supply, and costs. These are included in the tool developed in this study. However other factors which are currently not included, such as social acceptance of renewables for example, can be a hindrance to the use of renewables. Faiers et. al.

(2006) and Iniyan et. al. (2001) investigated social acceptance of renewables. These and other factors need to be considered when selecting renewable energy and CHP technologies for buildings. Initial ideas about the selection process are summarised in Figure 2.32.

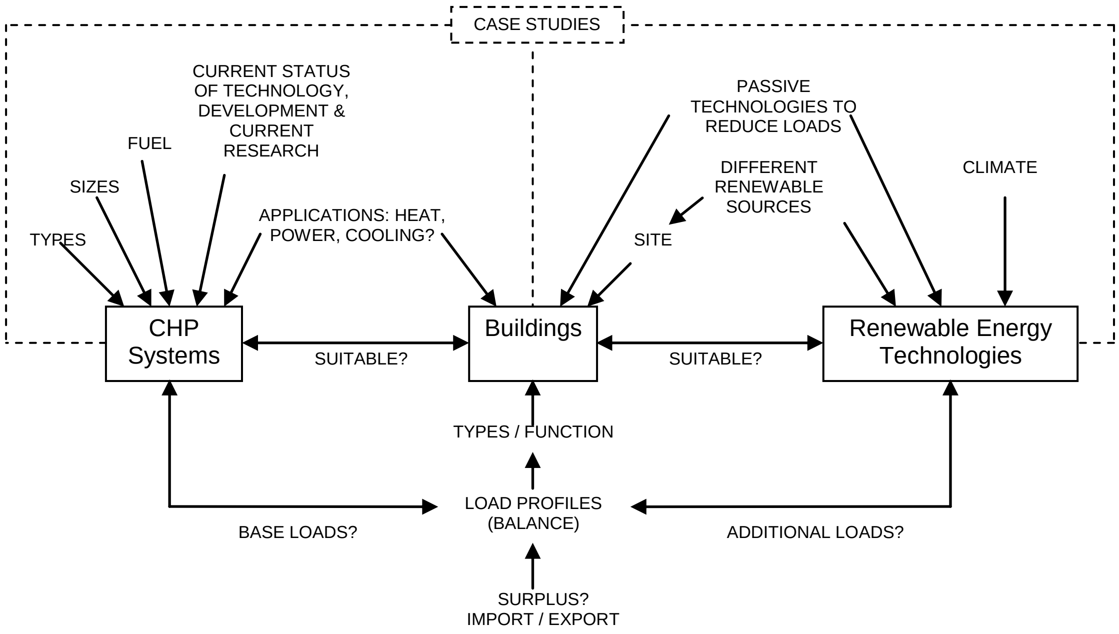


Figure 2.32 Initial ideas about selecting renewables and CHP for buildings

Huang et. al. (1995) describes the decision analysis process outlined in Figure 2.33 and summarises different decision analysis techniques. These include decision making under uncertainty, multiple criteria decision making, and decision support systems.

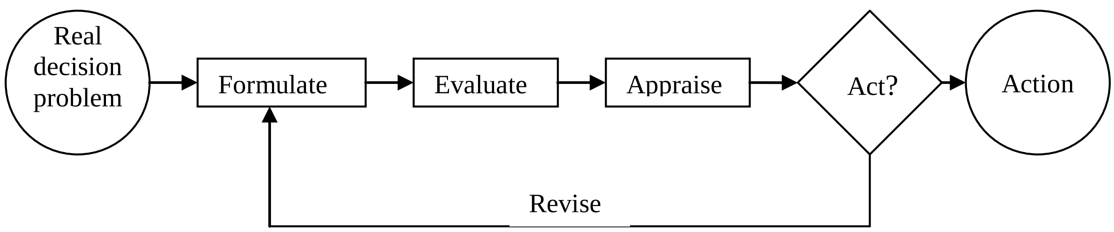


Figure 2.33 Schematic of the decision analysis process (Huang et. al. 1995)

Kaul et. al. (2004) outlined decision parameters for shifting towards alternative fuels from renewable resources. Assets and liabilities of renewable energy technologies and fossil fuels were compared in terms of cost, environmental impact, and social effects, all of which looked favourable for renewable energy. However the main barrier to the uptake of renewable energy technologies was identified to be political and industrial interests in continuing to use fossil-fuels.

Reneke et. al. (2002) mention that decision-makers often make decisions based on their experience and intuition. It is therefore difficult in some cases to model the whole decision-making process in decision-making tools. However certain factors in the decision-making process can be modelled to aid decision-makers in the form of analysis tools.

Rogers (2001) reviews decision-making techniques for engineering projects. The computer tool uses the economics-based project appraisal techniques which include net present value (NPV) and internal rate of return (IRR) evaluations described by Northcott (2002), combined with other appraisal factors such as emissions and environmental impact. Other factors can be taken into account by the user of the tool, who makes the final decision in the process.

Certain factors affecting the selection of energy systems for buildings can be predicted more or less accurately. However others such as building energy load profiles are difficult to predict as they are dependant on climate and occupancy behaviour. This uncertainty is usually not taken into account when selecting energy systems for buildings. With "conventional" energy systems (i.e. boilers and national electricity grid) hourly building energy load profiles are not usually required to size the energy systems. They are however important for the sizing of CHP and renewable energy systems for buildings. See Chapter 3 for building energy load profiles.

2.5.2 Analysis tools

Different analysis programs have varying levels of accuracy and are intended to be used at different stages in the design process. However, even the most sophisticated building analysis tools cannot always predict precisely. A building's construction quality and occupancy schedules are some of the factors that could vary dramatically from building to building.

The tool developed in this project determines building energy loads and load profiles and then finds the optimum sizes for the technologies for different technology combinations. (See chapter 4 for a more detailed description of the tool.) Different tools are available that carry out several of these stages.

Jebaraj et. al. (2004) review different energy models available. These include energy planning models, energy supply-demand models, forecasting models, optimisation models, and emission reduction models. Paradis (2004) gave a basic description of some energy analysis tools available and their applications for different stages in the design process.

a) Load prediction

The selection of appropriate technologies for a building is highly dependant on the loads of the building. Accurate load predictions are therefore important. Many load prediction/calculation tools are available, such as Hevacomp or Cymap. Load profiles however are more difficult to predict, as discussed in Chapter 3, and not many tools are capable of doing this.

Energy-10 PV simulates the hourly electrical load of the building to obtain realistic load profiles (Balcomb 2001). However, although the load profiles simulated are relatively realistic, a predicted load profile will always have some degree of uncertainty about it.

The tool developed in this study uses a compiled database of building energy load profiles and uses the Monte Carlo Method to take into account the uncertainties of building energy load profiles.

b) Economic analysis

Economics is another decision parameter. Economic assessment tools include the Building Life-Cycle Cost software (Paradis 2004).

Northcott (2002) compared different analysis methods for capital investment appraisal and concluded that NPV, a discounted cashflow method, takes into account the time value of money and avoids computational problems of other discounted cashflow methods. The tool developed in this study therefore uses NPV to compare economics of the different options.

c) Specific Technology Tools –CHP, solar thermal, PV

There are many tools that are designed for specific types of renewable energy system, for the design analysis of the technologies, some of which are: PVSYST, PV*SOL, PV-DesignPro, PVcad, and RETscreen (RETscreen International 2004) are used to design PV systems; SOLCHIPS (Lund et. al. 1992), Solar Benefits Model, SolarPro 2.0, SolDesigner, T*SOL, SOLCOST (Win 1980), TRYNSYS (University of Wisconsin 1990), WATSUN (University of Waterloo 1994), Polysun (Polysun 2000), EUROSOL (Lund 1995) and RETscreen (RETscreen International 2004) are used to design solar thermal systems; CHP Sizer (CIBSE 2004), Building Energy Analyzer and D-Gen PRO are used to design CHP systems (United States Department of Energy Office of Energy Efficiency and Renewable Energy 2008).

Renew is a renewable energy design tool for architects that investigates PV, wind power and solar water heating (Woolf 2003). Combinations of technologies can be considered in this design tool. The technologies are not optimally sized by the tool, but the user can change the inputs and quickly see the effect of these changes on the performance of the system. It is intended for designers with little experience of renewables and is meant to encourage architects to integrate renewables into their buildings. This “trial and error” approach in the sizing of technologies also makes this design tool a good medium for the designer to learn about the energy systems investigated and the effects the various parameters have on the system.

CHP Sizer (Carbon Trust 2004) is a software that carries out preliminary evaluations for CHP suitability in new or existing hospitals, hotels, halls of residence and leisure centres. A more detailed feasibility study should however be carried out before further considering CHP for a project.

EnergyPRO is a modelling and simulation software that carries out techno-economic analysis and optimisation of cogeneration and trigeneration energy projects for residential and non-residential buildings (Maeng et. al. 2002). Most small CHP systems in Denmark have been designed using the EnergyPRO tool (Lund et. al. 2005). This software however does not find the optimal sizes of technologies.

d) Geographic Parameters

Geographical parameters influence the selection of technologies and are especially important to consider when designing renewable energy systems. Jebaraj et. al. (2004) review solar energy models to predict solar irradiation. The tool developed in this study, however, uses average hourly irradiation values.

e) Simulation software

Simulation software is widely used to understand the operation and performance of renewable energy systems. TRNSYS, Simulink, MATLAB and ECLIPSE are some examples of simulation software.

TRNSYS probably is the most commonly used simulation software. The TRNSYS software (Beckman et al 1994) is a transient systems simulation program with a modular structure, which gives the program flexibility, and facilitates the addition of mathematical models to the program. TRNSYS can be used for the detailed analysis of systems whose behaviour is dependent on the passage of time. Applications include the study a solar combi-DHW system (Jordan et. al. 2000), modelling a hybrid PV- solar thermal system (Kalogirou 2001), carrying out building analysis studies for renewable energy systems (Mihalakakou 2002), and simulating a solar-hydrogen system (Ulleberg et. al. 1997).

Simulink, a product of MathWorks, is an interactive tool for simulating and analysing dynamic systems. It has been used to simulate hybrid energy systems (Iqbal 2003, El-Shatter 2002).

MATLAB is a simulation software which has been used to simulate process and performance information of a biomass gasifier-based power station (Jurado et. al. 2003), and to evaluate control strategies for a solar-hydrogen-biogas-fuel cell system (Hedstroem et. al. 2004).

ECLIPSE simulation package (Williams et. al. 2003) has been used to simulate wood-fired fuel cells in selected buildings (McIlveen-Wright et. al. 2003).

Simulation software is useful to understand the performance of energy systems, and can be used as part of the optimisation of technologies. However, not all aspects affecting the performance of the systems can be considered and modelled in simulations. A high skill level is required to make the correct judgements and produce accurate results. The tool developed in this study uses basic sizing procedures making use of simple simulation of the systems. The tool does not require many input parameters and does not require "expert" knowledge of the technologies investigated in order to operate the tool.

f) Optimisation Tools

Optimisation of the sizing and selection of energy systems is a main part of the computer tool developed in this PhD study. The optimisation process used is described in Chapter 4. Other optimisation tools are described below.

Models dealing with the optimisation of energy systems include MODEST (Model for Optimisation of Dynamic Energy Systems with Time dependent components and boundary conditions) (Henning 1998) and MARKAL (Fishbone et. al. 1981). They are used for municipal, regional, and national energy systems and to support national planning and policy decisions. Cosmi et. al. (2003) present an application of the R-

MARKAL model, investigating the feasibility of renewable energy on a local case study, taking into account legal issues and physical limits, and presenting the minimum cost solutions.

Deeco (Dynamic Energy, Emissions, and Cost Optimisation) is an energy optimization model, that analyses the effects of counteraction between energy technologies in local energy systems with respect to energy saving, emissions reductions, and cost. It determines best practice operation and is used to compute sustainability gains against financial costs. Lindenberger et. al. (2004) reported an extension to Deeco, taking into account passive technologies.

EnergyPro is a software package that calculates both energy and economics for heat, cooling and power plants, making combined technical and economic decisions more easily. It carries out a detailed analysis and can look at a number of combinations of technologies, including renewable energy and CHP technologies, calculating their energy conversion and outputting a report for each option separately. This tool is not, however, a decision-support software and cannot compare the various options.

RETScreen is a renewable energy technologies assessment tool for preliminary feasibility studies. The tool has three stages: Energy Model, Cost Analysis and Financial Summary and can be used for most building types. This tool however can only simulate one technology at a time.

Ameli et. al. (2007) presented the initial development of IDEAS, an integrated software package to design, optimize and monitor energy systems based on micro-turbines, fuel cells and internal combustion engines using fossil fuels and renewables. This software aimed to combine several existing commercial software packages. Links between the different software packages were developed to form a comprehensive selection tool to help in the decision-making process. A prototype has been developed with the aim of developing the actual software in the future.

The University of Strathclyde developed a tool to select energy efficiency measures and renewable energy and CHP technologies specifically for large estates (complex of different buildings). A University accommodation application was used as the basis for the model. Load profile prediction of other projects are then determined on this basis, scaling the profile as required. The results are categorized in different lists according to cost and emissions.

HOMER is a micro-power optimization model and is used to design systems for remote and distributed power. This software finds the least cost (life-cycle cost) combination of systems to satisfy the thermal and electrical loads. However the least cost combination of technologies for an application might not always be the best option. Other factors such as environmental performance need to be considered. It uses sensitivity analysis on most inputs to account for uncertainties. Values for uncertainty can be entered and the model shows the variation in the outputs due to these uncertainties. It however is difficult to model load profile uncertainty in HOMER as this uncertainty is difficult to quantify in values. This approach of taking uncertainty into account for the load profiles was therefore not adopted in the tool developed in this study.

Williams et. al. (2000) developed a tool meant for services engineers and which selects and sizes CHP systems for new buildings. Few inputs are required and the tool provides an indication of whether a more detailed investigation would be required. It estimates the building energy load profiles by using an average profile developed from a number of existing buildings. This, however, does not take into account the uncertainty of the load profiles in the sizing procedure.

2.6 CONCLUSIONS

Currently there is no computer tool available that selects suitable combinations of energy efficient technology such as CHP and renewable energy technologies for a project which takes into account the uncertainties of building energy load profiles using the Monte Carlo method. The aim of this research work was to develop a computer simulation tool to help in the decision making of choosing appropriate renewable energy and CHP systems for buildings. The tool uses the Monte Carlo method to take into account the uncertainty of building energy load profiles, using an existing large database of electricity, hot water and space heating load profiles. Details on energy load profiles of buildings and analysis of the developed computer tool is given in details in Chapter 3 and Chapter 4 respectively.

Chapter 3:

Energy Demand in Buildings

As discussed in Chapter 2, the energy consumption associated with buildings constitutes a large proportion of the total UK energy consumption.

When a new building is designed, it is important to consider energy at the very early stages of design. Considering the resources of the site, determining the best orientation of the building and making use of passive technologies can significantly reduce building energy requirements (Chwieduk 2003, Herbert 1998), before selecting energy technologies to cover the demand. Insulation and air tightness will reduce heating demand. However, too much insulation can cause overheating and therefore can create a need for cooling and air tightness can cause a need for mechanical ventilation. It is therefore essential that the various parameters of a building are carefully planned and balanced to ensure minimal energy wastage.

Figure 3.1 shows that domestic energy consumption has increased since 1970. This is due to there being more households since 1970 (Utley et. al. 2006). However, overall energy consumption per household has not increased since 1970 (Figure 3.2). This is due to increased energy efficiency balancing the increase in energy consumption which keeps it at a low level (Utley et. al. 2006).

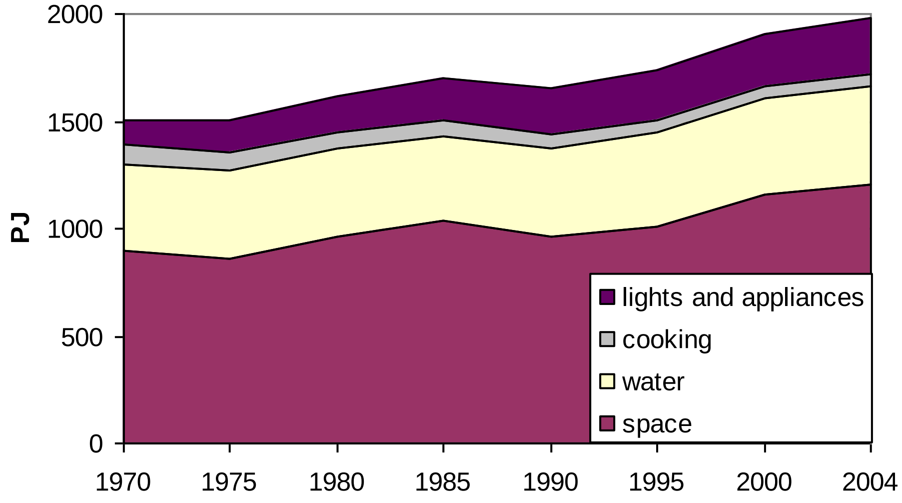


Figure 3.1 UK domestic energy consumption by end use (Utley et. al. 2006)

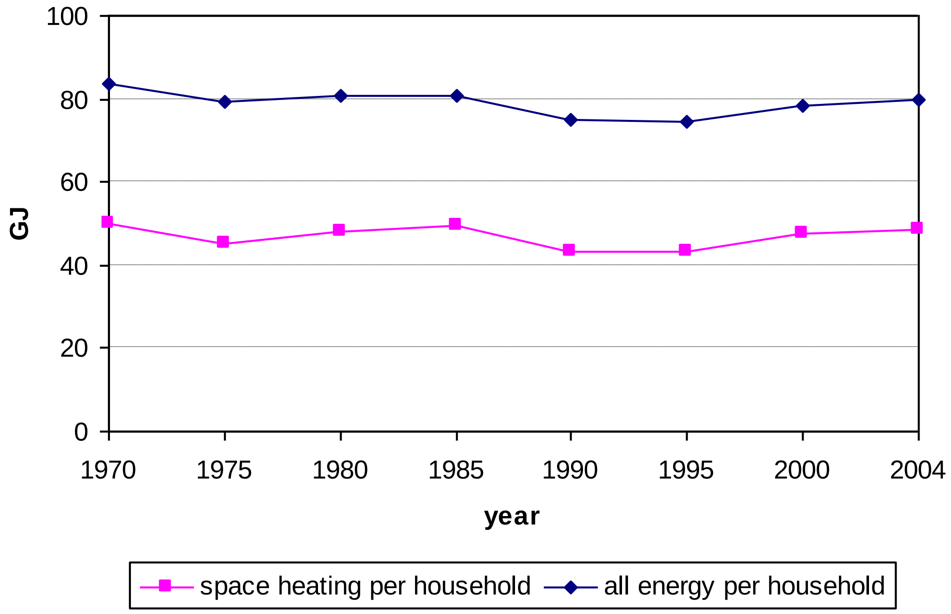


Figure 3.2 UK energy use per household (Utley et. al. 2006)

A building's energy consumption will be largely affected by climate, orientation, its function, building shape and form. Figure 3.2 shows a variation in domestic energy consumption over the years. This variation is due to temperature variations resulting in different heating requirements from year to year (Utley et. al. 2006). The use of the building and the behaviour of the users will also influence its electricity, hot water, space heating and cooling demand.

Typical energy loads for office buildings are shown in Figure 3.3. There is large variation in energy consumption between the different types of office buildings. The use of air-conditioning is the main use that adds considerably to the energy consumption in air-conditioned offices.

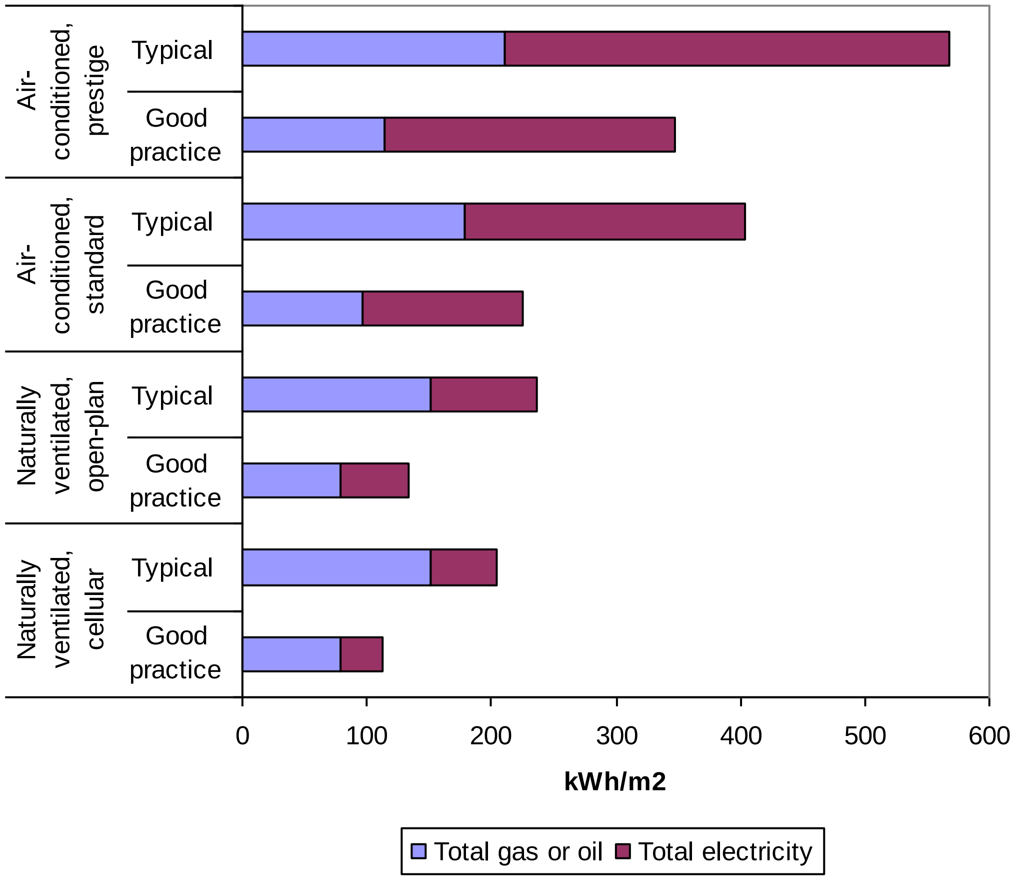


Figure 3.3 Annual delivered energy consumption for different office types ($\mathbf{kWh/m^2}$) (BRECSU 2000)

Rules of thumb building energy loads used in the tool are summarised in Tables 3.1 - 3.3.

Macmillan et. al. (2004) identified available data sources of energy use in the global building stock. The main sources identified for European data were: EUROSTAT, European Environment Agency and Enerdata. This data however is mostly annual data and does not include daily consumption patterns.

Table 3.1 Rules of Thumb Hot Water Demand (CIBSE 2004, BSRIA 2003, Institute of Plumbing 2002)

Source	Residential						Offices	
	terraced	Semi-detached	detached	1 bed flat	2 bed flat	3 bed flat	With canteen	Without canteen
	l/person/day			l/bed/day			l/person/day	
CIBSE	68 136	68 136	68 136				14 15	
BSRIA				115	75	55	15	10
IOPG				210	130	100	45	40
High Medium Low	136 102 68	136 102 68	136 102 68	210 162.5 115	130 102.5 75	100 77.5 55	45 22.25 14	40 25 10

Table 3.2 Rules of Thumb Electricity Demand (Action Energy 2000, BSRIA 2003, Institute of Plumbing 2002)

Source	Residential (kWh/m2/year)						Offices (kWh/m2/year)	
	terraced	Semi-detached	detached	1 bed flat	2 bed flat	3 bed flat	With canteen	Without canteen
ECON19							33 54	33 51
BSRIA							54 85	51 85
IOPG	77 80	77 40	39 79	48	41	39		
High Medium Low	80 79 77	77 59 40	79 59 39	48 48 48	41 41 41	39 39 39	85 54 33	85 53 33

Table 3.3 Rules of Thumb Space Heating Demand (BSRIA 2003)

Source	Residential (W/m2)						Offices (W/m2)	
	terraced	Semi-detached	detached	1 bed flat	2 bed flat	3 bed flat	With canteen	Without canteen
BSRIA	60	60	60	60	60	60	70	70
High Medium Low	60 60 60	60 60 60	60 60 60	60 60 60	60 60 60	60 60 60	70 70 70	70 70 70

Daily and hourly building energy load profiles are a good medium to help understand the energy consumption patterns of a building and they are especially useful for the design of renewable energy technologies and CHP systems, and are vital data used in the tool developed in this study.

3.1 BUILDING ENERGY LOAD PROFILES

Energy load profiles for buildings depend on many factors, such as the type of building, occupancy, climate and occupancy behaviour. Occupancy behaviour in residential buildings and their effect on energy demand is investigated by Pett et. al. (2004) and Michalik et. al. (1997), recognising the uncertainty associated with their behaviour.

Monitoring of past energy use of a building will give the most accurate predictions for future energy requirements (Parker 2003). However for a new-build or some refurbishments this will not be possible. In these cases typical load profiles are estimated, by taking the monitored load profile of a similar building, an average of several, or by simulating a typical profile.

Metering existing buildings to obtain “real” load profile data for similar buildings is more accurate. However, extensive metering projects of existing buildings to obtain real load profile data would be expensive and not feasible in all cases (Akbari 1995). An alternative is to simulate load profiles. However such techniques would nevertheless also require “real” data for them to be validated (Akbari 1995).

In their model, Hawkes et al (2005) used measured residential electricity demand profiles from the BRE and heating load profiles were generated assuming heating times in the mornings and evenings of winter days. “Typical” profiles were obtained for small, medium and large dwellings. The model in their study used 5 minute demand profiles for 6 days of the year (2 winter, 2 summer and 2 shoulder days).

Yao et. al. (2005) introduced a method to predict daily load profiles using the thermal resistant network method. The tool they developed can be used on both the macro and micro levels. They developed “typical” appliance, DHW and space heating load profiles for different dwelling types and different occupancy patterns. Paatero et. al. (2006) used a bottom-up load model, constructing the load profiles from elementary load components.

Aydinalp et. al. (2003) described a neural network method for modelling residential energy consumption. The most commonly used methods are the engineering method and the conditional demand analysis method (Aydinalp et. al. 2003).

Diversity of demand needs to be taken into account when loads are combined for a multi-unit building, as the probability of the peaks in energy demand occurring at the same time is quite small. This can be done by applying diversity factors. Stallcup (2004) defines diversity factor as: “*the ratio of the sum of the individual maximum demands of the various subdivisions of a system, or part of a system, to the maximum demand of the whole system, or part of the system, under consideration.”* In the computer tool developed in this study, diversity is taken into account by using different load profiles and the Monte Carlo method to take into account the uncertainty of building energy load profiles.

Taking an average or “typical” load profile and scaling it to suit the project is one way of generating a typical load profile. This method was used by Cockroft et. al. (2006) to generate load profiles to compare different heat and power sources for the

UK domestic sector. Load profiles however vary depending on many factors such as occupants behaviour and climate, which are difficult to predict and a "typical" load profile therefore can't represent all buildings of a kind. Appropriate simulation of demand patterns could possibly provide more realistic predictions. In the tool developed in this study, real load profiles are collected in a database and the Monte Carlo Method is used to take into account the uncertainty of the load profiles (see Chapter 4 for a description of the tool).

3.1.1 Monte Carlo Method

Kalos et. al. (1986) and Higham (2004) give a description of the Monte Carlo Method (MCM). *"In a Monte Carlo Method successive simulations are run with the randomly generated inputs until a statistically significant distribution of outputs is obtained"* (Isukapalli 1999). The MCM can be used to take uncertainties into account. Dolan et. al. (1996) used the MCM to model residential electric water heater loads and Takoudis et. al. (2004) assessed offshore wind farm cable reliability using the Monte Carlo Method. Nishio et. al. (2006) developed a Monte Carlo simulation-based tool to generate household demand data for Japan. The application of Monte Carlo sampling can be used to find the distribution of outputs given random input variables. Coates et. al (2003) used this method to solve engineering economy problems using commonly available simulation tools. Pons et. al. (2003) compared the design for system integrity (DSI), a probabilistic methodology using the discrete combinatorial method, with the MCM and fuzzy theory, both using random variables and are both commonly used in engineering applications. Both the DSI and the MCM yielded similar output accuracies, depending on the number of iterations in the

MCM. The fuzzy theory however was not as accurate. DSI however requires probabilities associated with each input.

Gamou et al (2002) treat building energy load profiles as random variables in the sizing of CHP systems. They use a sensitivity analysis and an enumeration method to take into account their uncertainty. A similar method is used in the tool developed in this study. The Monte Carlo Method is used to take into account the uncertainty of load profiles and can also be used to take diversity into account (McQueen et. al. 2004). In the tool developed in this study, the tool does not use the same load profile for a building consisting of several units. For example, for a residential building consisting of 10 flats, the tool uses 10 load profiles, each randomly selected to create a total load profile for the building. By adopting this approach, diversity is taken into account.

The Monte Carlo method is applied as follows in the tool:

1) Load profiles are randomly selected from the appropriate category of the tool's load profile database. E.g. For a building consisting of 5 flats and some office space, 5 load profiles are randomly selected from the flat category of the database and one load profile is selected from the office category of the database. The 6 load profiles are then combined to create one total load profile for the building. This process is carried out for electricity, space heating and hot water load profiles.
2) The technologies are sized for each technology combination in the tool, giving outputs for this option, which are then stored in a spreadsheet.
3) Steps 1 and 2 are repeated 100 times to obtain 100 sets of outputs.

4) From these outputs, the most probable technology sizes and their emissions and costs are found for each technology combination (i.e. the most frequently occurring option).

Chapter 4 gives a more detailed explanation about the application of the MCM in the tool.

3.1.2 Space heating load profiles

Space heating load profiles vary with climatic and weather conditions. In the UK space heating requirements will be highest in the winter months. “Typical” space heating load profiles peak in the morning and in the evening for domestic buildings (Yao et. al. 2005). Office space heating is required during office hours with a base heating only required during the night and weekends.

Little “real” space heating load profiles were found in the literature. The domestic space heating load profiles generated by Yao et. al. (2005) were therefore used in the tool and the space heating load profiles for offices were generated using rules of thumb (see Chapter 4). The load profiles could however be replaced with real data when it becomes available.

3.1.3 Electricity load profiles

Figure 3.4 shows the typical electricity demand profiles on the national grid based on their recorded data. This data however represents the total demand on the grid and does not reflect the demands of individual buildings.

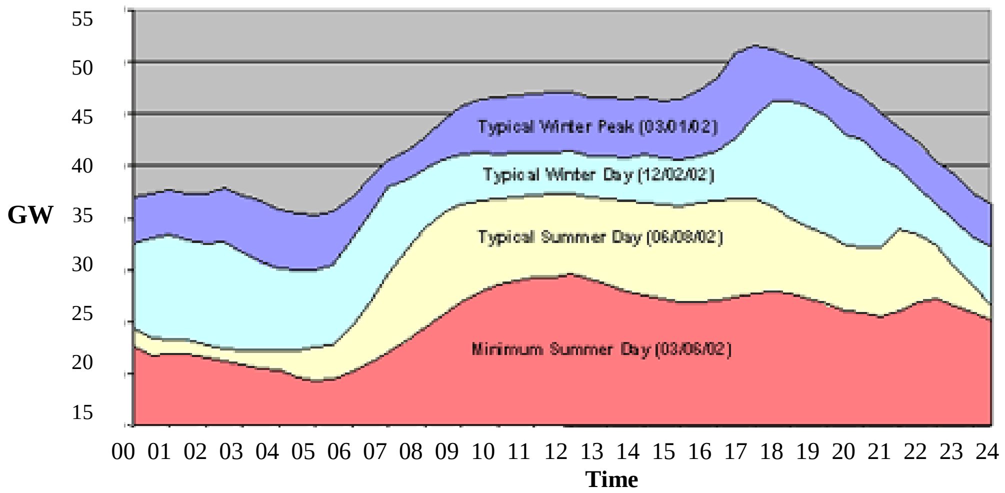


Figure 3.4 Actual national grid summer and winter demand for 2002 (National Grid Group 2004)

Stokes et. al. (2004) present a model of domestic lighting demand, based on half-hourly data measured for a sample of 100 homes in the UK and Yao et. al. (2005) developed "typical" electricity load profiles for different dwelling types.

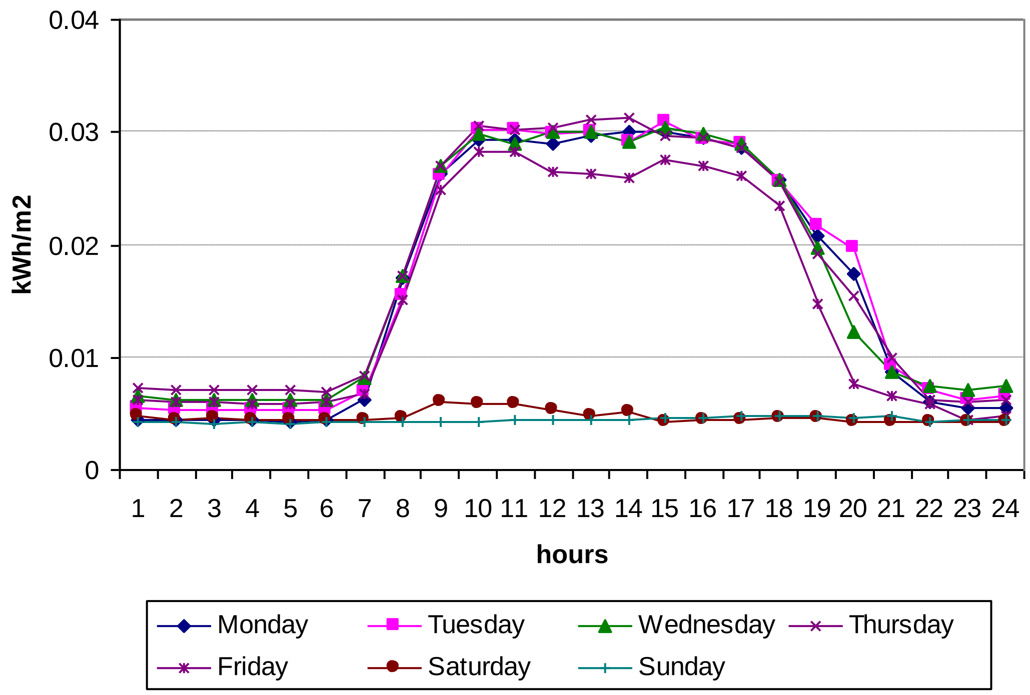


Figure 3.5 Typical weekly electricity consumption for an office building (Nottingham City Council 2004)

The different components of office building electricity demand profiles are investigated by Akbari (1995). The load profiles peak during office hours, with most equipment and lighting on during these times and a minimum base load during the weekend and non-occupied hours (Figure 3.5).

Nottingham City Council has kindly provided electricity load profile data from their buildings. Figure 3.5 shows an example week for one of their office buildings. This data has been incorporated into the computer tool developed in this study.

3.1.4 Hot water load profiles

Domestic hot water consumption affects many aspects of the design of a hot water system, such as the sizing of hot water stores (Jordan 2000) and CHP and renewable energy system design. A total domestic hot water demand per day can be calculated from rule of thumb data. However in order to determine the potential for CHP and renewables for a building, the distribution profile of this demand during the day is also of interest. Graphically presented 'instantaneous' heat and power demand load data (half-hourly or hourly data) are normally used for this purpose (CIBSE 1999).

Jordan et. al. (2001) and Lutz et. al. (1996) presented simulation modelling of hot water usage patterns. Load profiles vary depending on the building type, mix of building types and number of units (e.g. flats). With existing buildings, the DHW demand and profile could be recorded over a period of time. However with new build or refurbishments where occupancy may change, then the domestic hot water demand is estimated by simulation or by using real data from similar buildings.

Hot water demand in offices is minimal, compared to residential hot water demand and occurs mostly during office hours. Hot water demand can therefore be predicted relatively accurately by knowing office occupancy hours throughout the day. Domestic hot water demand however, is more difficult to predict.

Jordan et. al. (2000) generate realistic hot water load profiles using probabilities of hot water draw-offs of different appliances throughout the day for domestic buildings. The Energy Saving Trust is currently undertaking a monitoring study for domestic hot water energy throughout the UK (Scotland, North England, Midlands, South England) (EST 2005). This data however is not available at present.

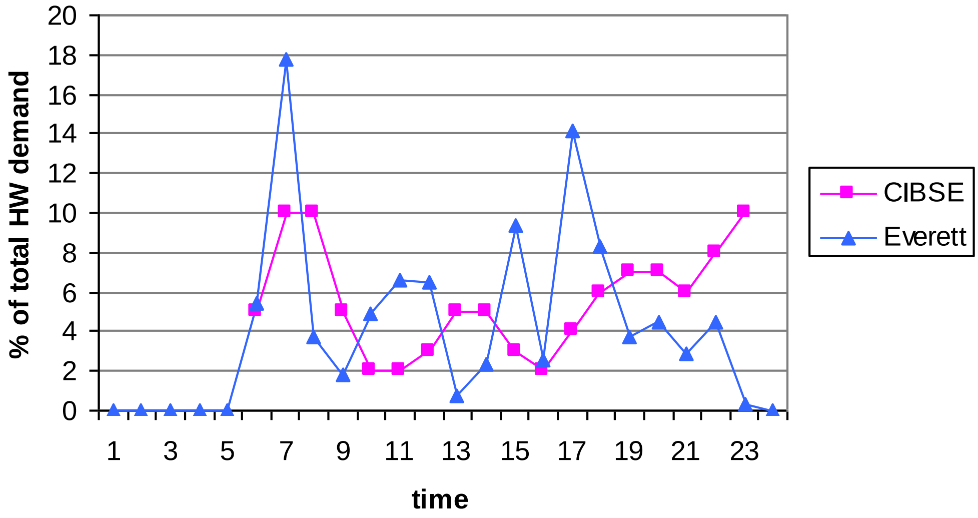


Figure 3.6 UK residential hot water profiles (CIBSE 2004, Everett et. al. 1985)

A literature search for typical residential hourly domestic hot water demand profiles identified a lack of reliable data for the UK. On the other hand, a vast amount of US data is available. Figure 3.6 shows that the UK data from different sources does not follow the same pattern, whereas the US data does (Figure 3.7), which indicates that the "typical" load profile data found by the different sources is relatively accurate. Therefore, as part of this research a survey was carried out to collect domestic hot water demand profiles for the UK.

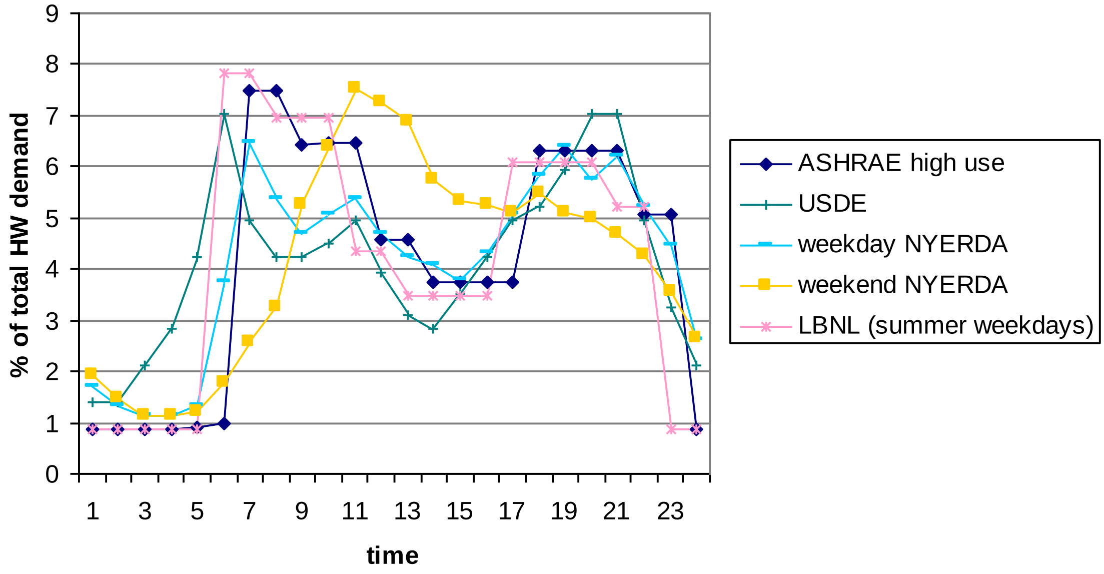


Figure 3.7 US residential hot water demand profiles (ASHRAE 1999, Wiehagen et. al. 2003, USDE 2000, Goldner 1994, Lutz et. al. 1996)

3.1.5 Conclusions

The accuracy of energy predictions is vital for a good energy system design, especially for CHP and renewable energy technologies. This data forms the basis of the design process and therefore is a major part of the tool developed in this study.

However, from the literature, not much UK load profile data has been published. The Nottingham City Council electricity load profile data for office buildings and the hot water demand survey carried out in this study are the major sources of data used in developing this tool. (See Chapter 4 for the data used in the tool.) Other load profiles could be added to the tool database as they become available.

3.2 DHW DEMAND SURVEY IN RESIDENTIAL BUILDINGS

As previously mentioned, data for actual UK residential hot water demand are limited in the literature. Although space heating demand is usually larger in the UK, space heating demand is related to climate and weather and therefore more easily predicted than hot water demand. Hot water load profiles are difficult to predict, especially for residential buildings, as they depend highly on occupancy and behaviour patterns. Load profiles can differ for different households and for different days in the same household. Thus, as part of this research, a survey of DHW demand in residential buildings was carried out to obtain real DHW load profile data that was used in the tool database, and is vital to the tools MCM simulation. The survey consists of two parts: a survey questionnaire and a monitoring study.

3.2.1 Survey Questionnaire

The questionnaire developed for this survey is outlined in Appendix 1. The survey consists of two parts: a general questionnaire about the dwelling and a diary study. The questionnaire enables the load profiles collected to be classified into different categories, such as building type or occupancy. In the diary study the hot water consumption patterns are recorded. The survey sample consists of 35 participants, each completing from 1 week to 18 weeks of the diary study.

The type of buildings, number of bedrooms and occupants considered in the survey is given Table 3.4.

Occupancy figures for each dwelling are usually not easily predicted when designing a new building and the number of bedrooms is usually related to the building type. The load profiles obtained were therefore classified according to building type in the tool database. Table 3.5 summarises the number of questionnaires completed for each building type.

Table 3.4 Occupancy and number of bedroom ranges

Building type	**Range of occupancy**	**Range of number of bedrooms**
Flat	2-3	1-2
Terraced house	1-5	1-4+
Semi-detached house	2-8	2-4+
Detached house	2-6	3-4+

Table 3.5 Number of questionnaires completed for each building type

Building type	**Completed questionnaires**
Flat	3
Terraced house	8
Semi-detached house	15
Detached house	9

3.1.2 Monitoring Study

The monitoring study was carried out in conjunction with the survey questionnaire. Six houses were monitored to record their hot water use. However, the reliability of measured data from two dwellings was not good and hence disregarded. The building types included in the study were: 1 flat, 2 terraced houses and 1 semi-detached house. Different options were compared to monitor the hot water consumption of the dwellings:

a) Use of one flow meter at boiler/hot water tank outlet: This option requires one flow meter. However, this does not allow separate monitoring of hot water used for say washing up, bath, etc.

b) Use of flow meters at boiler/hot water tank and at points of use: This option enables the monitoring of both the total flow and the flow at each point of use (kitchen, bathroom, etc…), giving a better understanding of the use of DHW in the dwelling. However the cost of flow meters is quite high as a non-intrusive ultra sonic flow meter which can be clamped to the water pipe costs around £2,000. This makes this option less cost effective and not viable for this study.
c) Use of temperature sensors to detect hot water usage at each appliance: Temperature sensors can give a good indication when hot water is used. The Market Transformation Programme (2007) used temperature sensors attached to the hot water pipes leading to each appliance to detect when and from which appliance hot water was used. A rise in Temperature within the pipe indicates that hot water is used, and a slow decrease in water temperature thereafter indicates hot water use has ceased. The use of temperature sensors is a less expensive and more viable option.
d) Use of a combination of flow meter and temperature sensors: Adding a flow meter at the outlet from the boiler/hot water tank to option c, would give a better understanding of the flow rates of the hot water used. A clamp-on flow meter was chosen for this purpose. Although an in-line flow meter provides more accurate readings, a clamp-on flow meter is less intrusive to the home owner and was therefore chosen for this study.

The monitoring in this study was carried out using temperature sensors attached to the hot water pipes of the different appliances within the dwellings (see Figure 3.8). When hot water was used, the temperature recorded by the sensor increased. This enabled the identification of when and from which appliance hot water was used throughout the day in the dwellings. Figure 3.9 shows an example of the temperature change throughout the day of the hot water pipes leading to the hand basin, bath and kitchen sink in one of the houses monitored. Market Transformation Programme (2007) used this method in their pilot study for domestic hot water consumption monitoring.

Figure 3.8 Temperature sensor

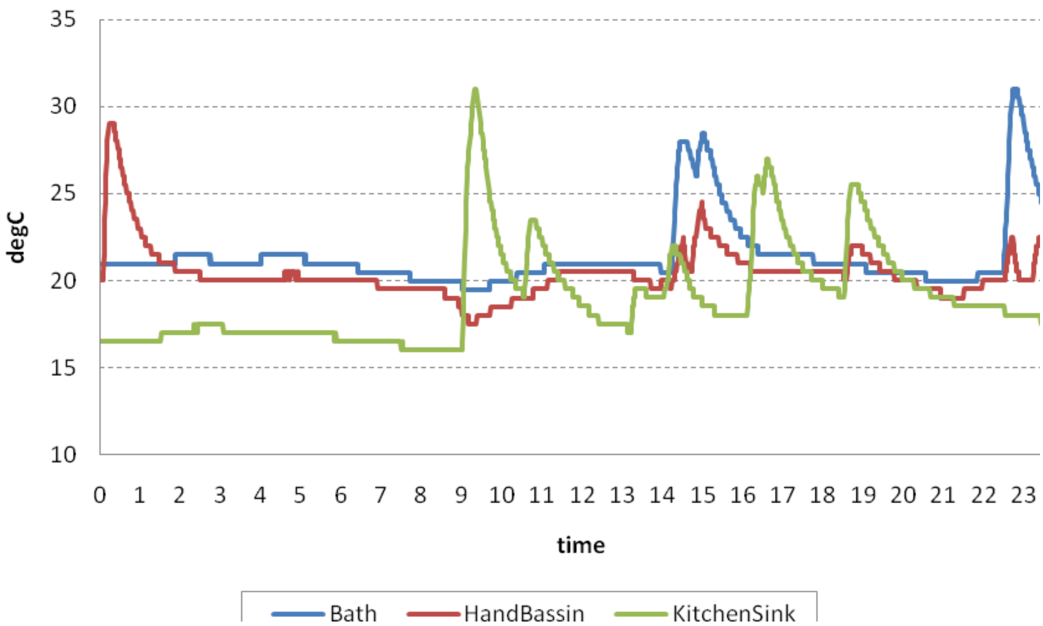


Figure 3.9 Example temperature sensors reading

It is worth noting that the location of temperature sensors is important. A larger pipe for example has a longer cooling period between draw-offs and would therefore make some draw-off difficult to identify. This issue was identified by the Market Transformation Programme (2007). In some instances, when very little water is used, hot water might leave the tank/boiler, but not reach the point of use. In this case, the temperature sensor at the boiler/tank outlet would indicate hot water use. However this hot water would not be able to be allocated to any point of use (Market Transformation Programme 2007).

Although the monitoring method of collecting data is more precise as it doesn't rely on participants remembering to record their hot water consumption, the questionnaire enabled more data to be collected. The data collected by both methods was used to form hourly hot water load profiles to be loaded into the tool.

3.1.3 Load profile formation

The temperature sensor and survey questionnaire data provides information on when hot water was used throughout the day. However, the amount of hot water (litres) that was used in each instance was not established. To determine this, typical hot water usage of different appliances were required.

Table 3.6 Appliance hot water flow rates and usage [* data from Grant 2002]

Appliance	**Average flow rate (l/min)**	**Usage period (minutes)**	**Usage (litres)**
Hand basin	1.15	3	3
Shower	3.39	5	17
Kitchen sink	1.01	5	5
Bath			70*

As mentioned in Section 3.1.2 a clamp-on flow meter was used to record flow rates of different appliances to determine typical flow rates. Usage time periods of different appliances were estimated and used to calculate the typical hot water usage of each appliance (see Table 3.6). For bath hot water usage 70 litres was assumed (Grant 2002).

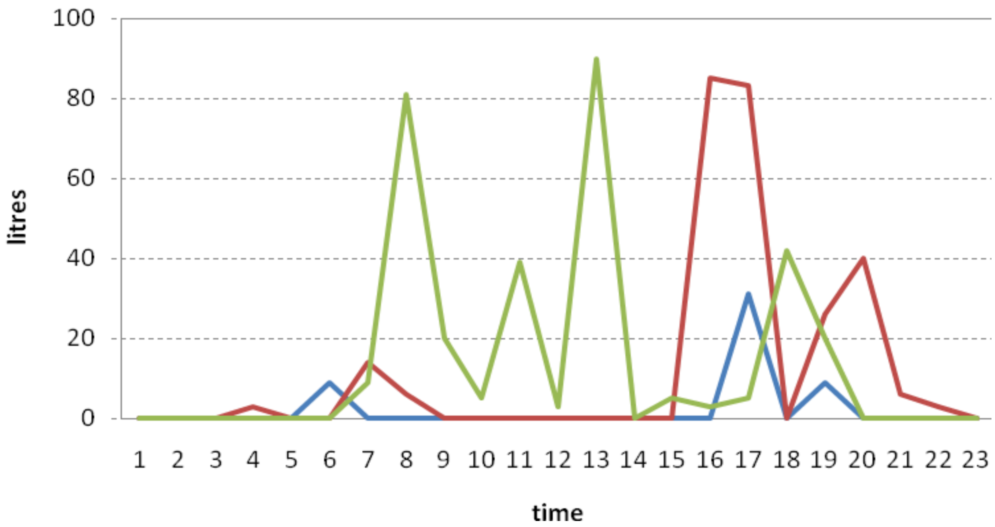


Figure 3.10 Example hot water load profiles for 3 different weekdays for a semi-detached house

Daily hot water consumption (litres per hour)

Residential flat (weekday)

hour

01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
78	0	0	0	0	0	0	40	20	0	0	0	0	0	0	0	0	3	0	8	0	5	17	3
0	0	0	0	0	0	0	37	0	20	0	0	0	0	0	0	0	3	0	5	3	10	0	0
0	3	0	0	0	0	0	20	20	0	17	0	0	0	0	0	0	0	0	0	0	3	5	0
0	0	0	0	0	17	0	20	20	3	0	0	0	0	0	0	0	0	0	0	0	5	3	0
0	0	0	0	0	0	0	20	0	0	17	17	0	0	0	0	0	0	0	0	0	0	78	17
0	0	0	0	0	0	0	0	40	17	0	0	0	0	0	0	0	5	0	0	0	22	0	0
0	0	0	0	0	0	0	17	37	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0
0	0	0	0	0	17	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	5	17	0
0	0	0	0	0	0	0	0	20	17	17	0	0	0	0	0	0	0	0	0	0	0	5	0
0	0	0	0	0	17	0	0	20	0	20	0	0	0	0	0	0	5	0	0	0	20	17	3
0	0	0	0	0	17	0	0	20	0	0	0	17	0	0	0	0	0	0	0	0	0	0	20
0	0	0	0	0	0	0	0	37	0	17	0	0	0	0	0	0	0	0	17	0	5	0	0
0	0	0	0	0	17	0	0	20	17	0	0	0	0	0	0	0	0	0	0	17	0	5	0
0	0	0	0	0	17	0	0	20	0	20	0	0	0	0	0	0	17	5	0	0	0	0	0
0	0	0	0	0	17	0	0	20	17	0	0	0	0	0	0	0	0	0	0	17	0	17	0
0	0	0	0	3	0	0	0	0	0	0	39	0	0	0	0	0	3	0	0	17	0	0	0
0	3	0	0	0	0	0	0	0	0	20	20	0	5	3	3	9	0	20	0	6	0	20	3
0	0	0	0	0	0	0	0	0	0	40	0	0	3	0	20	0	0	3	0	25	20	0	3
0	0	5	17	0	0	0	0	0	0	17	0	0	0	0	0	20	0	3	0	5	0	0	3
0	0	0	0	0	0	0	0	0	0	42	0	0	0	8	0	0	23	0	0	0	5	0	3
0	0	0	0	17	0	0	0	0	0	3	20	17	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	3	0	0	3	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	17	0	5	5
0	0	0	0	0	0	0	17	20	3	0	0	0	0	8	8	0	0	8	0	3	3	0	3
0	0	0	0	0	0	0	3	20	17	0	3	5	5	3	0	0	0	0	0	0	3	3	0

Figure 3.11 Screenshot of the tool's hot water load profile database

The typical hot water usages for the appliances were then combined with the survey questionnaire data and the data collected from the temperature sensors to form hot water load profiles (Figure 3.10). This data was loaded into the computer tool load profile database to be used in the tool. Figure 3.11 shows a sample screenshot of the database in the tool.

3.3 CONCLUSIONS

Building energy load profiles were collected as part of this work. However, not much domestic hot water demand data was available from the literature and a survey was therefore conducted to collect domestic hot water load profiles for different residential building types. The building energy load profiles from the literature and the survey were collated to form a database for the computer tool developed in this tool.

Chapter 4:

Computer Simulation Tool Development

4.1 INTRODUCTION

The development of the computer tool is described in this chapter. This computer tool allows suitable combinations of renewable energy technologies and combined heat and power (CHP) systems to be selected for a building. It enables the selection of more appropriate technologies for the supply of electricity, hot water and space heating by optimising the integration of the combined technologies for different building types. The tool also aims to facilitate the decision-making process of the designers, by identifying workable solutions for a project, as well as streamlining the number of options from which a reliable decision could be made.

4.2 DESCRIPTION OF THE COMPUTER TOOL

The computer tool was developed using Visual Basic for Application (VBA) in Excel to size and compare different combinations of CHP and renewable energy technologies for different building types. VBA in Excel was chosen as it is widely available to designers. The Monte Carlo Method is used to take into account the uncertainties of building energy load profiles in order to provide a most probable output from the tool. One of the specific outputs of the tool is the techno-economic analysis and carbon savings from which selected renewable energy/CHP combinations can be compared and provide the decision-makers with the required information.

The main technologies that can be analysed by the computer tool include one or a mixture of the following technologies: gas-fired CHP systems, solar thermal systems, PV panels, fossil fuel boilers and national grid electricity.

The tool is developed in two Excel files each combining a different renewable energy technology (Photovoltaics and Solar Thermal) with CHP. Each tool consists of 3 main blocks designated as block A to C where:

A. The building loads and load profiles are processed in Block A.
B. Sizing and selection of technical parameters of technologies followed by a financial and environmental analysis is carried out in Block B.
C. A comparison and evaluation analysis of technologies or combination of technologies is finally given in Block C that would facilitate the selection of the appropriate option.

A detail of each block is given as follows:

4.2.1 BLOCK A: Determining the building loads and load profiles

The first step in selecting a cost effective technology for a building using the computer tool is to determine the building’s energy loads and load profiles. The procedure for analysing energy loads of a building is given in the flow chart of Figure 4.1.

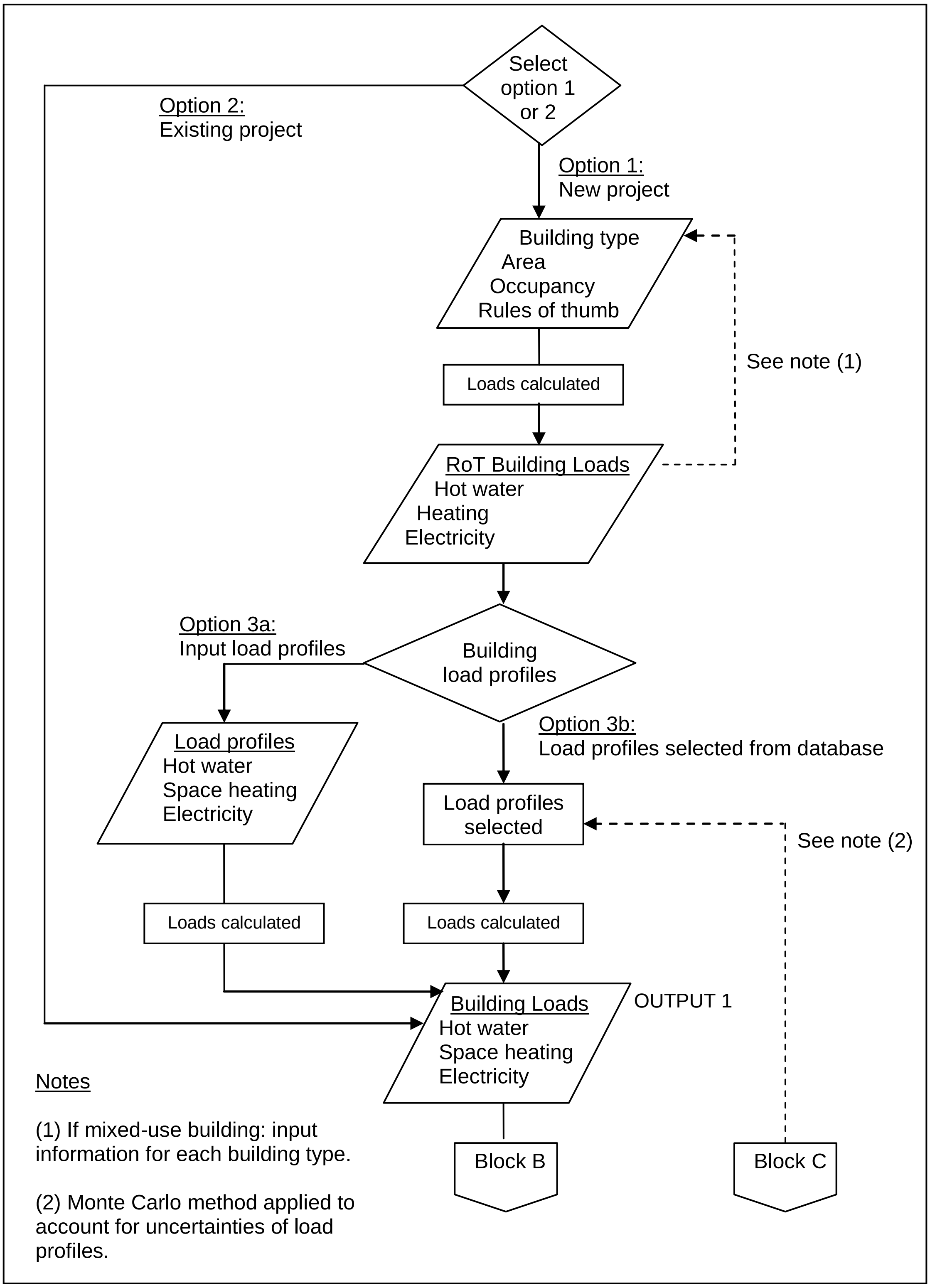


Figure 4.1 Block A - Building loads and load profiles

Prior to starting the analysis, in Block A a user interface window appears, as shown in Figure 4.2, that prompts the user to choose between two options: an already existing project or to start a new one. If an already existing project is selected, the tool skips the following steps of Block A and goes directly to the interface, summarizing the building loads (Figure 4.6). If a new project is selected further user interface windows, which form part of block A, will be displayed to perform the building energy loads calculations. These steps are described below.

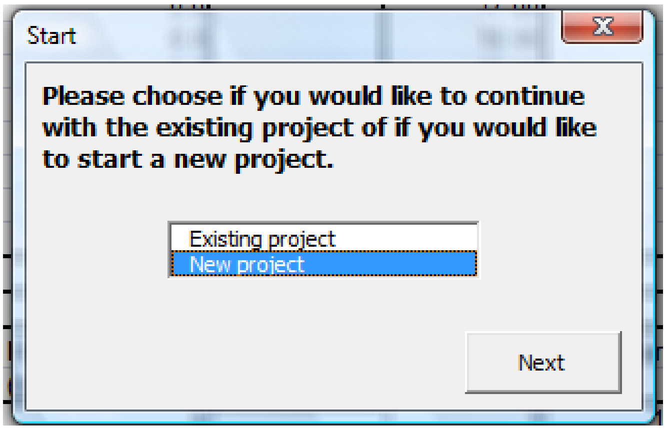


Figure 4.2 User interface start window

a) Building Energy Loads

If a new project is selected in Figure 4.2 information about the project building types is entered on the user interface shown in Figure 4.3. The tool first gives an estimate of energy consumption including building space heating, hot water and electrical power using rules of thumb data determined by the tool user. Cooling is currently not included in the tool; however it could be incorporated at a later stage. Rules of thumb energy consumption data for building is classified as high, medium or low. Rule of thumb oad data for different types of buildings have been formulated from the values reported in various reference sources (see Tables 3.1, 3.2 and 3.3). Depending on the characteristics of the building, high, medium or low building loads can be selected or other rules of thumb can be entered. For a mixed-use project (i.e. a complex with different building types) the information is entered for each building type. This is done by selecting “Next Building Type”, after having entered the information for the first building type. This is repeated until the information for each building type has been entered.

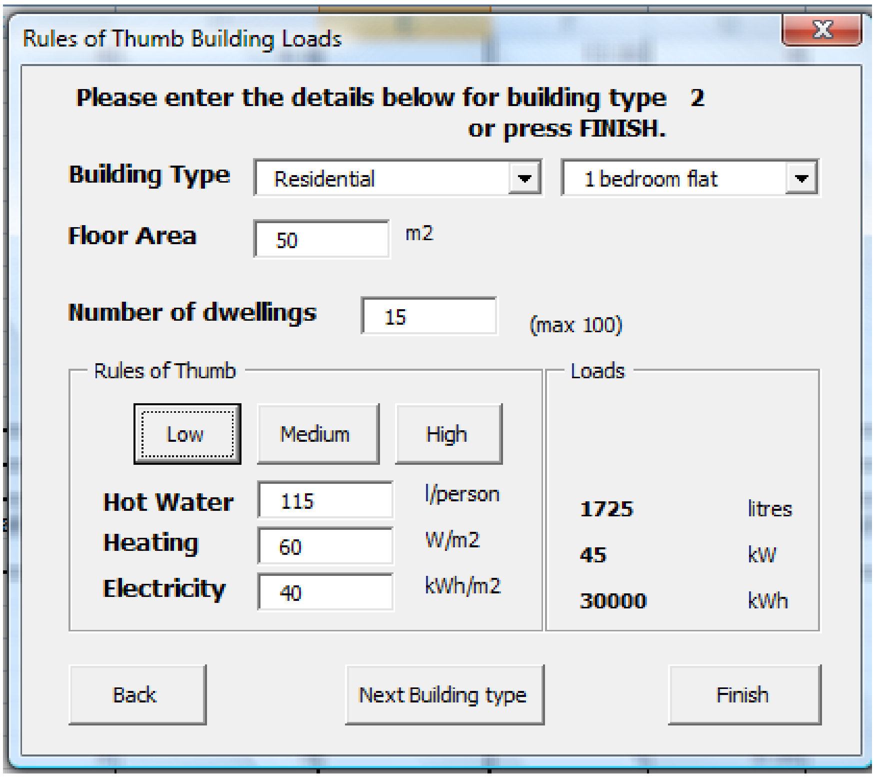


Figure 4.3 Rules of Thumb user interface

The rule of thumb (RoT) building energy load calculation is carried out by the tool as follows:

- RoT hot water demand (D_{HW}): Hot water rule of thumb loads are given in litres per person per day for houses and office and in litres per bedroom per day for flats.

For houses and offices:

D_{HW} (l/day) = RoT (l/person) × Occupancy Equation 4.1

For flats, hot water demand:

D_{HW} (l/day) = RoT (l/bedroom) × Number of bedrooms Equation 4.2

- RoT space heating demand (D_{SH}):

D_{SH} (W) = RoT (W/ m^2) × A_f (m^2) Equation 4.3

Where A_f is floor area (m^2)

- RoT electricity demand (D_e):

D_e (kWh/year) = RoT (kWh/m^2/year) x A_f (m^2) Equation 4.4

This calculation is carried out for each building type entered by the tool user and the results are added to provide total RoT hot water, space heating and electricity demands for the building or group of buildings considered in a project.

b) Building Energy Load Profiles

Hourly building energy load profiles for electricity, hot water and space heating consumption for a typical day are required for the tool to carry out the necessary calculations. This information can either be entered by the user or can be selected by the tool from its load profile database. The user interface window appears as shown in Figure 4.4. If load profiles are known with certainty, for example in the case of an existing building, then the hourly consumption for hot water, space heating and electricity can be entered in the user interface window as shown in Figure 4.5. A week-day load profile and a weekend load profile are entered for hot water (litres/hour), for space heating (kWh/hour), and for electricity (kWh/hour) for a day in January.

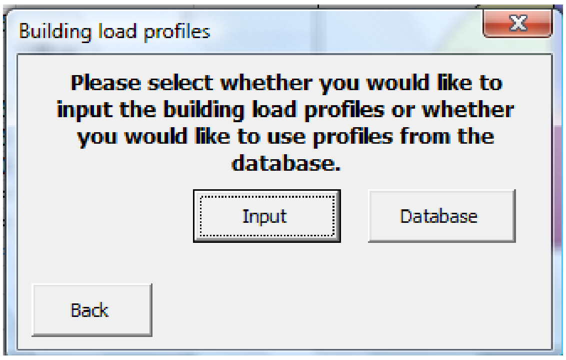


Figure 4.4 Load profile selection interface window

If the load profiles are known and entered by the user, a single process sizing calculation is carried out by the tool resulting in a single final output. However, if the load profiles are not known and it is required that this information is selected from the tool database, then a multiple process calculation is carried out using the Monte Carlo method, resulting in multiple results to reflect the uncertainty in the load profile data.

The database holds information on a number of daily load profiles for the building types RESIDENTIAL and OFFICES. The building energy load profiles data base was compiled from sources shown in Table 4.1. The data was collected from the domestic hot water demand survey as explained in Chapter 3, from the literature, and where no data was available, load profiles were derived using the rules of thumb given in Tables 3.1, 3.2 and 3.3. Then the derived load profiles would progressively be replaced with actual load profiles, as and when these become available.

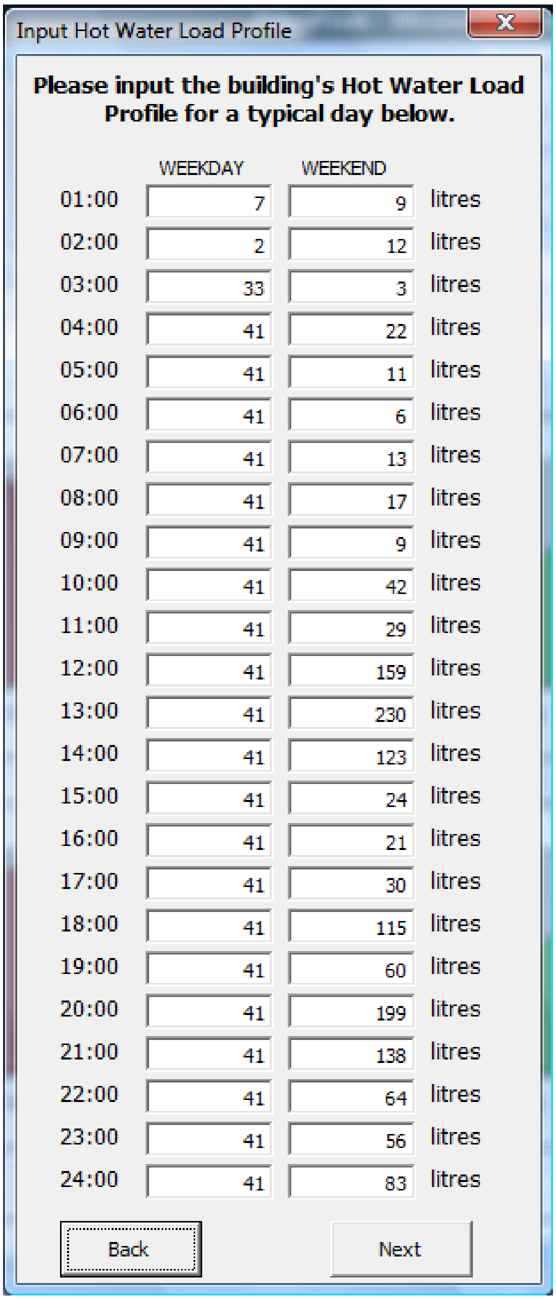


Figure 4.5 Load Profile input interface window

Table 4.1 Building Energy Load Profile Data Sources

Building type	**Space heating**	**Hot water**	**Electricity**
Residential	Literature (Yao 2005)	Survey (section 3.2)	Literature (Yao 2005)
Office	Derived from rules of thumb	Derived from rules of thumb	Nottingham City Council for council office buildings

Data used for residential load profiles are classified under building types, i.e. flats, terraced houses, semi-detached houses and detached houses. This classification was chosen as residential building types have certain size, occupancy, and occupancy behaviour pattern associated with them, which have an effect on their energy load profiles. Office load profiles are presented in energy units per square meter of floor area, as offices can be of many different sizes and the loads and load profiles are mainly dependant on the size of the office. Building energy load profiles for both residential and office buildings are further classified under weekday or weekend, as energy consumption behaviour is generally different for these days. The units of the load profiles are shown in Table 4.2.

Table 4.2 Building energy load profile units

Building type	**Space heating**	**Hot water**	**Electricity**
Residential	kWh/ dwelling	Litres/ dwelling	kWh/ dwelling
Office	kWh/ m^2	Litres/ m^2	kWh/ m^2

If the building energy load profiles are not known, the tool selects load profiles from its database in the following manner: Each load profile has a number associated with it. From these, the tool generates a random number, and then selects the load profile associated with this number. For example, there are 43 hot water load profiles for flats. So if a building consisting of 5 flats is investigated, a number from 1 to 43 is randomly generated, assume it is 4 then the load profile number 4 is selected. This is then repeated 4 times in this case to generate 5 load profiles for flats. These are then combined to give one load profile for the building of 5 flats. This process is repeated for space heating and electricity demand profiles and for a weekday and a weekend day respectively.

The loads of every hour in a day for a typical January day are summed up to give daily building loads. These are summarised in a user interface window as shown in Figure 4.6.

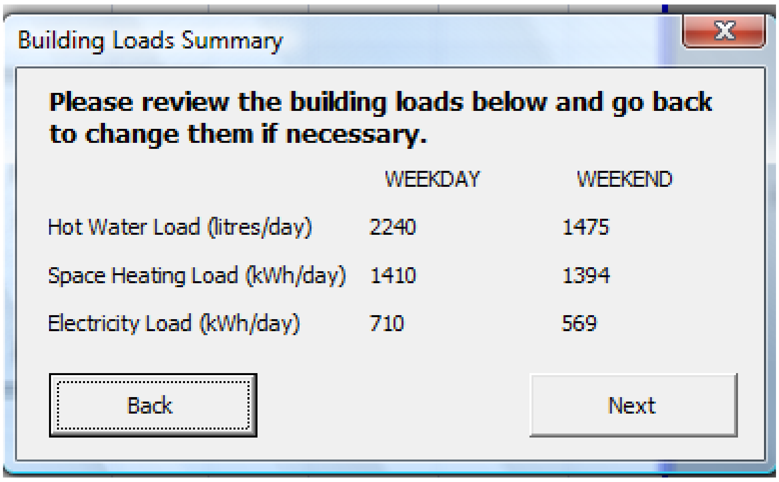


Figure 4.6 Loads output interface window

The hot water demand profile is converted from litres to kWh. The energy required to heat a specific amount of water is:

$$Q_E = mc_p\Delta T \qquad \text{Equation 4.5}$$

Where, Q is energy (J), m is mass (g), c_p is specific heat capacity (J/gK) = 4.2 J/gK for water and ΔT is the temperature difference between the temperature of the cold water supply to the building and the hot water temperature required (K).

Assuming 1 litre = 1 kg and ΔT = 60-5 = 55K, equation 4.6 is used to calculate the hot water demand in kWh:

$$D_{HW}\ (\text{kWh}) = D_{HW}\ (\text{litres}) \times 4.2 \times 55 / 3600. \qquad \text{Equation 4.6}$$

Given the difficulty in obtaining hot water load profiles and for the purpose of the computer tool, these are assumed to be the same throughout the year. In addition, seasonal variation in space heating and power consumption is taken into account by applying a load factor to the space heating and electricity loads in order to calculate the total monthly loads, as shown in Table 4.3.

To calculate monthly loads, it is assumed that there are 365 x 5 / 7 /12 = 21.726 weekdays per months and 365 × 2 / 7 /12 = 8.69 weekend days per month. Monthly loads for space heating, hot water and electricity are therefore calculated as:

$$D_M = [(21.726 \times D_{M,WD}) + (8.69 \times D_{M,WE})] \times f \qquad \text{Equation 4.7}$$

Where, D_M is total monthly load (kWh), $D_{M,WD}$ is monthly weekday demand (kWh), $D_{M,WE}$ is monthly weekend demand (kWh), and f is monthly load factor.

Table 4.3 Space heating and electricity load factors for the UK (Elexon 2006)

Month	Space heating load factors	Electricity load factors
January	1.00	1.00
February	0.89	0.92
March	0.73	0.83
April	0.51	0.74
May	0.21	0.68
June	0.00	0.64
July	0.00	0.62
August	0.00	0.63
September	0.00	0.67
October	0.27	0.77
November	0.63	0.90
December	0.89	0.98

The annual demands of space hot water, space heating and electricity are calculated by adding the demands for each month.

4.2.2 BLOCK B: Technology combinations: sizing and financial and environmental appraisals

In this section, different combinations of technologies are evaluated to provide energy in a building in a cost effective and environmentally friendly way.

The following technologies and combination of technologies have been considered for the supply of heat and power in buildings:

i) Option 1: A combination of Boiler and electricity grid (Boiler + EGrid)
ii) Option 2: A combination of CHP system for base heat and power load, Boiler and Electricity Grid (CHP + Boiler + EGrid)
iii) Option 3: Combination of Renewable energy systems (PV or Solar Thermal), Boiler and Electrical Grid (PV/Solar Thermal + Boiler + EGrid)
iv) Option 4: Combination of Combined Heat and Power, renewables (PV or Solar Thermal), Boiler and Electrical grid (CHP + PV/Solar Thermal + Boiler + EGrid)

Two models have been developed: combinations of the above with either Solar Thermal (ST) or Photovoltaics (PV) as the renewable energy. Each of these combination options have been developed as a separate Excel spreadsheet subroutine model. The sizing orders of the technologies for each option developed as part of Block B is given in the flow chart diagram of Figure 4.7.

Option 1 represents the conventional way of supplying heat and power in buildings, using the electricity grid for power and a boiler for hot water and space heating,. This option forms the base case in the computer tool.

Option 2 takes into account the use of a CHP system to meet part of the heat and power demand of the building. The CHP system in such a scheme is usually sized to provide base load heat in order to maximise the number of running hours per year. The boiler and grid are used to supply peak heat and power loads respectively.

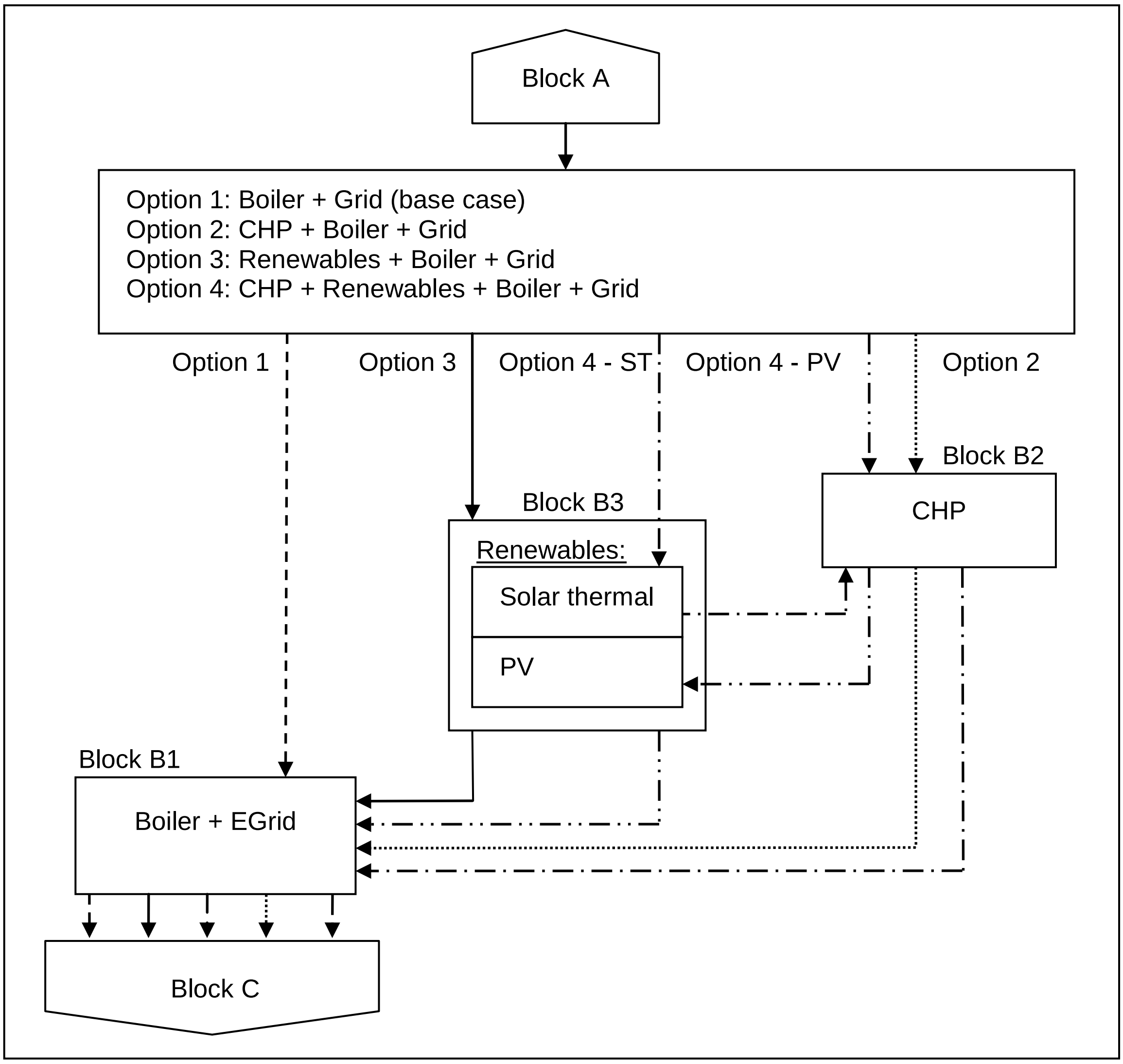


Figure 4.7 Block B –Technology combinations flow chart

In option 3, renewable solar energy systems with PV and/or Solar Thermal (ST) collectors are combined with boiler and grid. Again, the renewable energy systems provide the base load and the boiler and electricity grid supply the remaining heat and electricity demand.

In option 4, all the technologies are considered. In the PV subroutine tool, CHP provides the base load, then PV providing the intermediate load and finally a boiler and grid demand supply peak loads. For the ST subroutine tool, there is an optimum combination of CHP and ST with the boiler and grid supplying the remaining heat and electricity demands.

a) Block B1: Boiler and electricity grid (Boiler+EGrid) combination

The boiler and grid option is the conventional means of supplying heat and electricity and is, therefore, the base case against which all other combinations are compared in terms of costs and emissions. The Boiler + EGrid option is incorporated into all other technology combinations. The flow chart for Block B1 is given in Figure 4.8.

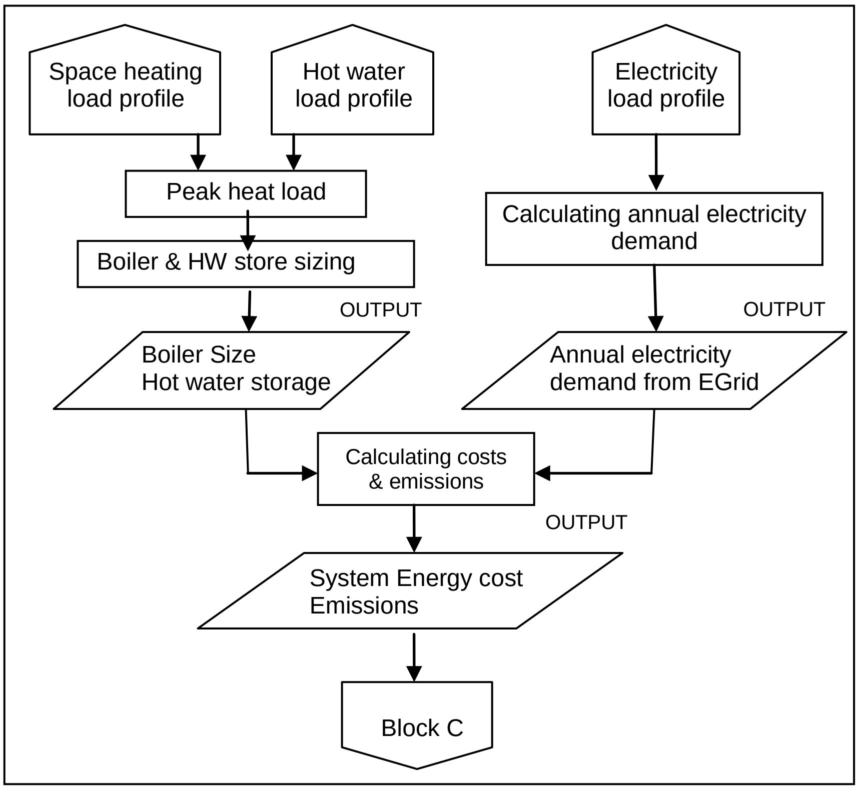


Figure 4.8 Block B1: Boiler + EGrid

The sizing procedures carried out by the tool for the boiler, hot water storage, and electricity grid demand are outlined as follows:

The boiler should be sized to meet the heat demand of the building at a design temperature consistent with prevailing weather conditions. The boiler energy rate could be given as follows:

$$S_b = \frac{D_{H,p}}{\eta_b} \qquad \text{Equation 4.8}$$

Where, S_b = boiler size (kW), $D_{H,p}$ = peak heat demand (kW) and η_b = gross boiler efficiency (%).

The peak space heating load (in kW) is obtained from the daily space heating load profile for severe weather conditions which often coincide with the month of January. The peak domestic hot water demand is obtained from the daily hot water demand profile defined in Block A. In this work it was assumed that a boiler has a minimum efficiency of 80% gross (Harvey 2006). The hot water storage is sized to provide 1/3 of the daily hot water demand (The Institute of Plumbing 2002) and is given in litres. The electricity demand is met by the national electricity grid. The electricity from the grid is given as annual demand expressed in kWh/year and which is calculated from the electricity load profile. The output parameters of Block B1 subroutine is shown in the user interface window of Figure 4.9.

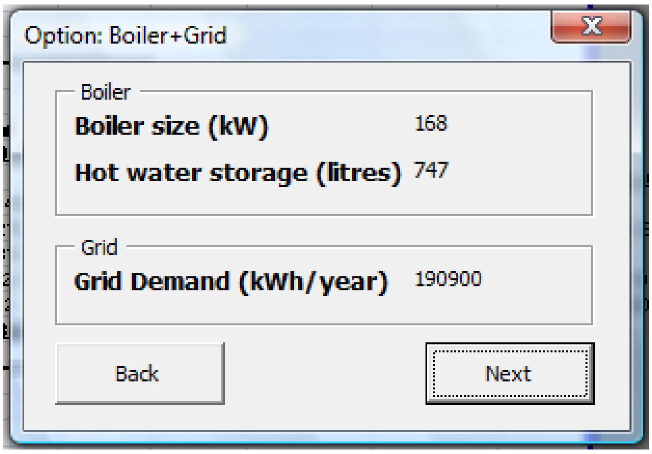


Figure 4.9 Outputs parameters of block B1: Boiler and Grid (Boiler + EGrid)

Next an economic and environmental evaluation is carried out by determining cost and emissions for the boiler and grid option. The tariffs for gas to run the boiler and electricity from the grid are assumed to be 2.28p/kWh and 8.2p/kWh respectively (DTI 2006). Like CHP systems, a boiler capital cost is assumed to vary according to its size in kW as shown Figure 4.10. However the capital cost of boilers are about 150£/kW lower than that of CHP systems (EST 2006).

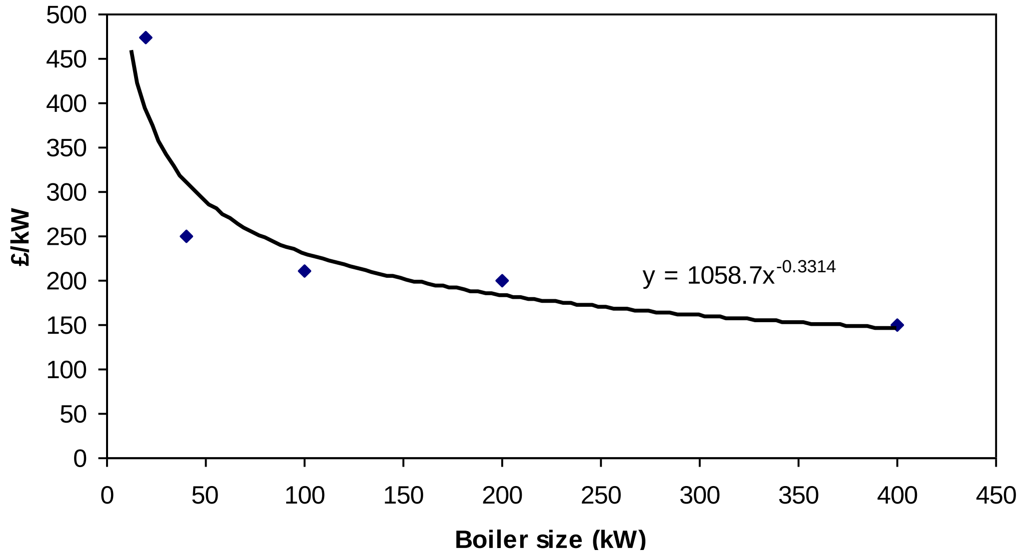


Figure 4.10 Boiler installed capital costs (EST 2006, University of Strathclyde 2006)

The annual cost of boiler maintenance is assumed to be 2% of the boiler capital cost (EST 2006, University of Strathclyde 2006). In addition the cost of the boiler disposal needs to be taken into account and this is estimated to be equivalent to twice the annual boiler maintenance cost.

Cost parameters of the system can be altered on the next user interface window as shown in Figure 4.11.

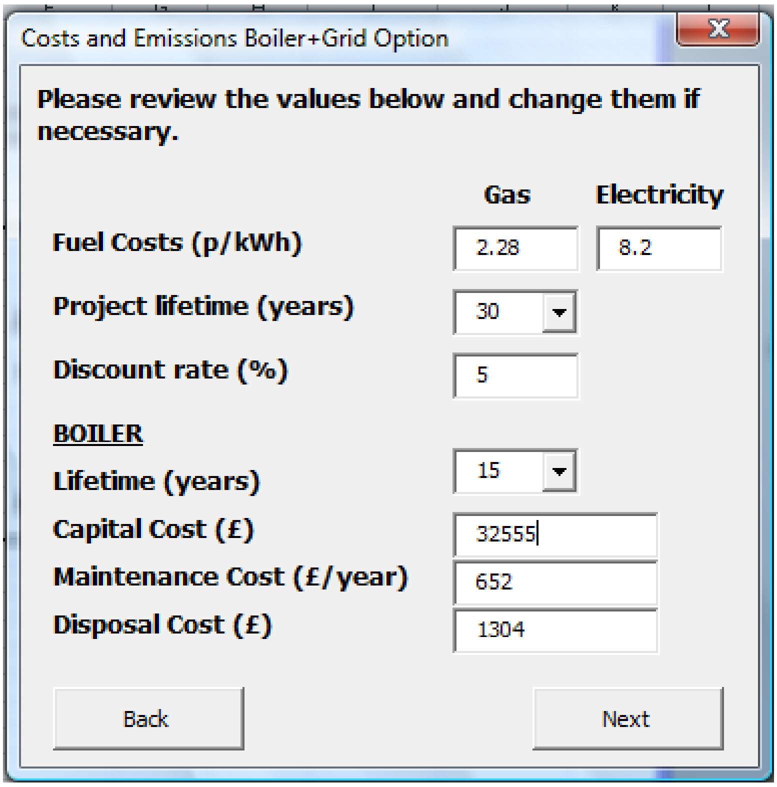


Figure 4.11 Boiler and Grid Costs and Emissions

The tool calculates the gas and electricity consumption for each combination of technologies (in kWh/year), taking into account the efficiencies of the technologies for electricity and gas. If renewable energy technologies are used, then the total fuel consumption of the technology combination can be reduced.

To calculate emissions associated with each option, emission factors are assumed to be 0.43 kg CO_2 /kWh for grid electricity, 0.19 kg CO_2 /kWh for natural gas and 0 kg CO_2 /kWh for Renewables (DEFRA 2005). For the ST system, emissions associated with the electricity consumption of the pump are taken into account.

The tool calculates the total CO_2 emission in kg CO_2 for each technology combination using the following equation:

$$E_{CO_2} = \left(D_e \times EF_e\right) + \left(D_g \times EF_g\right) \qquad \text{Equation 4.9}$$

where, E_{CO2} is CO_2 Emissions (kg CO_2), D_e *is* electricity consumption (kWh), EF_e is electricity emission factor (kg CO_2/kWh), D_g is gas consumption (kWh), and EF_g is gas emission factor (kg CO_2/kWh).

To enable comparison of the different options, the unit cost of energy production (in p/kWh) is calculated. The net present value (NPV) methodology is adopted in the tool (Northcott 2002).

The life cycle energy cost is calculated for each combination option modelled in the tool. For example, considering the Boiler + EGrid option, the overall system life cycle cost is calculated as follows;

- The lifetime energy output is calculated for the boiler using the following expression:

$$O_L = O_A \times n \qquad \text{Equation 4.10}$$

where, O_L is the lifetime output (kWh), O_A is the annual output (kWh), and n is the project lifetime (years).

- NPV capital cost:

$$CC_{NPV} = CC_{current} + CC_{NPVreplacement} \qquad \text{Equation 4.11}$$

where, CC_{NPV} is Capital cost (£), $CC_{current}$ is Current capital cost (£), $CC_{NPVreplacement}$ is NPV replacement cost (£).

The replacement of the boiler is taken into account in the capital cost if the boiler lifetime is shorter than the project lifetime.

- NPV boiler replacement cost:

$CC_{NPVreplacement} = CC_{current} \times (1 + DR)^{-n}$ Equation 4.12

Where, DR is the discount rate (%).

- NPV fuel cost:

$FC_{NPV} = FC_{current} \times [1 - (1 + DR)^{-n}] \div DR$ Equation 4.13

where, FC_{NPV} = NPV Fuel cost (£) and $FC_{current}$ = Current annual fuel cost (£)

- NPV maintenance cost:

$MC_{NPV} = MC_{current} \times [1 - (1 + DR)^{-n}] \div DR$ Equation 4.14

where, MC_{NPV} = NPV Maintenance cost (£), $MC_{current}$ = Current annual maintenance cost (£)

- NPV disposal cost:

$DC_{NPV} = DC_{current} \times (1 + DR)^{-n}$ Equation 4.15

where, DC_{NPV} = NPV Disposal cost (£), $DC_{current}$ = Current disposal cost (£)

- The costs are summed up to give a total net present value cost:

$C_{NPVtotal} = CC_{NPV} + FC_{NPV} + MC_{NPV} + DC_{NPV}$ Equation 4.16

where, $C_{NPVtotal}$ = Total NPV cost (£)

- The boiler energy cost is obtained as follows:

$$EC_{boiler} = \frac{C_{NPVtotal}}{O_L} \times 100$$ Equation 4.17

where, EC_{boiler} = Boiler system energy cost (p/kWh), $C_{NPV,total}$ = Total NPV cost of boiler system (£) and O_L = lifetime boiler output (kWh)

- System energy cost:

The system energy cost is evaluated by first calculating the energy cost for the production of heat (in this case the boiler energy cost) and for the production of electricity (in this case the grid electricity cost). A system energy cost for the option Boiler + EGrid is obtained using the equation below:

$$EC_{system} = \frac{\left[\left(EC_{boiler} \times D_h\right) + \left(EC_{EGrid} \times D_e\right)\right]}{\left(D_h + D_e\right)} \qquad \text{Equation 4.18}$$

where, EC_{system} is System energy cost (p/kWh), EC_{EGrid} is Electricity Grid Energy cost (p/kWh), D_h is heat demand (kWh), and D_e is electricity demand (kWh).

Energy cost calculations for the options "CHP+Boiler+EGrid", "PV+Boiler+EGrid", "PV+CHP+Boiler+EGrid", "ST+Boiler+EGrid", and "ST+CHP+Boiler+EGrid" are carried out in a similar fashion.

Annual CO2 emissions and emissions per kWh are calculated next for the Boiler and Grid option. Annual emissions are calculated as follows:

$$E_{CO2} = f_E \times FI \qquad \text{Equation 4.19}$$

Where, E_{CO2} is annual emissions (kg CO_2), f_E is the CO_2 emissions factor (0.19 kg CO_2/kWh for gas and 0.43 kg CO_2/kWh for electricity), and FI is the annual fuel input (kWh).

The total annual emissions, $E_{CO2,Total}$ (kg CO_2) are calculated for the boiler:

$$E_{CO2,Total} = E_{CO2,boiler} + E_{CO2,grid} \qquad \text{Equation 4.20}$$

Where, annual emissions (kg CO_2) from the boiler: $E_{CO2,boiler} = 0.19 \times FI$ and annual emissions (kg CO_2) from the grid: $E_{CO2,grid} = 0.43 \times FI$

Emissions per kWh are calculated as follows:

$$E_{CO2/kWh} = \frac{E_{CO2,total}}{(D_H + D_e)} \qquad \text{Equation 4.21}$$

Where, $E_{CO2/kWh}$ is emissions (kg CO_2/kWh), D_H is annual heat demand (kWh) and D_e is annual electricity demand (kWh).

b) Block B2: CHP

Figure 4.12 shows the flow chart for Block B2. In this tool it is assumed that the CHP heat to power fraction is 2:1. The overall efficiency of CHP system is usually considered to be 80% or above.

The suitability of CHP schemes depends strongly on the number of running hours with 4500 hours per annum as a general guideline for implementation of CHP projects (CIBSE 1999). Therefore, the tool's subroutine of Block B2 first checks if there is a demand for at least 4500 hours from the hot water and space heating load profiles. Only when this criterion is met then the CHP sizing is carried out.

For every hour, it is assumed that the CHP is running when there is a heat demand in that hour. The hours the CHP is running are then added up by the tool to give total running hours per year.

CHP is usually sized to match base heat load (BRECSU 1996). The base load would normally be the hot water demand of a building as this is the load that is present throughout the year. However, sizing the CHP system above base load is usually favoured as it offers better returns on investments and the reduction of CO_2 emissions. Table 4.4 shows a simple comparative study of two CHP schemes with one providing base load and the other above base load in 10 residential flats. It can be seen that option 1, which sizes the CHP above base load, achieves lower emissions with a smaller CHP size and a lower system cost than option 2 which provides only base heat load. The computer tool therefore sizes CHP by using the total heat load profile for the project. The optimum size of CHP in terms of costs and emissions is calculated by minimising the saved costs of emissions in £/kg CO_2.

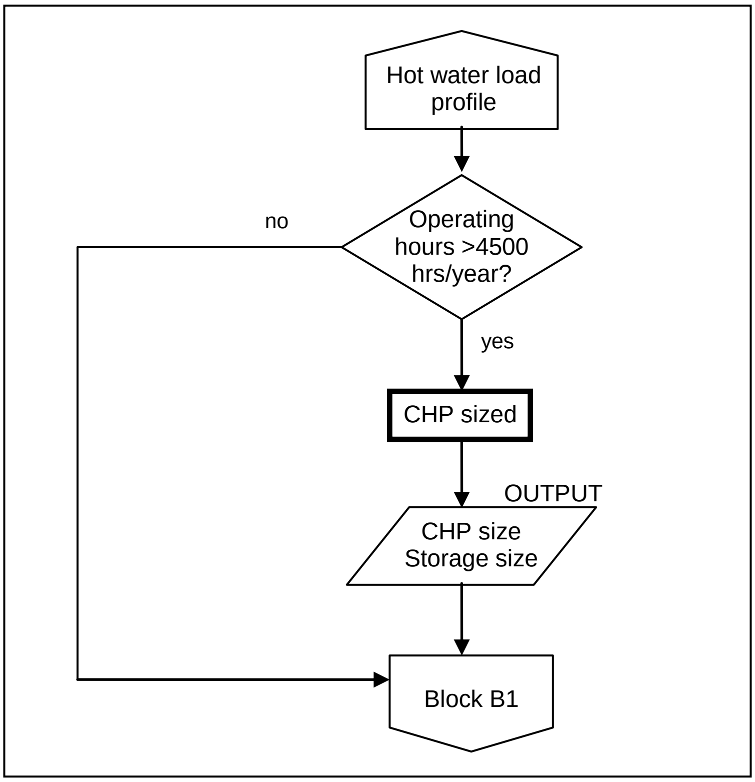


Figure 4.12 Block B2: CHP

If the CHP unit is sized above the base load and there is no demand for heat, then hot water could be stored or the system shut down. Any surplus heat produced could be stored for the next period of the heating cycle where a boiler would supply any deficit in heat generation. In this computer subroutine, the storage capacity is assumed to be 50% of the surplus heat produced by the CHP in a summer day of the month July.

Table 4.4 Comparison of CHP Sizing options

	Option 1 (sized on total heat load: above base load)	**Option 2** (sized on water load: base load only)
Optimum CHP size (kWth)	4	3
System cost (p/kWh)	2.6	2.9
Emissions (kg CO_2/kWh)	0.24	0.26
£/kg CO_2 saved	2.2	5.1

The sizing procedure for the CHP is as follows: The tool records cost of emissions saved (£/kg CO_2 saved) for every kW thermal rating of CHP starting with 1 kW until a CHP size is reached that achieves less than 4500 running hours. From this list, the tool then selects the CHP size achieving the lowest £/kg CO_2 saved.

Table 4.7 shows an example table calculating the demand and supply of heat and power for the CHP system and CHP running hours for a typical January day. Hourly heat and electricity demands are listed in the table. CHP running hours are determined (CHP is running if there is a heat demand), and the CHP heat and electricity outputs are listed. The deficit and surplus heat and electricity are calculated for each hour:

$$Deficit = D - O_{CHP} \quad \text{Equation 4.22}$$

$$Surplus = O_{CHP} - D \quad \text{Equation 4.23}$$

Where, D is electricity or heat demand (kWh) and O_{CHP} CHP electricity or heat output (kWh).

The total heat deficit for a day is calculated taking into account the heat storage. The equation used in the cell in the Excel sheet is:

If Surplus (kWh/day) < Storage capacity (kWh/day),

Then *Total Deficit* = *Deficit* – *Surplus*,

Else *Total Deficit* = *Deficit* – *Storage capacity*. Equation 4.24

Where, *Total Deficit* is the heat deficit taking into account heat storage (kWh/day), *Deficit* is the heat deficit before taking into account the heat storage (kWh/day) and *Surplus* is the heat surplus (kWh/day).

In the tool's CHP spreadsheet, there are 12 tables like Table 4.5, one for a typical day in each month.

Table 4.5 January demand vs supply for CHP

January

Time	Heat demand (kWh)			CHP	CHP (kWh)			Electricity	CHP (kWh)		
	SH	HW	Total	hours	Output	Deficit	Surplus	demand	Output	Deficit	Surplus
1	7.4	1.0	8.3	1	10	0.0	1.7	6.0	5	1.0	0.0
2	14.7	1.3	15.9	1	10	5.9	0.0	4.9	5	0.0	0.1
3	21.8	0.0	21.8	1	10	11.8	0.0	5.1	5	0.1	0.0
4	14.2	0.0	14.2	1	10	4.2	0.0	4.8	5	0.0	0.2
5	19.9	0.0	19.9	1	10	9.9	0.0	4.7	5	0.0	0.3
6	10.0	0.4	10.3	1	10	0.3	0.0	4.9	5	0.0	0.1
7	128.1	3.3	131.3	1	10	121.3	0.0	7.3	5	2.3	0.0
8	104.4	0.0	104.4	1	10	94.4	0.0	16.1	5	11.1	0.0
9	109.4	13.7	123.1	1	10	113.1	0.0	21.2	5	16.2	0.0
10	35.4	8.3	43.7	1	10	33.7	0.0	22.0	5	17.0	0.0
11	41.2	10.2	51.4	1	10	41.4	0.0	23.0	5	18.0	0.0
12	38.6	14.9	53.5	1	10	43.5	0.0	21.7	5	16.7	0.0
13	32.6	10.8	43.4	1	10	33.4	0.0	23.2	5	18.2	0.0
14	49.1	8.0	57.1	1	10	47.1	0.0	24.3	5	19.3	0.0
15	37.8	13.3	51.2	1	10	41.2	0.0	23.2	5	18.2	0.0
16	58.4	5.8	64.2	1	10	54.2	0.0	22.6	5	17.6	0.0
17	51.2	4.5	55.7	1	10	45.7	0.0	23.6	5	18.6	0.0
18	102.8	7.6	110.4	1	10	100.4	0.0	22.6	5	17.6	0.0
19	67.4	5.6	72.9	1	10	62.9	0.0	24.6	5	19.6	0.0
20	80.4	1.0	81.3	1	10	71.3	0.0	30.0	5	25.0	0.0
21	64.6	8.1	72.7	1	10	62.7	0.0	25.9	5	20.9	0.0
22	33.9	5.9	39.8	1	10	29.8	0.0	23.4	5	18.4	0.0
23	7.4	5.1	12.4	1	10	2.4	0.0	15.8	5	10.8	0.0
24	12.1	14.7	26.7	1	10	16.7	0.0	9.8	5	4.8	0.0
			1285.7		240	1047.3	1.7	410.5903	120	291.3	0.71207
						1045.7	1.7			6335.8	

The annual heat and electricity deficits and surpluses are calculated by first calculating monthly figures (assuming each day in the same month is the same) and then adding the monthly figures to obtain yearly ones.

For heat and electricity:

- $Deficit_{monthly} = [(Deficit_{WD} \times 21.726) + (Deficit_{WE} \times 8.69)]$ Equation 4.25

Where, $Deficit_{monthly}$ is monthly deficit (kWh), $Deficit_{WD}$ is weekday deficit (kWh), and $Deficit_{WE}$ is weekend day deficit (kWh).

- $Surplus_{monthly} = [(Surplus_{WD} \times 21.726) + (Surplus_{WE} \times 8.69)]$ Equation 4.26

Where, $Surplus_{monthly}$ is monthly surplus (kWh), $Surplus_{WD}$ is weekday surplus (kWh), and $Surplus_{WE}$ is weekend day surplus (kWh).

Any surplus electricity generated is exported to the grid and the annual electricity demand from the grid is equal to the annual electricity deficit as calculated above. The optimum CHP size is found as explained above, and the CHP heat store is assumed to be 50% of the surplus heat produced by the CHP in a summer day of the month July. The Boiler is sized on the deficit heat demand as in block B1. Figure 4.14 shows the user interface window that summarises these outputs.

Like boilers, installed capital and maintenance costs for CHP are strongly dependent on power rating in kW of electrical output with the disposal cost to be equivalent to twice the annual maintenance cost. Figure 4.14 shows the trend for capital cost of CHP systems. Maintenance costs are assumed to be 2% of capital costs of the CHP (EST 2006, University of Strathclyde 2006) and disposal costs are double the annual maintenance costs.

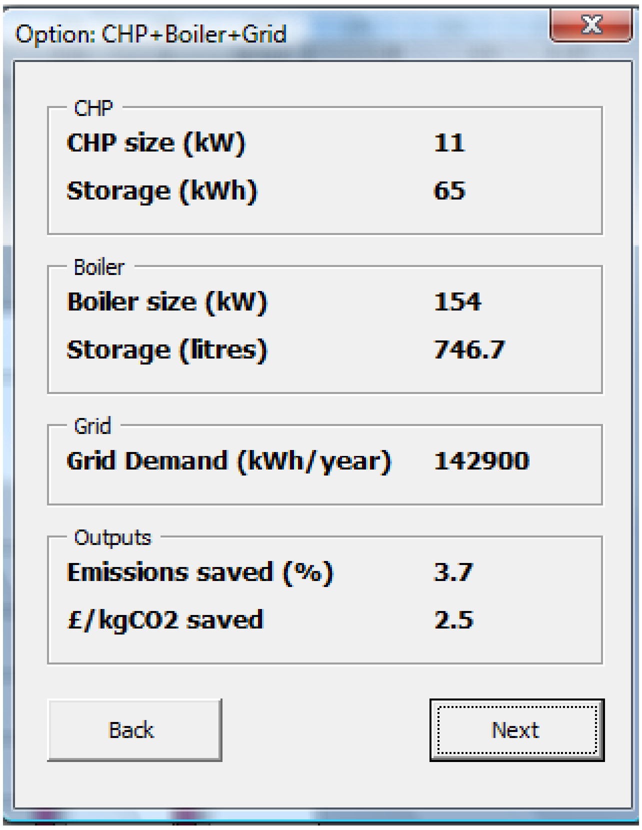


Figure 4.13: CHP, Boiler and Grid Sizing Outputs interface

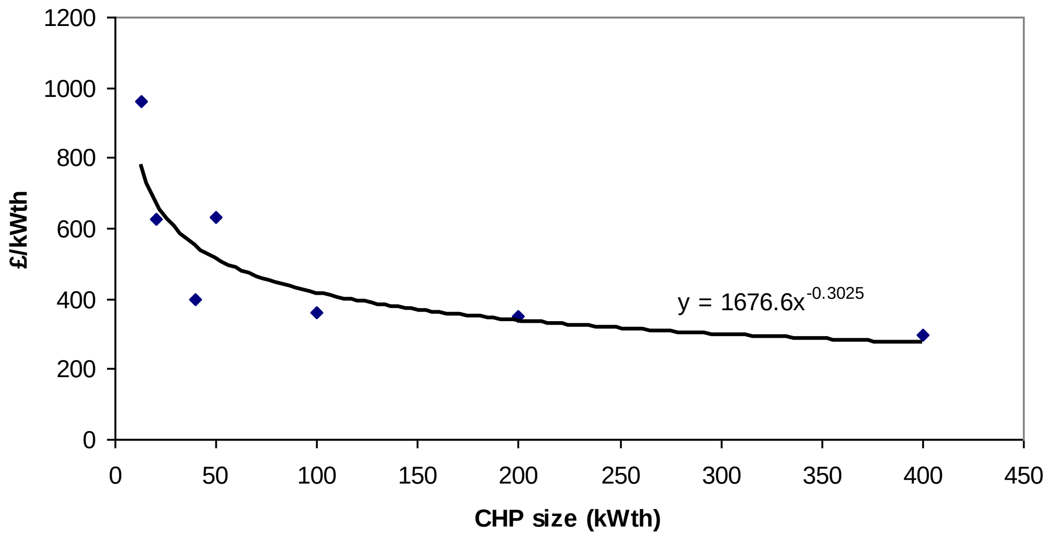


Figure 4.14 Installed CHP capital costs (EST 2006, University of Strathclyde 2006)

Then another user interface asks for further changes of data, such as service life, capital cost, etc as shown in Figure 4.15.

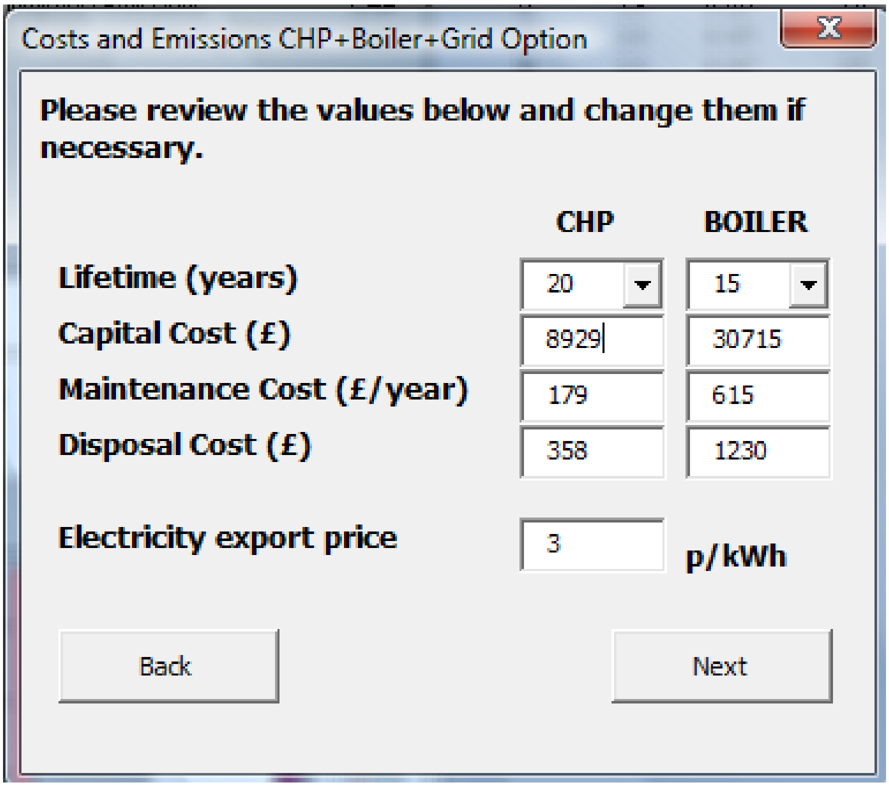


Figure 4.15: CHP and boiler costs interface

Emissions and NPV system energy cost are calculated in a similar fashion as in Block B1. In addition, cost of emissions savings (£/kg CO_2 saved) and % emissions saved figures are calculated for this technology combination using the Boiler and Grid option as the base case.

Emissions saved, ES_{CO2} (kg CO_2 saved) for the CHP, Boiler and Grid option is:

$$ES_{CO2,CBG} = E_{CO2,BG} - E_{CO2,CBG} \qquad \text{Equation 4.27}$$

Where, $ES_{CO2,CBG}$ is emissions saved in the CHP, Boiler and Grid option (kg CO_2 saved), $E_{CO2,BG}$ is emissions of the boiler and grid option (kg CO_2), and $E_{CO2,CBG}$ is emissions of the CHP, boiler and grid option (kg CO_2).

Cost per emissions savings, ESC (£/kg CO_2 saved) is calculated for the CHP, Boiler and Grid option:

$$ESC = \frac{(D_H + D_e) \times EC_{system}}{ES_{CO_2}} \qquad \text{Equation 4.28}$$

Where, ESC is cost per emissions savings (£/kg CO_2 saved), D_H is heat demand (kWh), $EC_{system,heat}$ is systems energy cost for heat (£/kWh), D_e is heat demand (kWh), and $EC_{system,electricity}$ is systems energy cost for heat (£/kWh).

c) Block B3: Renewable Energy Technologies

Block B3 has been developed for the two different Excel tools:

i) A combination of Photovoltaic (PV) + CHP + Boiler + Grid

ii) A Combination of Solar thermal (ST) + CHP + Boiler + Grid

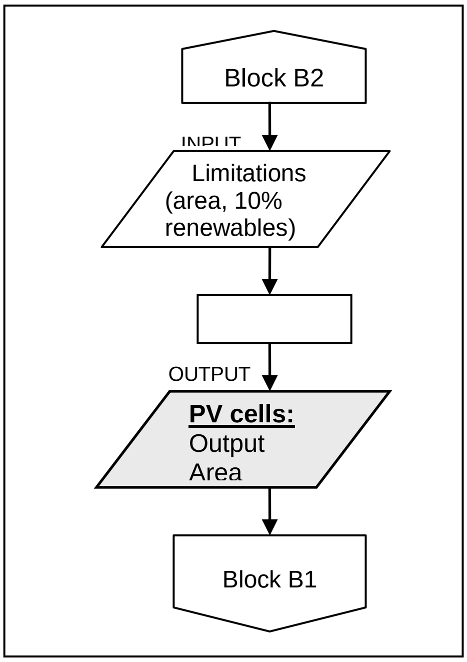


Figure 4.16: Block B3a – PV

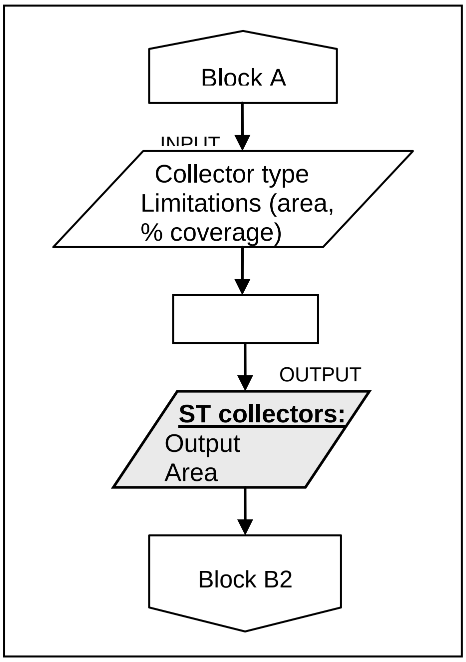


Figure 4.17: Block B3b – ST

Figures 4.16 and 4.17 show the flow diagrams of the two subroutine programmes for block B3. The subroutine programmes of block B3 specifically enable the determination of the required size for PV and solar thermal technology using the following procedures.

i) PV sizing

To maximise conversion of solar radiation into electricity a PV panel should have a tilt angle equal to approximately ± 15 degrees the angle of latitude of the site. In the UK, a south facing PV panel with a 30 degrees tilt angle from the horizontal yields the best results [DTI (1999)]. Assuming that the PV panel is not shaded, the area of the panel for a given amount of electrical energy to be harvested over a period of time is by CIBSE (2000):

$$S_{PV} = \frac{D_e}{I_s(1-L)\eta_{PV}} \qquad \text{Equation 4.29}$$

where, S_{PV} is the PV required area(m^2), D_e is the electricity demand (kW), I_s *is* the incident solar radiation (kW/m^2), η_{PV} is the efficiency of the PV cells, and (1- *L)* is the efficiency of the power conditioner (inverter, controller), transformer and interconnection.

Polycrystalline PV panels are currently the most commonly used type of PV cells (International Energy Agency 2003). With a maximum efficiency of 14% and losses of 25% due to the power conditioner (inverter, controller), transformer and interconnection (CIBSE 2000), polycrystalline panels have been adopted in this computer tool. However, other types of PV could be incorporated. In this way the user could compare the different PV cells before choosing the type of PV to be installed.

Table 4.6 shows the hourly simulation of the PV system for a typical July day. The system is simulated for a typical day in each month, to get an understanding of the yearly performance of the system.

Table 4.6 Hourly PV simulations for a typical July day

July	0.62	0.62						
Time	weekday Electricity demand	weekend Electricity demand	Solar irradiance (W/m2)	PV output (kWh)	weekday deficit (kWh)	weekday surplus (kWh)	weekend deficit (kWh)	weekend surplus (kWh)
1	4.4	4.2		0	4.4	0	4.2	0
2	5.9	4.5		0	5.9	0	4.5	0
3	7.0	5.3		0	7.0	0	5.3	0
4	6.9	5.6	27	1.44	5.4	0	4.2	0
5	7.0	6.1	70.5	3.76	3.3	0	2.3	0
6	6.9	6.3	143.25	7.64	0.0	0.71	0.0	1.37
7	9.1	6.9	246	13.12	0.0	4.05	0.0	6.18
8	14.2	10.1	346	18.46	0.0	4.25	0.0	8.37
9	17.7	12.2	429.5	22.91	0.0	5.17	0.0	10.70
10	19.1	12.5	488.75	26.07	0.0	6.99	0.0	13.61
11	21.4	15.2	519.25	27.70	0.0	6.25	0.0	12.53
12	21.7	15.1	519.25	27.70	0.0	5.98	0.0	12.58
13	21.1	15.0	488.75	26.07	0.0	5.01	0.0	11.04
14	22.6	16.0	429.5	22.91	0.0	0.35	0.0	6.94
15	22.9	15.5	346	18.46	4.5	0	0.0	2.94
16	23.0	15.4	246	13.12	9.9	0	2.3	0
17	24.4	16.7	143.25	7.64	16.8	0	9.1	0
18	26.3	18.5	70.5	3.76	22.6	0	14.7	0
19	29.1	22.5	27	1.44	27.7	0	21.1	0
20	30.8	28.4		0	30.8	0	28.4	0
21	28.5	29.0		0	28.5	0	29.0	0
22	28.1	28.4		0	28.1	0	28.4	0
23	23.6	23.8		0	23.6	0	23.8	0
24	21.1	21.2		0	21.1	0	21.2	0
	442.9	354.5	4540.5					

Hourly PV output, O_{PV} (kW) is calculated:

$$O_{PV} = S_{PV} I_S (1 - L) \eta_{PV} \quad \text{Equation 4.30}$$

Where, O_{PV} is PV output (kW).

Assuming a constant output for the PV during each hour, O_{PV} can also have kWh units, as is shown in Table 4.6. Deficit and surplus are also calculated for each hour. It is assumed here that any surplus is exported to the grid and any deficit is imported from the grid. Yearly surplus and deficit figures are therefore calculated using equation 4.25.

Figure 4.18 shows that there is an optimum PV panel size (m^2) that would yield the lowest cost of saved CO_2 emission. However, in some cases, there is a trivial solution to the optimum PV area and hence the PV panel would be sized to generate required power for the month of July when solar radiation is at its highest value.

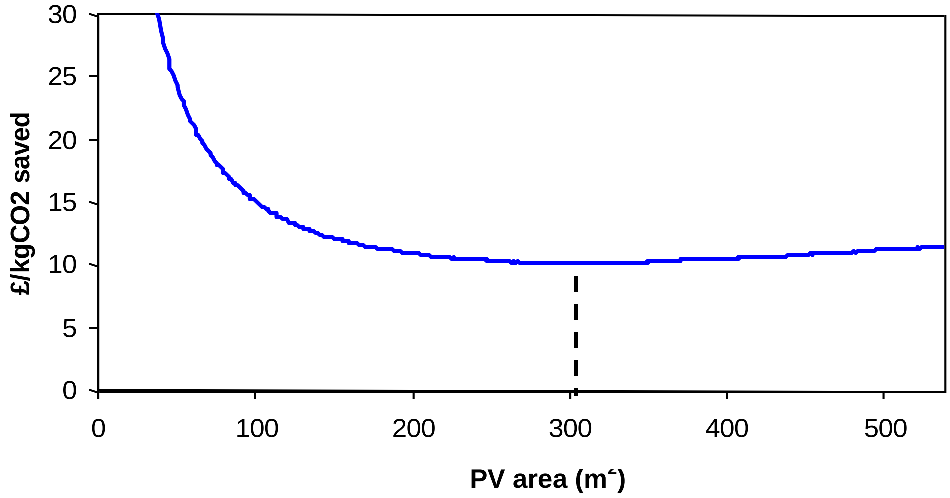


Figure 4.18 Variation of PV panel area with cost of CO_2 saved

In the computer tool, the user can select to size the PV panel to provide the optimum annual electricity demand, providing there is no restriction on the amount of roof area and capital cost. Alternatively, the user can select to size the PV panels either restricting the maximum available area for the PV or selecting a 10% reduction in CO_2 emission of the site as shown in the user interface of Figure 4.19 and Figure 4.20.

If the tool calculates a PV area larger than the restricted area specified by the user, then this restricted area is taken as the maximum area for the PV array. If the project requirement is to reduce carbon emissions by 10%, as is more frequently becoming the case throughout the UK, the tool then calculates a PV size to achieve this target.

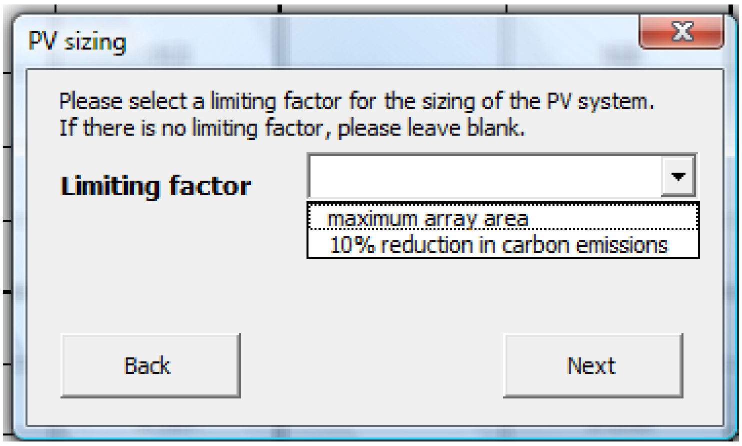


Figure 4.19 PV sizing options

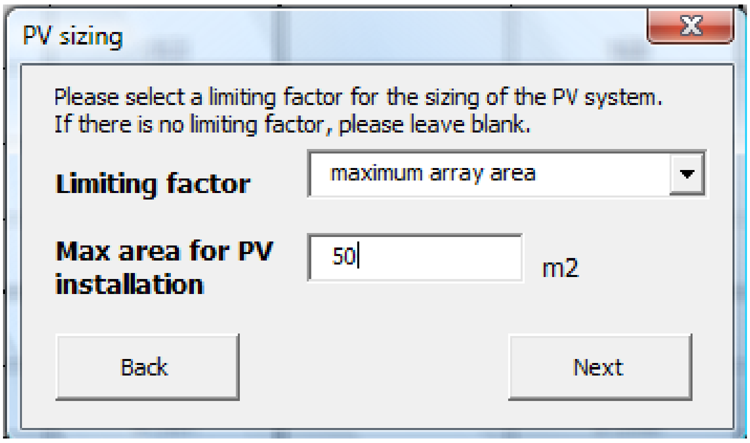


Figure 4.20 Entering maximum array area available

The tool investigates two options that include PV:

- PV + Boiler + Grid (Option 3 – see Figure 4.7)
- CHP + PV + Boiler + Grid (Option 4 – see Figure 4.7)

For the PV + Boiler + Grid combination of technologies, the PV is sized first, as described above. The boiler supplies the total heating demand and the grid supplies the electricity demand not met by the PV.

Table 4.7 and Figure 4.21 show that CHP achieves a lower cost of emissions savings than PV. Therefore in the CHP + PV + Boiler + Grid option, the CHP is sized first as described in Block B2. The sizing of the CHP is based on the heat demand. If all the electricity demand is met by the CHP, then the tool indicates that no PV installation is required. If PV is required then the PV system is sized as described above. Figure 4.21 shows that the optimum size of PV with CHP would be 0m^2. However, since the tool examines the combination of PV with CHP, the CHP is sized first and then considered with different sizes of PV in order to find an optimum size of PV. The boiler and EGrid then supplies any remaining heat demand and electricity demand.

Table 4.7 Example Costs of emissions savings for CHP and PV

Example	Optimum CHP size	Optimum PV size
Cost of Emissions savings (£/kgCO_2 saved)	6.3	10.1

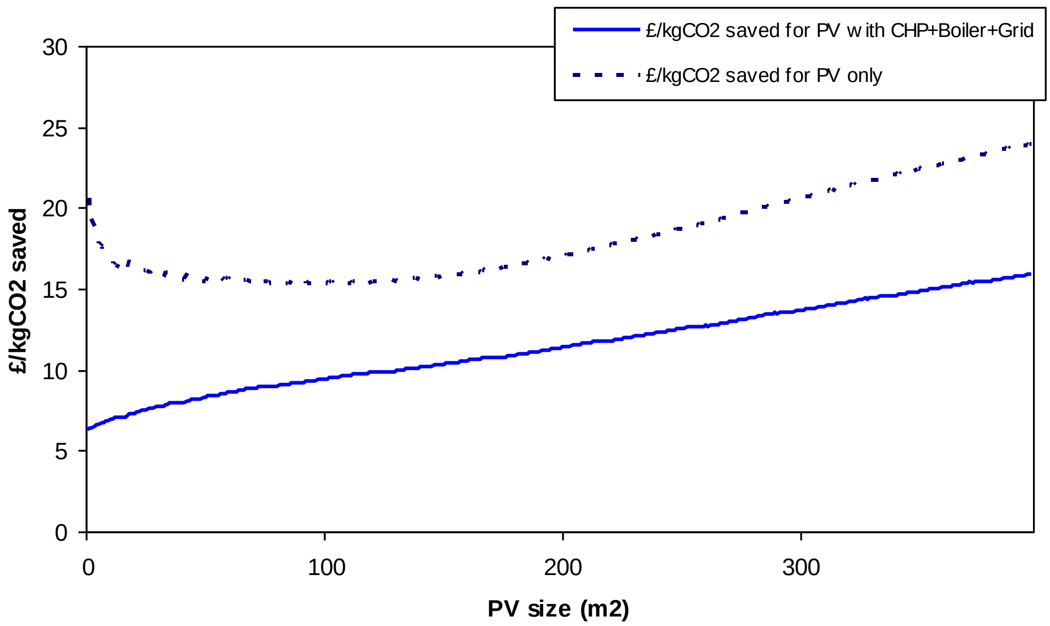


Figure 4.21 Optimum size of PV with CHP+Boiler+Grid

Figure 4.22 shows sizes of the PV, Boiler and Grid and the percentage of emissions saved in this option. The tool calculates estimated costs of the PV system (Figure 4.23). Figure 4.24 shows the typical costs collected and the formula used to estimate the PV capital cost. PV maintenance and disposal costs are assumed to be 1% and 2% respectively of the capital costs. The costs and lifetime of the PV systems can again be changed by the user (Figure 4.23).

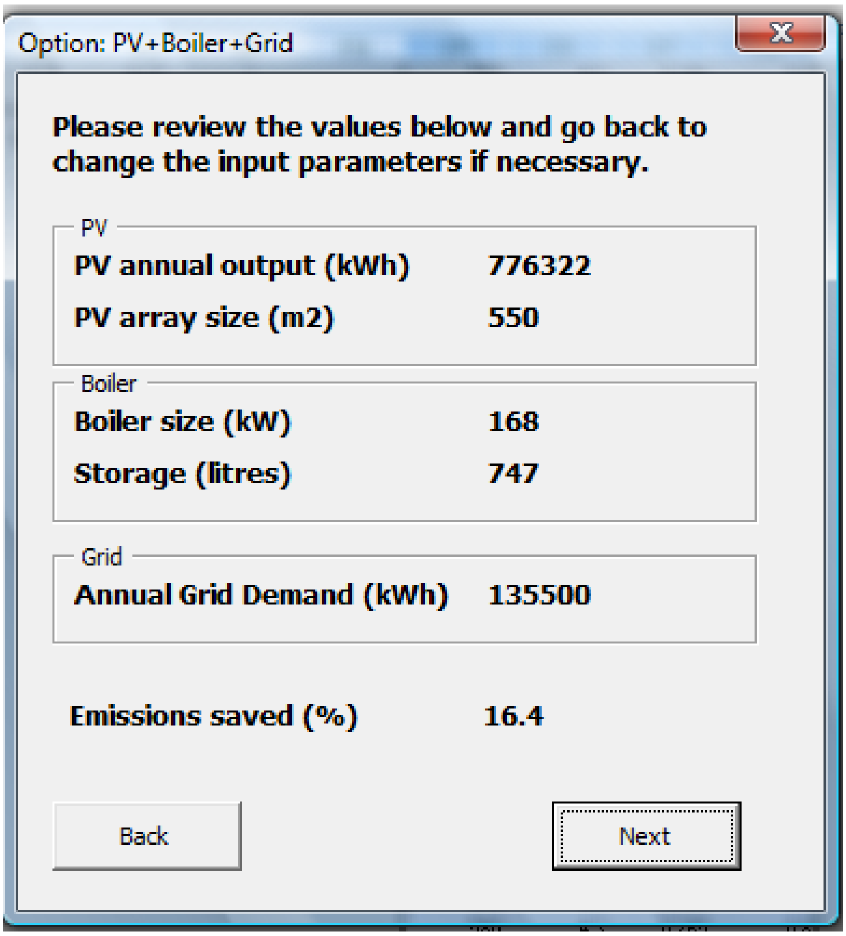


Figure 4.22 PV + Boiler + Grid Outputs

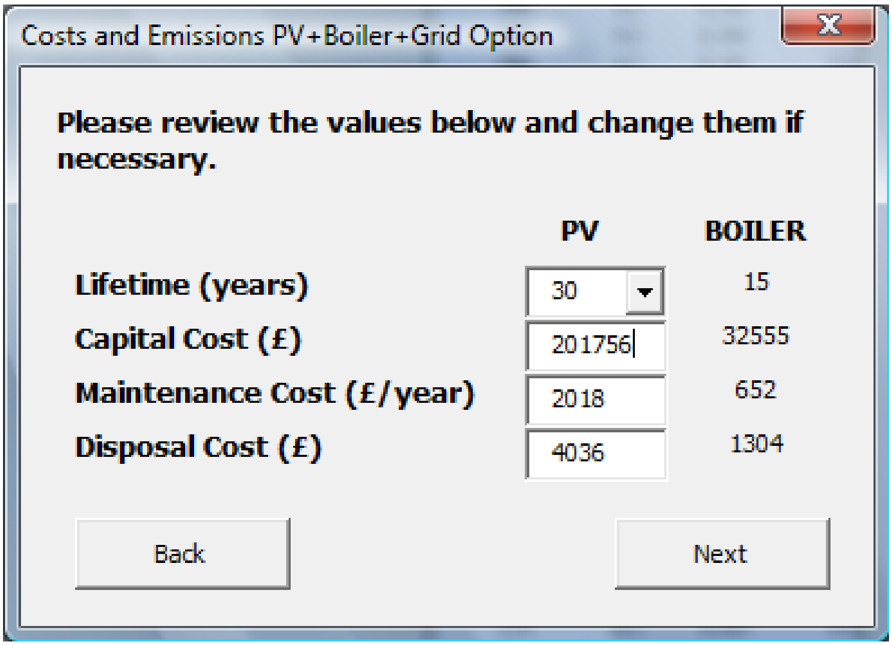


Figure 4.23 PV lifetime and costs

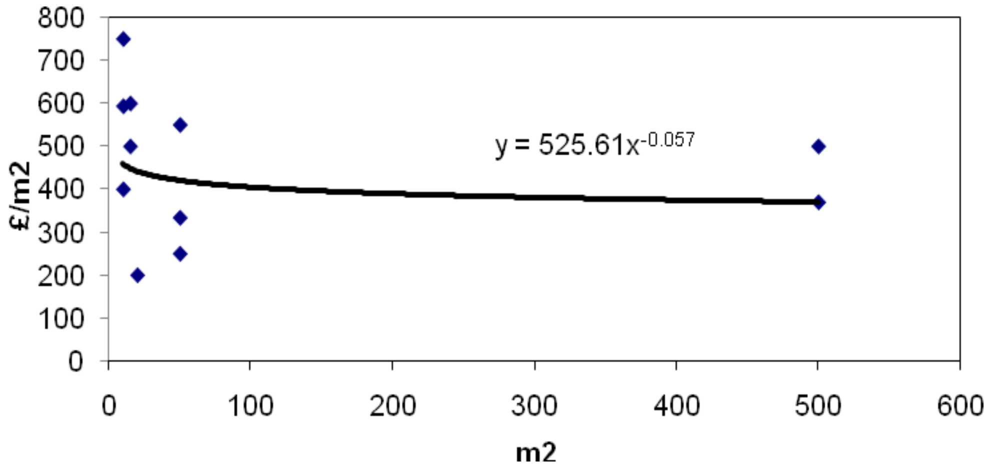


Figure 4.24 Installed PV costs (Faber Maunsell 2003, EST 2006, DTI 2006, IEA 2003, IEA 2006)

Figure 4.25 shows sizes of the PV, CHP, Boiler and Grid and the percentage of emissions saved in this option. The tool calculates cost estimates of the PV system. Figure 4.26 shows the estimated costs and lifetime of the PV system, which can again be changed by the user.

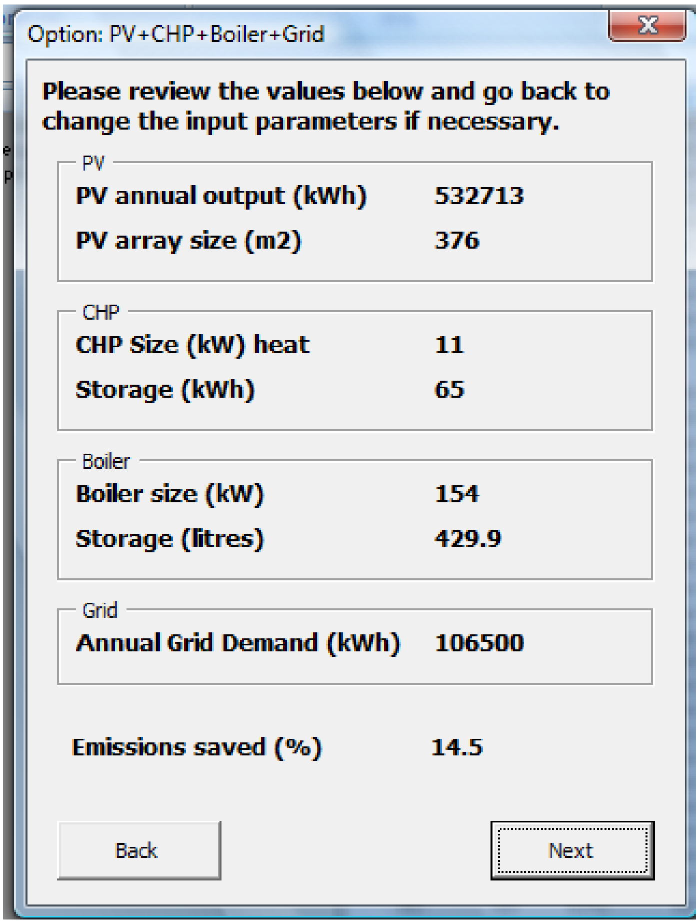


Figure 4.25 PV+CHP+Boiler+Grid Outputs

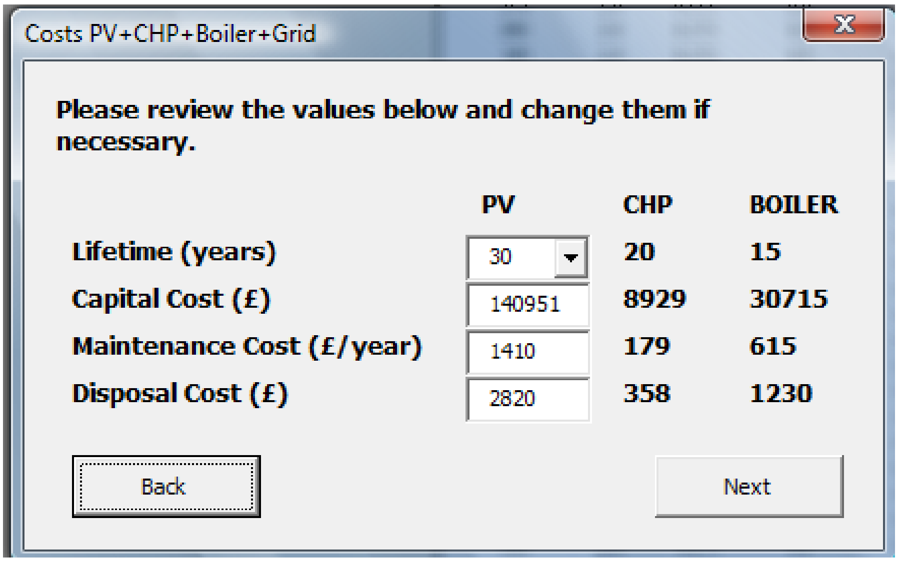


Figure 4.26 PV costs and lifetime

Finally, system energy costs, emissions, % emissions saved and the cost of emissions savings are calculated for the PV+Boiler+Grid and the CHP+PV+Boiler+Grid options, as for the other options.

ii) Solar Thermal (ST) sizing

In this work it is assumed that the solar thermal system supplies only domestic hot water. Given that evacuated tube solar thermal collectors are most suitable for North European climate, its characteristics were included in the computer tool. However, other types of solar collectors could be included in the computer tool through separate subroutines in future work. The computer tool evaluates the solar collector output on an hourly basis for a typical day and for each month as follows (Duffie 1991). Table 4.8 shows an example of the solar thermal system simulation for a typical day in July.

Table 4.8 Hourly solar thermal system simulation for a typical July day

July	1.00	1.00											
Time	Weekday Hot water demand (kWh)	Weekend Hot water demand (kWh)	Abient temperature (degC)	Solar irradiance (W/m2)	Collector efficiency	ST output (kWh)	weekday deficit (kWh)	weekday deficit after storage (kWh)	weekday surplus (kWh)	weeken d deficit (kWh)	weekend day deficit after storage (kWh)	weeken d surplus (kWh)	Pump running hours
1	0.4	0.6			0	0	0.4	0.0	0	0.6	0.5	0	0
2	0.1	0.8			0	0	0.1	0.0	0	0.8	0.8	0	0
3	2.1	0.2			0	0	2.1	1.5	0	0.2	0.2	0	0
4	2.6	1.4	12.3	27	0	0	2.6	2.6	0	1.4	1.4	0	0
5	2.6	0.7	13.8	70.5	0	0	2.6	2.6	0	0.7	0.7	0	0
6	1.4	0.4	15.1	143.25	0	0	1.4	1.4	0	0.4	0.4	0	0
7	3.7	0.8	16.4	246	0.18	5.67	0.00	0.00	2.01	0.00	0.00	4.84	1
8	0.4	1.1	17.5	346	0.34	15.03	0.00	0.00	14.58	0.00	0.00	13.94	1
9	13.9	0.6	18.5	429.5	0.42	22.86	0.00	0.00	9.00	0.00	0.00	22.29	1
10	12.6	2.7	19.3	488.75	0.46	28.49	0.00	0.00	15.91	0.00	0.00	25.79	1
11	11.6	1.9	20.0	519.25	0.48	31.49	0.00	0.00	19.94	0.00	0.00	29.63	1
12	14.6	10.2	20.6	519.25	0.48	31.72	0.00	0.00	17.09	0.00	0.00	21.52	1
13	8.7	14.8	20.9	488.75	0.47	29.16	0.00	0.00	20.43	0.00	0.00	14.40	1
14	9.8	7.9	21.1	429.5	0.44	23.95	0.00	0.00	14.14	0.00	0.00	16.06	1
15	7.7	1.5	21.0	346	0.38	16.52	0.00	0.00	8.82	0.00	0.00	14.98	1
16	4.7	1.3	20.8	246	0.24	7.52	0.00	0.00	2.83	0.00	0.00	6.17	1
17	5.7	1.9	20.3	143.25	0	0	5.7	0.0	0	1.9	0.0	0	0
18	10.8	7.4	19.6	70.5	0	0	10.8	0.0	0	7.4	0.0	0	0
19	6.8	3.9	18.7	27	0	0	6.8	0.0	0	3.9	0.0	0	0
20	2.2	12.8			0	0	2.2	0.0	0	12.8	0.0	0	0
21	3.4	8.9			0	0	3.4	0.0	0	8.9	0.0	0	0
22	9.1	4.1			0	0	9.1	0.0	0	4.1	0.0	0	0
23	5.0	3.6			0	0	5.0	0.0	0	3.6	0.0	0	0
24	3.7	5.3			0	0	3.7	0.0	0	5.3	0.0	0	0
	143.7	94.6		4540.5			8.2	8.2	124.77	3.94	3.94	169.62	310
									47.91			47.91	

The output of the solar thermal system is calculated:

$$Q_{sc} = A_{sc} I_s \eta_{sc} \qquad \text{Equation 4.31}$$

where, Q_{sc} is the collector output rating (kW), A_{sc} is the collector area (m^2), I_s is the incident solar radiation normal to the collector (kW/m^2), and η_{sc} is the collector efficiency (%).

Typical evacuated solar collector efficiency can be expressed by the following empirical relationship (Atmaca 2003):

$$\eta_{sc} = 0.7 - 3.3\frac{T_{SCav} - T_{Am}}{I_s} \qquad \text{Equation 4.32}$$

where, T_{SCav} and T_{Am} are the average collector temperature (°C) and ambient temperature (°C) respectively.

Ambient temperatures and solar radiation at 30 degrees tilt south-facing at different times throughout the day and year were obtained from the European Commission Directorate General Joint Research Centre. The average collector temperature is assumed to be 55°C.

The hot water storage capacity is assumed to be 1/3 of the daily hot water demand, as is the case for the boiler system. Hourly deficit and surplus values are calculated, as well as the hourly deficit after hot water storage has been taken into account. The latter is especially important for the sizing of solar thermal with CHP.

Like in most active solar thermal collectors, the electrical power consumption of the pump to circulate the heat carrying fluid could be substantial. The pump is usually activated by a dedicated controller when there is sufficient temperature difference (e.g., 3°C) between the solar collector and hot water storage tank. The power consumption can be calculated as:

$$D_{ep} = P_p H \quad \text{Equation 4.33}$$

where, D_{ep} is the pump electricity consumption (kWh), P_p is the pump power rating (kW) and *H is* the number of operating hours (hours).

Typical power consumption of a solar thermal collector pump depends essentially on the size of the solar collector. Table 4.9 shows estimates of power consumption of a solar collector pump obtained through private communication from the solar thermal department of Viessmann, a solar technology company based in Telford, Shropshire. This data is incorporated into the computer tool to calculate the power consumption of the solar collector.

Table 4.9 Pump power estimates (Viessmann 2007)

Solar thermal collector size (m^2)	**Pump power (W)**
1-5	40
5-10	60
10-15	75
15-20	140
20-25	210
25-30	245

The tool optimises the solar thermal system to find the collector size to achieve an optimum cost of emission saving in £/kg CO_2 saved. Figure 4.27 shows that the cost of emissions saved varies with the size of ST collector and there is an optimum size for a given building load (e.g., a building consisting of 20 2-bedroom flats has an optimum surface area of about 70m^2 and would cost about £11 per kg of CO_2 saved).

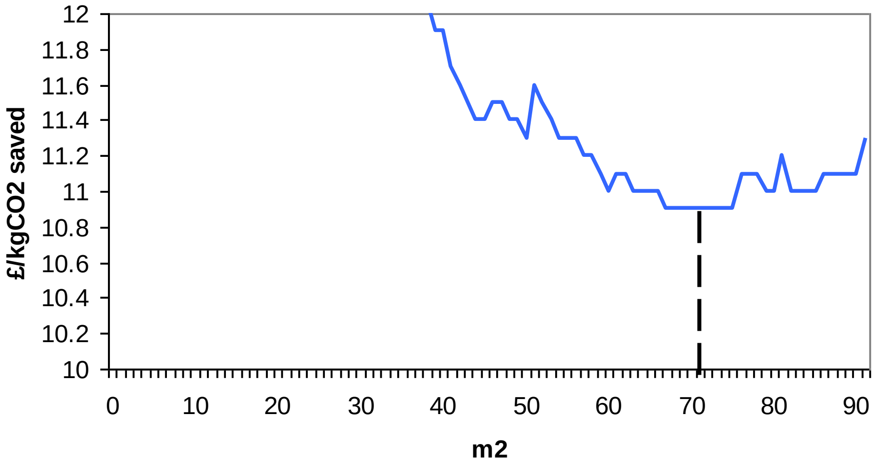


Figure 4.27 Optimum ST collector size

As in the PV sizing tool, the user can select a limitation in the sizing procedure as shown in Figure 4.28. A maximum collector array area can be entered or the user can select the option where the tool calculates an array area that achieves the maximum reduction in carbon emissions. If no limitation is selected the ST collector is sized as described above.

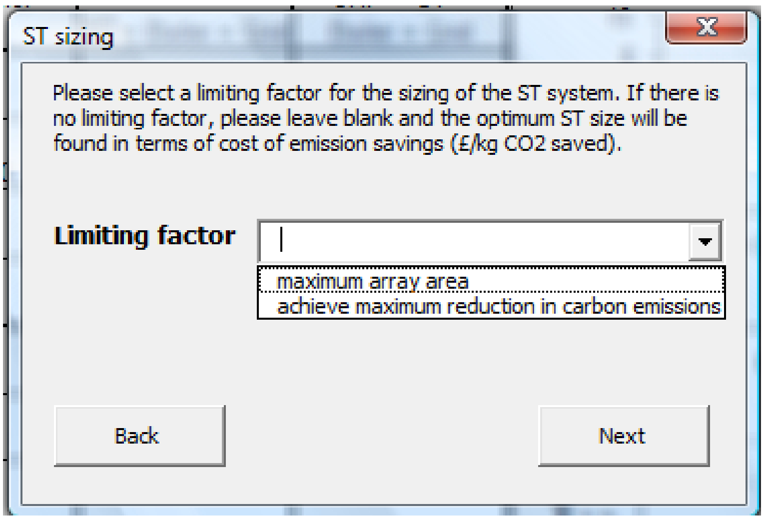


Figure 4.28 ST sizing options

The option of achieving a 10% reduction in emissions is not available in the ST tool. This is due to the fact that the ST only supplies hot water and from Figure 4.29, this figure could not be achieved by using ST alone, unless seasonal storage was used and this option therefore is currently not included in the tool.

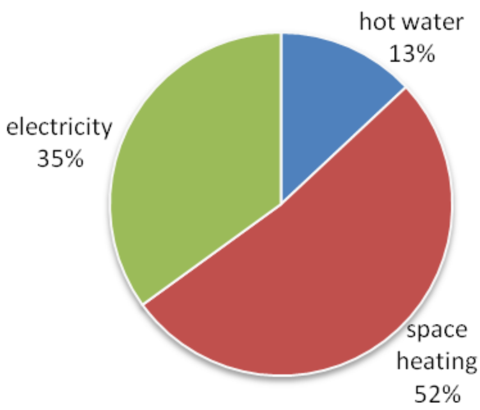


Figure 4.29 Yearly energy demand distribution for example building

The sizing tool for ST considers two options that include:

- ST + Boiler + Grid
- ST + CHP + Boiler + Grid

For the first option (i.e., ST + Boiler + Grid combination), the solar thermal collector is sized to provide as much heat as permissible within the design limitations described above. Then the boiler is used to supply the remaining hot water and heating demand, whereas the Grid would supply the electricity demand. Figures 4.30 and 4.31 show the user interface windows of the sizing tool for the technology and the associated costs and emissions. Furthermore, lifetime and cost estimates are calculated separately as shown in Figure 4.31, for which the user can choose appropriate operational parameters.

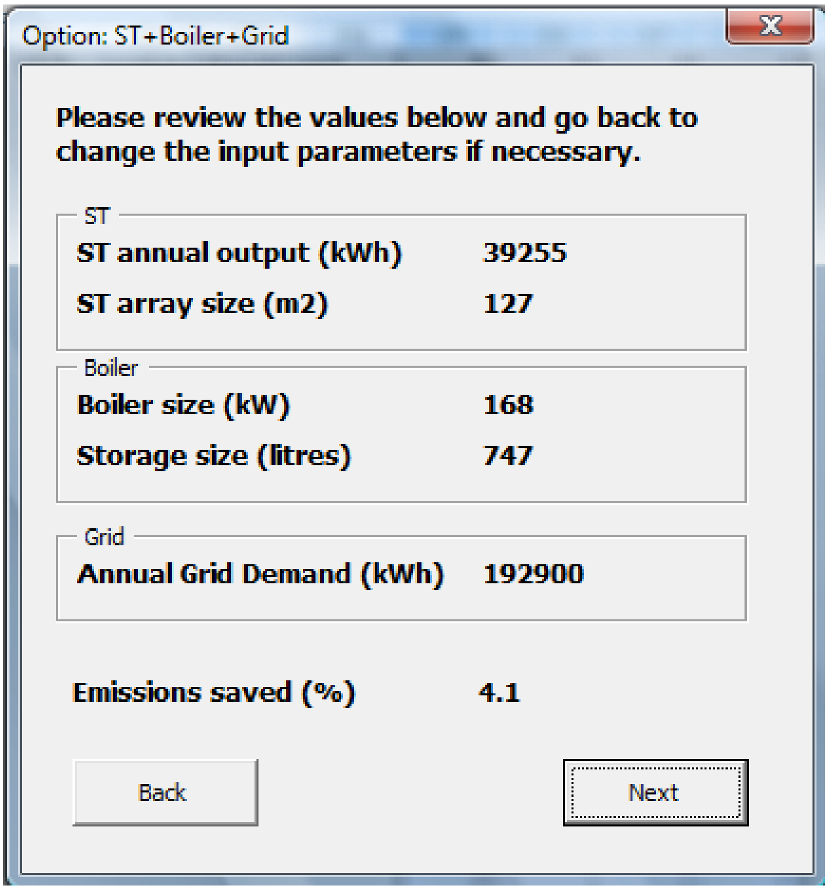


Figure 4.30 ST+Boiler+Grid Outputs

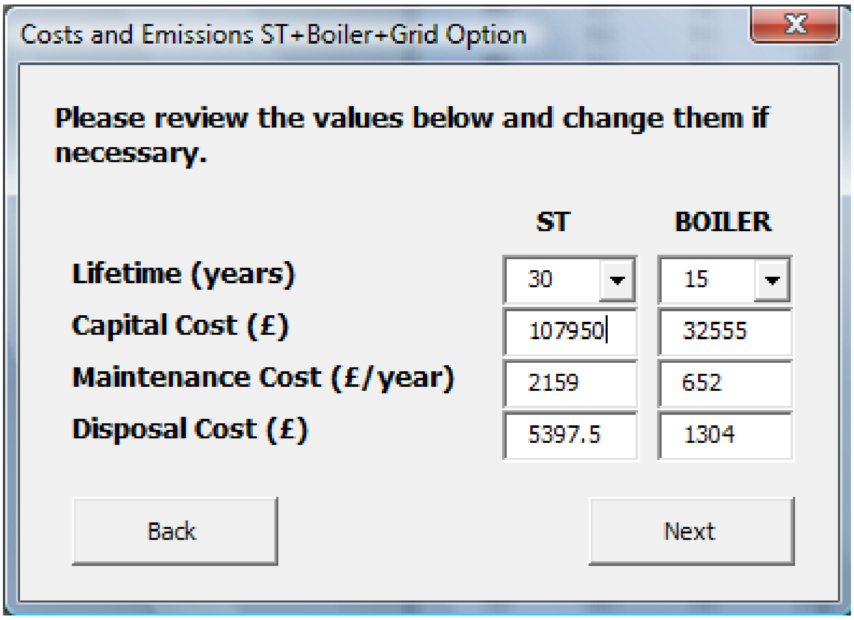


Figure 4.31 ST+Boiler lifetime & costs

The second option which integrates solar thermal with CHP in the ST + CHP + Boiler + Grid option is less straight forward than integrating PV with CHP as solar thermal and CHP technologies are both sized on heat demand. Solar thermal provides higher CO_2 emissions savings than CHP; however CHP is economically more viable than solar thermal. Approximate costs of solar thermal installations are summarized in Table 4.10. Solar thermal maintenance costs and disposal costs were assumed to be 2% and 5% respectively of the installed capital cost.

Table 4.10 Installed solar thermal costs (Faber Mausell 2003, EST 2006)

price (£) for 4 m^2 of ST collectors	£/m^2
3500	875
3150	787.5
4000	1000
3000	750
Average	**853**

For the ST + CHP + Boiler + Grid option, the tool calculates the optimum CHP size for different ST collector sizes to find an optimum combination of ST and CHP in terms of £/kgCO_2 saved. However if an area limitation was selected by the user as described in Figure 4.28, then the ST areas considered in this calculation will be limited to the value entered by the user. If the limitation selected was to achieve a maximum CO_2 emissions reduction, then the tool will find the combination of CHP and ST to achieve the highest % carbon emissions saved.

As was the case for the PV tool, the user can review the outputs of the ST tool and go back to revise any of the inputs if necessary, as shown in Figure 4.32. Technology lifetime, capital cost, maintenance cost and disposal costs can also be changed by the user in a separate procedure as shown in Figure 4.33.

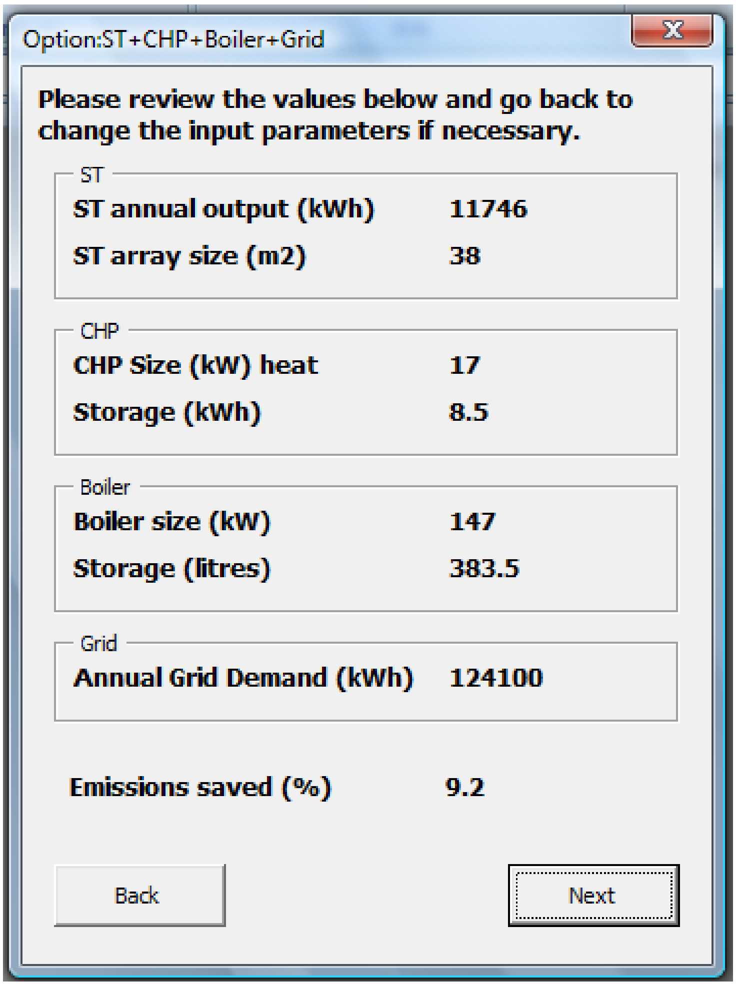


Figure 4.32 ST+CHP Outputs

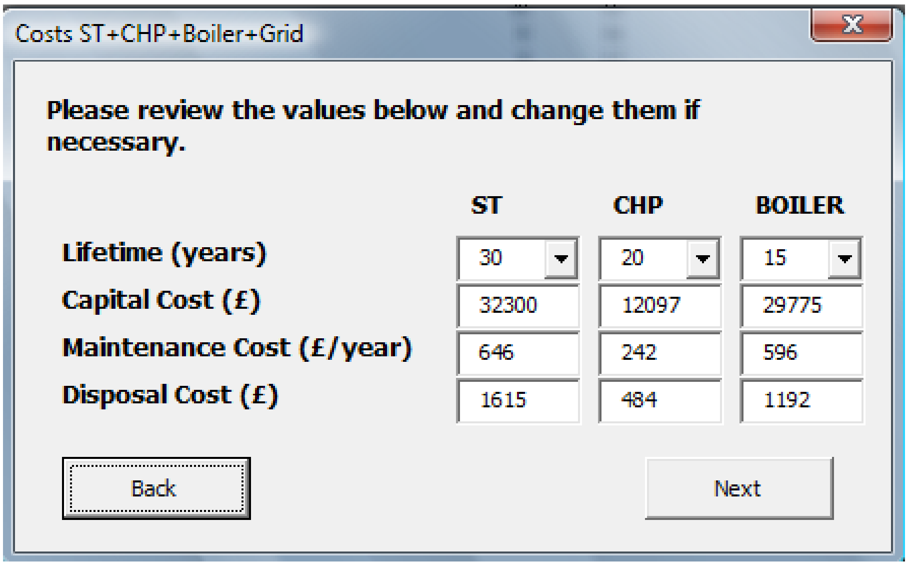


Figure 4.33 ST+CHP+Boiler lifetime & costs

Finally, system energy costs, emissions, % emissions saved and the cost of emissions savings are calculated for the ST+Boiler+Grid and the ST+CHP+Boiler+Grid options, as for the other options.

4.2.3 BLOCK C: Most Probable Options and their Comparison

Figure 4.34 shows the flow chart for Block C. The Monte Carlo method is applied to take into account the uncertainty of building energy load profiles.

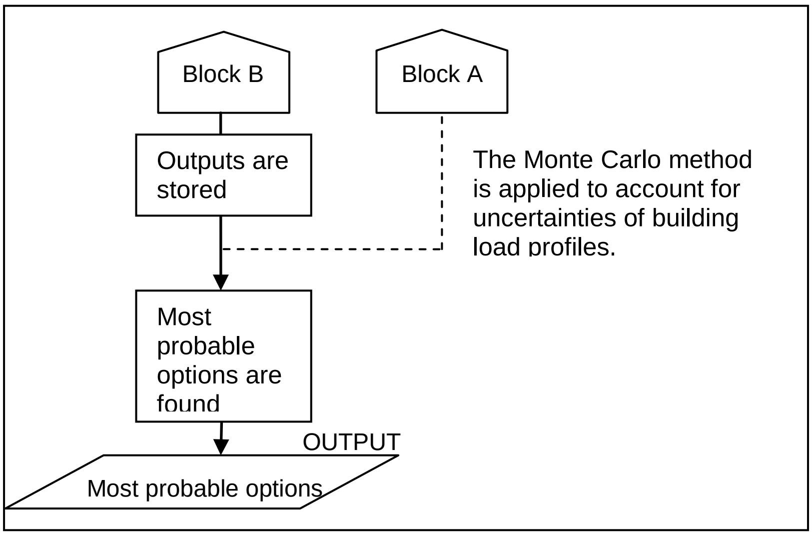
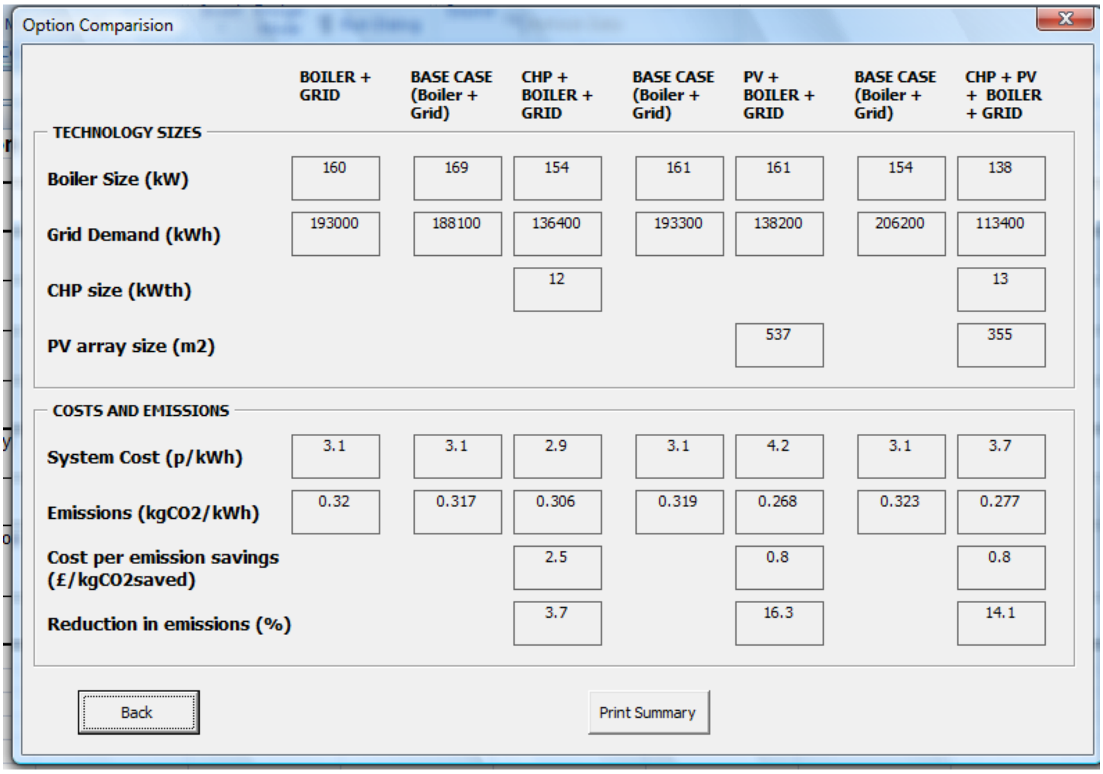


Figure 4.34 Block C – Most probable options and their comparison

The most probable options from the outputs from block B are found and are summarized in terms of system energy costs and emissions (Figures 4.35 and 4.36). The user can subsequently make an informed decision as to which technology combination to choose.

Load profiles, which are an important input to the tool, are difficult to predict and are therefore largely uncertain. The Monte Carlo Method is used to account for this uncertainty by sizing each of the combination options described above for 100 different load profiles.

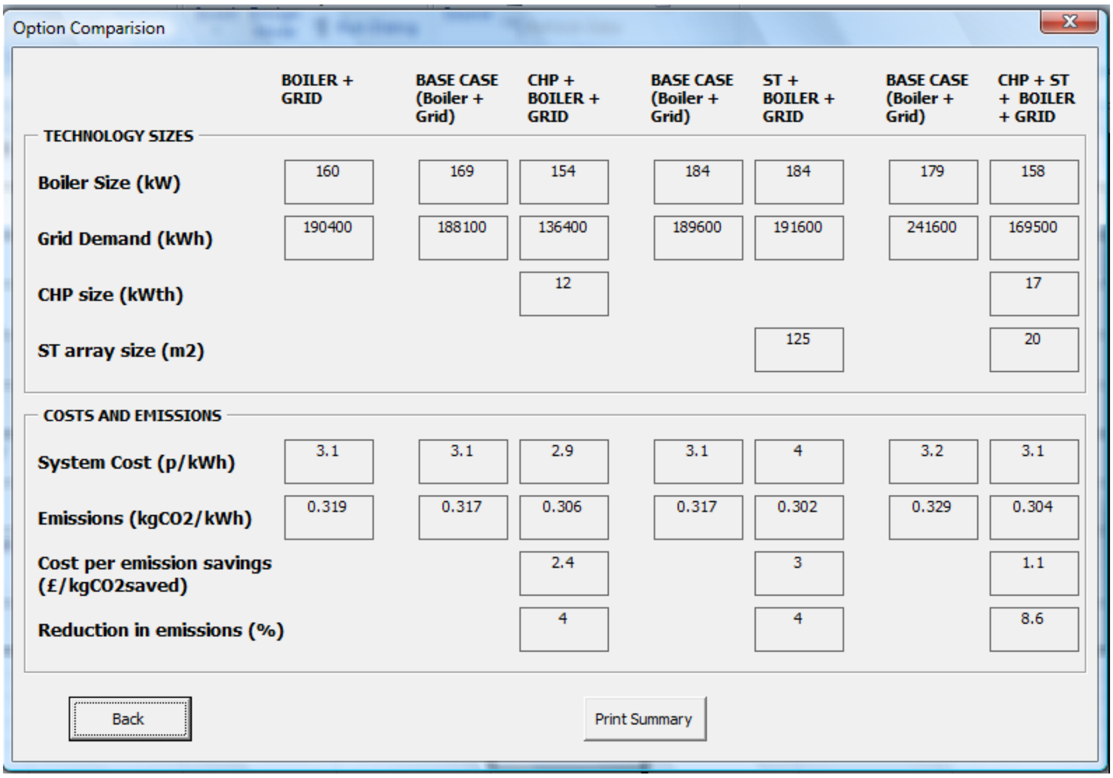


Option Comparision

	BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + BOILER + GRID	BASE CASE (Boiler + Grid)	PV + BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + PV + BOILER + GRID
TECHNOLOGY SIZES							
Boiler Size (kW)	160	169	154	161	161	154	138
Grid Demand (kWh)	193000	188100	136400	193300	138200	206200	113400
CHP size (kWth)			12				13
PV array size (m2)					537		355
COSTS AND EMISSIONS							
System Cost (p/kWh)	3.1	3.1	2.9	3.1	4.2	3.1	3.7
Emissions (kgCO2/kWh)	0.32	0.317	0.306	0.319	0.268	0.323	0.277
Cost per emission savings (£/kgCO2saved)			2.5		0.8		0.8
Reduction in emissions (%)			3.7		16.3		14.1

Back Print Summary

Figure 4.35 PV Tool Option Comparison



Option Comparision

	BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + BOILER + GRID	BASE CASE (Boiler + Grid)	ST + BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + ST + BOILER + GRID
TECHNOLOGY SIZES							
Boiler Size (kW)	160	169	154	184	184	179	158
Grid Demand (kWh)	190400	188100	136400	189600	191600	241600	169500
CHP size (kWth)			12				17
ST array size (m2)					125		20
COSTS AND EMISSIONS							
System Cost (p/kWh)	3.1	3.1	2.9	3.1	4	3.2	3.1
Emissions (kgCO2/kWh)	0.319	0.317	0.306	0.317	0.302	0.329	0.304
Cost per emission savings (£/kgCO2saved)			2.4		3		1.1
Reduction in emissions (%)			4		4		8.6

Back Print Summary

Figure 4.36 ST Tool Option Comparison

This is an iterative process and the number of times this simulation process is carried out depends on the determination of the number of trials required for the Monte Carlo method to give a significant confidence level. In this tool 100 iterations were performed for the simulation to achieve a high confidence level. The method is carried out as follows:

- Each load profile present in the sizing tool is assigned a number.
- Then the tool generates a random number, and selects the load profile associated to the generated random number.
- Using the selected load profile, the simulation is run for each of the technology combination options for sizing and cost analysis.
- The cost and emissions for each technology combination option are obtained and recorded in a spreadsheet. Figure 4.37 shows an extract of this spreadsheet.
- The simulation process is repeated for the estimated number of trials (i.e., 100). Therefore yielding 100 outputs.
- For each combination the most likely technology sizes, costs and emissions are obtained.

These results can then be compared by the user (as described in Figure 4.35 and Figure 4.36), to make the ultimate decision based on the economical and environmental criteria of the project. The random selection of load profiles is explained in more detail using an example in the next chapter in section 5.2.1.

Finally, feedback into the tool is important, so that the tool can be updated and improved as it is being used. For example, costs will change over time and will therefore need to be updated regularly; and, as more building energy load profiles become available, these could be added into the tool.

Option 1 Boiler + Grid				Option 2 CHP + Boiler + Grid							
Boiler Size (kW)	Grid demand (kWh/year)	Energy Cost (p/kWh)	CO2 emissions (kg CO2/kWh)	CHP size (kWheat)	Store size (kWh/day)	Boiler size (kW)	Grid demand (kWh/year)	Energy Cost (p/kWh)	CO2 emissions (kg CO2/kWh)	£/kg CO2 saved	% emission saved
168	190900	3.1	0.318	11	65	154	142900	2.9	0.307	2.5	3.7
168	190900	3.1	0.318	11	65	154	142900	2.9	0.307	2.5	3.7
152	195900	3.1	0.321	13	87	136	139600	2.9	0.309	2.4	3.8
152	259200	3.2	0.334	15	106	133	193900	3	0.322	2.6	3.6
163	276600	3.3	0.336	17	129	142	202200	3.1	0.325	2.6	3.6
176	253800	3.2	0.331	17	124	155	179300	3	0.318	2.4	3.8
154	206200	3.1	0.323	13	85	138	149600	2.9	0.311	2.4	3.8
160	193000	3.1	0.32	13	83	144	136600	2.9	0.307	2.3	4
179	241600	3.2	0.329	17	131	158	167200	3	0.317	2.4	3.8
179	211500	3.1	0.322	16	116	159	142500	2.9	0.31	2.3	4
174	184500	3	0.315	12	69	159	132200	2.9	0.302	2.2	4.2
184	189600	3.1	0.317	13	82	168	133300	2.9	0.304	2.3	4
171	178900	3	0.314	12	69	156	126700	2.9	0.301	2.2	4.2
164	232400	3.2	0.328	17	136	143	158100	3	0.316	2.4	3.8
161	193300	3.1	0.319	12	70	146	141200	2.9	0.307	2.4	3.8
168	221000	3.2	0.326	17	137	147	146500	3	0.313	2.3	4
169	217000	3.1	0.324	17	127	148	142600	2.9	0.31	2.2	4.1
189	187000	3.1	0.315	12	71	174	135000	2.9	0.303	2.4	3.9
170	193200	3.1	0.32	13	83	153	136800	2.9	0.308	2.4	3.9
168	210600	3.1	0.323	11	66	154	162700	3	0.312	2.6	3.6
172	242200	3.2	0.329	15	105	153	176900	3	0.317	2.5	3.7
184	209100	3.2	0.323	12	73	169	156800	3	0.311	2.6	3.6
160	190900	3.1	0.319	12	67	145	138700	2.9	0.305	2.2	4.2
163	178200	3	0.316	11	63	149	130200	2.9	0.303	2.3	4
164	190900	3.1	0.319	12	80	149	138700	2.9	0.307	2.4	3.8
170	222500	3.2	0.327	17	142	149	148300	3	0.315	2.5	3.7
174	208100	3.1	0.323	16	120	154	138400	2.9	0.31	2.3	4
161	206800	3.1	0.322	13	81	144	150300	2.9	0.31	2.4	3.8
174	227100	3.2	0.326	15	110	156	161800	3	0.314	2.5	3.7
167	181000	3.1	0.316	12	72	152	128900	2.9	0.304	2.4	3.9
175	183900	3	0.315	11	58	161	136000	2.9	0.302	2.3	4
165	263800	3.2	0.333	15	101	146	199100	3	0.322	2.7	3.4
179	216700	3.1	0.323	12	81	164	164300	3	0.312	2.6	3.6
173	200700	3.1	0.32	14	92	156	139800	2.9	0.307	2.3	4
162	210300	3.1	0.323	15	103	143	145100	2.9	0.31	2.3	4
171	196300	3.1	0.319	14	94	154	135700	2.9	0.307	2.4	3.8
169	191500	3.1	0.318	12	70	154	139400	2.9	0.305	2.3	4
165	220400	3.1	0.325	16	114	145	150300	2.9	0.312	2.2	4.1
175	208900	3.1	0.323	16	122	155	139500	2.9	0.311	2.4	3.8
180	191800	3.1	0.319	12	76	165	139600	2.9	0.306	2.4	3.9
170	198000	3.1	0.319	12	74	155	145900	2.9	0.307	2.4	3.8
177	182100	3	0.315	11	59	163	134100	2.9	0.302	2.2	4.2
151	179700	3	0.317	11	58	137	131700	2.9	0.304	2.2	4.1
160	220500	3.2	0.327	16	118	140	150400	3	0.313	2.2	4.1
186	240000	3.2	0.328	19	158	162	156900	3	0.315	2.4	3.8
175	238600	3.2	0.328	17	134	154	164200	3	0.316	2.4	3.9
176	242000	3.2	0.328	19	154	152	158900	3	0.315	2.3	4
173	186400	3.1	0.317	13	86	157	130200	2.9	0.305	2.4	3.8
163	222200	3.1	0.325	17	119	142	147200	2.9	0.311	2.1	4.3
155	185300	3.1	0.318	11	61	141	137300	2.9	0.305	2.3	4
166	184400	3.1	0.316	11	58	152	136500	2.9	0.304	2.3	4
160	220100	3.1	0.325	18	144	137	141400	2.9	0.312	2.2	4.1
166	189900	3.1	0.318	15	106	148	124600	2.9	0.304	2.1	4.3
158	178600	3	0.315	11	57	144	130700	2.9	0.302	2.2	4.2
163	201300	3.1	0.321	15	105	144	136200	2.9	0.308	2.3	4

Option 3 PV + Boiler + Grid							Option 4 CHP + PV + Boiler + Grid								
PV size (m2)	Boiler size (kW)	Grid demand (kWh/year)	Energy Cost (p/kWh)	CO2 emissions (kg CO2/kWh)	£/kg CO2 saved	% emission saved	CHP size (kW)	Store size (kWh)	PV size (m2)	Boiler size (kW)	Grid demand (kWh/year)	Energy Cost (p/kWh)	CO2 emissions (kg CO2/kWh)	£/kg CO2 saved	% emission saved
550	168	135500	4.2	0.266	0.8	16.4	11	65	385	154	106000	3.8	0.272	0.8	14.6
550	168	135500	4.2	0.266	0.8	16.4	11	65	385	154	106000	3.8	0.272	0.8	14.6
500	152	142000	4.1	0.27	0.8	16	13	87	375	136	103700	3.7	0.275	0.8	14.4
860	152	178100	4.7	0.267	0.7	20.1	15	106	421	133	150900	3.8	0.287	0.8	14.2
894	163	191700	4.8	0.269	0.7	20.1	17	129	421	142	157700	3.8	0.289	0.8	14.1
814	176	173700	4.6	0.265	0.7	19.8	17	124	386	155	138200	3.7	0.285	0.8	14
510	154	150600	4.1	0.272	0.8	15.9	13	85	355	138	113400	3.7	0.277	0.8	14.1
521	160	138500	4.2	0.268	0.8	16.2	13	83	386	144	101000	3.7	0.273	0.8	14.5
559	179	179700	4.2	0.277	0.8	16	17	131	398	158	126900	3.8	0.283	0.8	14.2
621	179	151300	4.3	0.269	0.8	16.7	16	116	292	159	113200	3.5	0.284	0.9	12.1
601	174	127900	4.3	0.262	0.8	16.8	12	69	395	159	96900	3.7	0.269	0.8	14.6
533	184	134100	4.2	0.265	0.8	16.3	13	82	403	168	96700	3.7	0.27	0.8	14.7
570	171	124100	4.2	0.262	0.8	16.7	12	69	390	156	92200	3.7	0.269	0.8	14.7
551	164	172300	4.2	0.276	0.8	16	17	136	418	143	118300	3.8	0.282	0.8	14.3
537	161	138200	4.2	0.268	0.8	16.3	12	70	376	146	105200	3.7	0.273	0.8	14.4
538	168	162500	4.2	0.274	0.8	16	17	137	429	147	107900	3.8	0.279	0.8	14.5
639	169	155900	4.4	0.27	0.8	16.7	17	127	285	148	114100	3.5	0.285	0.9	11.9
551	189	131100	4.2	0.264	0.8	16.5	12	71	399	174	98000	3.7	0.269	0.8	14.7
537	170	138100	4.2	0.268	0.8	16.4	13	83	403	153	100200	3.8	0.273	0.8	14.7
517	168	153700	4.1	0.272	0.8	15.9	11	66	354	154	124500	3.7	0.277	0.8	14.2
907	172	161000	4.8	0.261	0.7	20.8	15	105	408	153	135500	3.8	0.282	0.8	14.2
537	184	151600	4.2	0.271	0.8	16.2	12	73	387	169	117700	3.8	0.276	0.8	14.6
555	160	135600	4.2	0.266	0.8	16.4	12	67	352	145	104800	3.7	0.273	0.8	14.2
547	163	124600	4.2	0.263	0.8	16.6	11	63	360	149	96200	3.7	0.27	0.8	14.5
523	164	136400	4.2	0.267	0.8	16.2	12	80	357	149	103300	3.7	0.273	0.8	14.3
545	170	163700	4.2	0.274	0.8	16.1	17	142	489	149	106700	4	0.278	0.8	15
546	174	150700	4.2	0.271	0.8	16.2	16	120	476	154	99200	3.9	0.274	0.8	15
508	161	150900	4.1	0.271	0.8	15.9	13	81	353	144	113900	3.7	0.277	0.8	14.1
557	174	167000	4.2	0.274	0.8	16	15	110	416	156	121300	3.8	0.279	0.8	14.4
534	167	127300	4.2	0.264	0.8	16.4	12	72	404	152	93000	3.8	0.269	0.8	14.8
558	175	128500	4.2	0.263	0.8	16.5	11	58	350	161	101300	3.6	0.27	0.8	14.3
889	165	180500	4.7	0.266	0.7	20.2	15	101	452	146	153800	3.9	0.286	0.8	14.4
563	179	157400	4.2	0.271	0.8	16.2	12	81	397	164	124200	3.8	0.277	0.8	14.5
550	173	143800	4.2	0.268	0.8	16.3	14	92	412	156	102500	3.8	0.273	0.8	14.6
552	162	152600	4.2	0.271	0.8	16.1	15	103	412	143	107600	3.8	0.276	0.8	14.4
527	171	140700	4.2	0.268	0.8	16.1	14	94	430	154	97800	3.8	0.272	0.8	14.8
516	169	136700	4.1	0.267	0.8	16.1	12	70	351	154	104500	3.6	0.273	0.8	14.2
529	165	162100	4.2	0.274	0.8	15.9	16	114	355	145	114200	3.7	0.28	0.8	13.9
542	175	151500	4.2	0.271	0.8	16.2	16	122	498	155	99100	4	0.274	0.8	15.2
511	180	137100	4.2	0.267	0.8	16.2	12	76	352	165	104100	3.7	0.273	0.8	14.4
526	170	142100	4.1	0.268	0.8	16.1	12	74	356	155	109700	3.7	0.274	0.8	14.2
586	177	126200	4.3	0.262	0.8	16.8	11	59	345	163	100400	3.6	0.27	0.8	14.3
505	151	127500	4.1	0.266	0.8	16.2	11	58	323	137	99400	3.6	0.272	0.8	14.1
536	160	162500	4.2	0.275	0.8	16	16	118	364	140	114300	3.7	0.281	0.8	14.1
562	186	177700	4.2	0.276	0.8	15.9	19	158	440	162	115500	3.8	0.281	0.8	14.4
558	175	177000	4.2	0.276	0.8	15.9	17	134	397	154	124300	3.7	0.282	0.8	14.1
1053	176	156200	5	0.257	0.7	21.8	19	154	420	152	118700	3.7	0.282	0.8	14.2
542	173	131500	4.2	0.265	0.8	16.4	13	86	451	157	92300	3.9	0.269	0.8	15.1
536	163	163500	4.2	0.274	0.8	15.9	17	119	355	142	112300	3.6	0.28	0.8	13.8
544	155	131200	4.2	0.266	0.8	16.4	11	61	354	141	103000	3.7	0.272	0.8	14.4
542	166	130000	4.2	0.265	0.8	16.4	11	58	349	152	102100	3.7	0.271	0.8	14.3
560	160	161200	4.2	0.273	0.8	16.1	18	144	274	137	113100	3.5	0.287	0.9	11.8
431	166	143500	4	0.274	0.9	13.8	15	106	268	148	98600	3.5	0.28	0.9	12
542	158	125000	4.2	0.263	0.8	16.4	11	57	330	144	98100	3.6	0.271	0.8	14.1
538	163	145100	4.2	0.269	0.8	16.2	15	105	422	144	99100	3.8	0.274	0.8	14.6

Figure 4.37 Option outputs spreadsheet

4.3 CONCLUSION

A thorough description of the technology sizing tool was carried out in this section. The sizing procedures of the different technologies (i.e., gas-fired CHP systems, solar thermal systems, PV panels, fossil fuel boilers and national grid electricity) and combinations of technologies were described as well as the economic and environmental analysis of the options. The application of the Monte Carlo method in the tool, to take into account the uncertainty of building energy load profiles, was also outlined in this chapter.

In the following chapter a case study is used to run the tool and to show results of the tool together with a manual calculation for the same example to check the tools outputs are correct.

Chapter 5:

Computer tool evaluation and results

5.1 INTRODUCTION

Using the case study outlined below, a sample calculation is carried out to show the tool's calculation procedures in section 5.2. The tool is then run in section 5.3 using the same example. The outputs of the sample calculation and the tool's outputs are then compared to check the tool's outputs are correct. The case study used is a mixed-use office and residential building located in the UK. The building, with a total floor area of 1750m^2, consists of three clusters of 5 two-bedroom flats of 100m^2 each, 15 one-bedroom flats of 50m^2 each, and 500m^2 of office space with occupancy capacity of 50 people. In this analysis, it is assumed that the building loads and load profiles are not known in advance and hence the tool uses its database of load profiles that match each cluster building. Three different technologies are evaluated in the tool: combined heat and power, solar thermal collectors for hot water and photovoltaic panels for electivity generation with an operation life time of 15, 20 and 30 years respectively. To evaluate the economic viability and compare different technologies that may be suitable for this type of building project, it was assumed that gas prices and mains electricity tariff are 2.28p/kWh and 8.2p/kWh respectively, whereas on-site generated surplus electrical power is sold back to the grid at 3p/kWh. The project lifetime is assumed to be 30 years and at a discount cash flow rate of 5%.

5.2 SAMPLE CALCULATION

The tool's calculation procedures are outlined below using the case just described.

5.2.1 Building loads

a) Rule of Thumb energy loads

The rule of thumb (RoT) building energy load calculation is carried out by the tool as follows using equations 4.1 - 4.4:

For this example:

- For the 5 two-bedroom flats of 100 m^2 each, using RoT of 75 l/bedroom/day for hot water, 60 W/m^2 for space heating and 41 kWh/m^2/year for electricity:

D_{HW} = 75 x 2 x 5 = 750 l/day.

D_{SH} = 60 x 100 x 5 = 30 000 W = 30 kW

D_e = 41 x 100 x 5 = 20 500 kWh/year

- for the 15 one-bedroom flats of 50 m^2 each, using RoT of 115 l/bedroom/day for hot water, 60 W/m^2 for space heating and 41 kWh/m^2/year for electricity:

D_{HW} = 115 x 1 x 15 = 1725 l/day.

D_{SH} = 60 x 50 x 15 = 45 000 W = 45 kW

D_e = 40 x 50 x 15 = 30 000 kWh/year

- for the 500 m^2 office space without canteen with an occupancy of 50, using RoT of 10 l/person/day for hot water, 70 W/m^2 for space heating and 33 kWh/m^2/year for electricity:

D_{HW} = 10 x 50 = 500 l/day.

D_{SH} = 70 x 500 = 35 000 W = 35 kW

D_e = 33 x 500 = 16 500 kWh/year

Total loads are then calculated in the spreadsheet (Figure 5.1):

D_{HW} = 750 + 1725 + 500 = 2975 l/day.

D_{SH} = 30 + 45 + 35 = 110 kW

D_e = 20 500 + 30 000 + 16 500 = 67 000 kWh/year

Rules of Thumb Building Loads:			21	
Occupancy			50	
Floor area(m2)	500	750	500	
Number of building	5	15	1	
Building type	Residential	Residential	Office	
	2 bedroom flat	1 bedroom flat	without canteen	
Heating (kW)	30	45	35	
Hot Water (litres)	750	1725	500	
Electricity (kWh)	20500	30000	16500	
Totals:		Heating (kW) =	**110**	kWh
		Hot water (litres) =	**2975**	litres
		Electricity (kWh) =	**67000**	kWh

Figure 5.1 RoT building energy loads summary

b) Load profiles

In this example, it is assumed the load profiles are not known and the database of load profiles is therefore used to determine the building energy load profiles for this building. The following calculation procedures however are only for one set of load profiles and the Monte Carlo method is only applied in section 5.3 when the tool is run.

daily hot water load profiles (litres/hour)

weekday

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	3	3	0	0	20	0	0	0
0	0	0	0	0	0	0	37	0	20	0	0	0	0	0	0	0	3	0	5	3	10	0	0
3	0	0	0	0	0	0	0	0	3	0	3	0	3	0	0	0	0	0	0	20	0	0	3
0	0	0	0	0	0	0	0	0	20	3	0	0	0	0	0	0	0	0	3	0	0	0	0
0	0	0	0	17	0	0	0	0	0	3	20	17	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	25	20	0	0	0	0	0	3	0	20	0	0	0	3
0	0	0	0	0	0	0	17	20	0	0	3	6	0	0	0	3	0	6	0	0	0	5	0
0	0	0	0	0	0	0	17	20	3	0	0	0	0	0	3	8	3	3	0	0	3	0	0
0	0	0	0	0	17	0	0	20	17	0	0	0	0	0	0	0	0	0	0	17	0	5	0
0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	3	0	3	0
0	0	0	0	0	0	0	0	0	0	40	0	0	3	0	20	0	0	3	0	25	20	0	3
0	0	0	0	0	0	0	0	20	17	17	0	0	0	0	0	0	0	0	0	0	0	5	0
0	0	25	20	0	0	0	0	0	0	20	3	0	0	0	0	17	0	0	0	25	0	0	3
0	0	5	17	0	0	0	0	0	0	17	0	0	0	0	0	20	0	3	0	5	0	0	3
0	0	0	0	0	0	0	37	0	20	0	0	0	0	0	0	0	3	0	5	3	10	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
0	0	0	0	0	17	0	0	20	0	0	0	17	0	0	0	0	0	0	0	0	0	0	20
0	0	0	0	0	17	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	5	17	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
0	0	0	0	0	0	0	0	0	0	42	0	0	0	8	0	0	23	0	0	0	5	0	3
0	0	0	0	0	0	0	100	50	50	50	50	100	100	50	50	100	50	0	0	0	0	0	0

weekend

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	0	0	0	0	6	3	0	20	20	0	0	0	0	0	0	0	5	3	3
0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	20	5	20	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	20	5	20	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	17	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	6	34	0	0	0	0	0	17	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	3	3	0	17	0	0	0	3	0	25	0	5	0	3
0	0	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	28	8	8	25
5	0	0	0	0	0	0	0	0	20	0	34	0	0	0	0	3	0	0	0	0	0	11	0
0	5	0	6	0	0	0	0	0	0	0	20	0	17	0	0	5	0	0	17	5	3	0	0
0	0	0	0	0	0	0	0	0	0	0	6	17	6	3	0	0	0	3	20	17	0	0	0
0	0	0	0	0	0	0	0	0	0	0	6	17	6	3	0	0	0	3	20	17	0	0	0
0	0	0	0	3	0	3	3	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	17	0	0	0	0	0	0
0	5	0	6	0	0	0	0	0	0	0	20	0	17	0	0	5	0	0	17	5	3	0	0
0	0	0	0	3	0	3	3	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	6	17	6	3	0	0	0	3	20	17	0	0	0
0	0	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	28	8	8	25
0	0	0	0	0	0	0	0	0	6	3	0	20	20	0	0	0	0	0	0	0	5	3	3
0	0	0	0	0	0	0	3	0	0	3	0	17	0	0	5	0	0	0	0	0	5	0	0
0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	20	5	20	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.2 Hourly hot water demands for typical January weekday and weekend day

For this example building, consisting of 15 one-bedroom flats, 5 two-bedroom flats and 500 m^2 of office space where the load profiles are not known, the tool selects 20 load profiles randomly from the "flats" section of the load profile database for hot water, space heating and hot water respectively. A load profile is then randomly selected for each hot water, space heating and electricity from the office database, which are then multiplied by 500 to give the load profiles for the office space of 500 m^2. This is carried out for both weekend and weekday profiles. The data for these load profiles are shown in Figures 5.2-5.4. The load profiles for the different building types are then summed up to give total hot water, space heating and electricity load profiles for the building for a weekday and weekend day respectively (Figure 5.5).

Heating Load Profiles

weekday

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4

weekend

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
0	0.3	0.2	0.05	0.3	0	3.5	4.2	3.5	1.1	1	1	0.7	1.2	0.7	1.6	1.5	3.3	3	3	2.6	1	0	0.3
0	0.4	1	0.5	0.8	0.2	7.4	5.2	5.4	1	1.5	1.3	1	2	1.4	2.5	2	5	3	4	3	1.5	0	0.2
10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4

Figure 5.3 Hourly space heating demands for a typical January weekday and weekend day

To calculate monthly loads, it is assumed that there are 365 x 5 / 7 /12 = 21.726 weekdays per months and 365 × 2 / 7 /12 = 8.69 weekend days per month. January hot water load, (cell B49) is therefore calculated as:

$$D_{HW,J} = (21.726 \times D_{HW,J,WD}) + (8.69 \times D_{HW,J,WE}) \qquad \text{Equation 4.5}$$

Where, $D_{HW,J}$ is total January hot water load (litres), $D_{HW,J,WD}$ is January weekday hot water demand (litres) and $D_{HW,J,WE}$ is January weekend hot water demand (litres).

In this case: $D_{HW,J}$ = (21.726 × B45) + (8.69 × G45) = (21.726 × 2240) + (8.69 × 1475) = 61 485 l

Electricity Load Profiles

weekday

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.2	0.2	0.2	0.2	0.4	0.75	1	0.95	1.05	0.9	0.75	0.95	0.7	0.8	0.6	0.3
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.2	0.2	0.2	0.2	0.4	0.75	1	0.95	1.05	0.9	0.75	0.95	0.7	0.8	0.6	0.3
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.5	0.6	0.7	0.5	1.05	0.85	0.5	0.45	0.55	0.6	0.65	0.85	1	0.65	0.75	0.45
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.2	0.2	0.2	0.2	0.4	0.75	1	0.95	1.05	0.9	0.75	0.95	0.7	0.8	0.6	0.3
2.28	2.24	2.28	2.26	2.28	2.86	5.29	8.36	12.6	14	14.3	14.3	14.2	14.1	14.1	14	13.6	11.5	8.93	6	3.38	2.38	2.02	2

weekend

hours																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.2	0.2	0.2	0.2	0.4	0.75	1	0.95	1.05	0.9	0.75	0.95	0.7	0.8	0.6	0.3
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.5	0.6	0.7	0.5	1.05	0.85	0.5	0.45	0.55	0.6	0.65	0.85	1	0.65	0.75	0.45
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.4	0.45	0.5	0.4	0.3	0.4	0.3	0.35	0.4	0.55	0.9	1.1	1	1	0.7	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.5	0.6	0.7	0.5	1.05	0.85	0.5	0.45	0.55	0.6	0.65	0.85	1	0.65	0.75	0.45
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.5	0.6	0.7	0.5	1.05	0.85	0.5	0.45	0.55	0.6	0.65	0.85	1	0.65	0.75	0.45
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.5	0.6	0.7	0.5	1.05	0.85	0.5	0.45	0.55	0.6	0.65	0.85	1	0.65	0.75	0.45
0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.2	0.2	0.2	0.2	0.4	0.75	1	0.95	1.05	0.9	0.75	0.95	0.7	0.8	0.6	0.3
0.15	0.75	0.9	0.65	0.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.4	1.2	1.65	1.2	0.85	0.85	0.6	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.4	1.4	0.5	0.6	0.45	0.2	0.15	0.15	0.4	0.55	0.9	0.85	0.5	0.4
0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7	1.9	1.8	1.7	0.75	0.4
1.9	1.9	1.91	1.88	1.97	1.95	2.02	2.07	2.07	1.97	2	1.93	1.98	1.98	1.97	2.03	2.09	2.12	2.07	2.05	2.03	2.07	1.9	1.97

Figure 5.4 Hourly electricity demands for a typical January weekday and weekend day

Space heating and electricity loads are calculated in the same way. For other months in the year, factors are applied to take into account the varying demand throughout the year.

$$D_{HW} = [(21.726 \times D_{HW,WD}) + (8.69 \times D_{HW,WE})] \times f \qquad \text{Equation 4.6}$$

Where, f is the monthly factor.

For example space heating for April (cell C52) is calculated as [(21.726×C45)+(8.69×H45)]×G52 = [(21.726×1410)+(8.69×1394)]×0.51 = 21669 kWh (Figure 5.6).

Daily week day	Hot Water (litres)	Heating (January) (kWh)	Electricity (kWh)
01:00	7	11	7.0
02:00	2	20	9.5
03:00	33	26	11.3
04:00	41	20	11.0
05:00	41	27	11.3
06:00	22	19	11.1
07:00	57	130	14.5
08:00	7	113	22.8
09:00	216	110	28.4
10:00	196	41	30.6
11:00	180	47	34.4
12:00	228	46	34.8
13:00	136	41	33.7
14:00	153	57	36.2
15:00	120	47	36.7
16:00	73	68	36.8
17:00	89	63	39.2
18:00	168	113	42.2
19:00	106	89	46.7
20:00	34	101	49.4
21:00	53	88	45.6
22:00	142	58	45.0
23:00	78	33	37.9
00:00	58	39	33.8
Total	2240	1410	710

Daily weekend	Hot Water (litres)	Heating (January) (kWh)	Electricity (kWh)
01:00	9	11	6.7
02:00	12	19	7.2
03:00	3	25	8.5
04:00	22	20	9.0
05:00	11	26	9.8
06:00	6	18	10.0
07:00	13	126	11.1
08:00	17	112	16.2
09:00	9	108	19.6
10:00	42	41	20.0
11:00	29	46	24.3
12:00	159	45	24.2
13:00	230	40	24.1
14:00	123	56	25.6
15:00	24	46	24.9
16:00	21	67	24.7
17:00	30	62	26.8
18:00	115	111	29.6
19:00	60	89	36.1
20:00	199	100	45.6
21:00	138	87	46.5
22:00	64	57	45.6
23:00	56	33	38.2
00:00	83	39	34.0
Total	1475	1394	569

Figure 5.5 Daily building energy load profiles summary

Yearly	Hot Water (litres)	Space Heating (kWh)	Electricity (kWh)		HW factors	SH factors	E factors
January	61485	42748	20370		1	1.00	1.00
February	61485	38179	18686		1	0.89	0.92
March	61485	31103	16848		1	0.73	0.83
April	61485	21669	15010		1	0.51	0.74
May	61485	8992	13785		1	0.21	0.68
June	61485	0	13019		1	0.00	0.64
July	61485	0	12712		1	0.00	0.62
August	61485	0	12866		1	0.00	0.63
September	61485	0	13631		1	0.00	0.67
October	61485	11498	15776		1	0.27	0.77
November	61485	27123	18379		1	0.63	0.90
December	61485	38031	19911		1	0.89	0.98

Figure 5.6 Monthly building energy loads and monthly load factors

The hot water demand profile is converted from litres to kWh in columns C and F in Figure 5.7 using equation 4.6. For example, at 01:00 on a weekday hot water demand is 7 litres (Figure 5.5). The demand in kWh during that hour (Cell C14

Figure 5.7) therefore is: D_{HW} (kWh) = D_{HW} (litres) × 4.2 × 55 / 3600 = 7 × 4.2 × 55 / 3600 = 0.4 kWh

Annual heat load D_H (kWh) (cell D40 in Figure 5.7) is calculated by adding the space heating load D_{SH} (kWh) and the hot water load D_{HW} (kWh).

$D_h = D_{SH} + D_{HW}$ = 219 294 + 47 344 = 266 637 kWh/year

The annual electricity demand (cell J40 in Figure 5.7) is calculated by adding the demands for each month and is rounded to the nearest 100 kWh. Therefore, in this example, the electricity demand, D_e = 190 900 kWh.

5.2.2 Supply of heat and electricity from a Boiler and Grid

a) Boiler sizing

OPTION 1:	Boiler + Grid									
Boiler Size								Grid Demand		
peak heat demand =			134	kW						
boiler efficiency =			0.8							
boiler size =		167	168	kW						
Hot water storage size		747	747	litres	(daily HW demand/3)					
January										
Time	Weekday Heat Demand (kWh)			Weekend Heat Demand (kWh)				Week day electricity (kWh)	Weekend electricity (kWh)	
	SH	HW	Total	SH	HW	Total				
1	11.4	0.4	11.9	11.4	0.6	12.0		7.0	6.7	
2	19.5	0.1	19.6	19.4	0.8	20.2		9.5	7.2	
3	26.2	2.1	28.3	25.4	0.2	25.6		11.3	8.5	
4	20.4	2.6	23.0	19.9	1.4	21.3		11.0	9.0	
5	26.9	2.6	29.5	26.4	0.7	27.1		11.3	9.8	
6	18.6	1.4	20.0	18.4	0.4	18.8		11.1	10.0	
7	130.3	3.7	134.0	126.4	0.8	127.3		14.5	11.1	
8	113.4	0.4	113.9	112.4	1.1	113.5		22.8	16.2	
9	110.3	13.9	124.2	108.4	0.6	109.0		28.4	19.6	
10	41.3	12.6	53.9	41.4	2.7	44.1		30.6	20.0	
11	46.9	11.6	58.5	46.4	1.9	48.3		34.4	24.3	
12	45.7	14.6	60.3	45.4	10.2	55.6		34.8	24.2	
13	40.7	8.7	49.4	40.4	14.8	55.2		33.7	24.1	
14	57.2	9.8	67.0	56.4	7.9	64.3		36.2	25.6	
15	47.1	7.7	54.8	46.4	1.5	48.0		36.7	24.9	
16	68.3	4.7	73.0	67.4	1.3	68.8		36.8	24.7	
17	62.9	5.7	68.6	62.4	1.9	64.3		39.2	26.8	
18	113.1	10.8	123.9	111.4	7.4	118.8		42.2	29.6	
19	89.4	6.8	96.2	89.4	3.9	93.3		46.7	36.1	
20	101.4	2.2	103.6	100.4	12.8	113.2		49.4	45.6	
21	87.8	3.4	91.2	87.4	8.9	96.3		45.6	46.5	
22	57.9	9.1	67.0	57.4	4.1	61.5		45.0	45.6	
23	33.4	5.0	38.4	33.4	3.6	37.0		37.9	38.2	
24	39.3	3.7	43.0	39.4	5.3	44.7		33.8	34.0	
			1553.5			1488.15		709.7	568.1	
	Annual heat load =		266637	kWhyear		Annual electricity load =			190900	kWh/year

Figure 5.7 Boiler Sizing spreadsheet

The peak heat demand (cell D5) is found from the weekday and weekend heat load profiles (rows D and G). In this example, peak heat demand, $D_{H,p}$ = 134 kW and boiler efficiency, η_b = 80%. Therefore using equation 4.8, the boiler size, S_b is:

$S_b = \frac{D_{H,p}}{\eta_b}$ = 134 / 0.8 = 167 kW. The boiler size is rounded up to the nearest kW. The boiler size in this case therefore is 168 kW.

The hot water storage is assumed to be 1/3 of a day's hot water demand of either weekday or weekend day, depending on which demand is largest. In this case, the storage is therefore assumed to be 2240 / 3 = 747 litres.

Costs							
	Project Lifetime (years) =	30					
	Discount rate (%) =	5					
	Gas cost =	2.28	Gas emission factor =	0.19			
	Electricity cost =	8.2	Electricity emission factor =	0.43			
System							
	System =	Boiler				System =	Grid
	Lifetime (years) =	15					
	Efficiency =	0.80		PW		Annual electricity output (kWh) =	190900
	Annual heat output (kWh) =	266637		7999115		Life time output (kWh) =	5727000
						annual fuel costs (£) =	15653.8
	Fuel input (kWh) =	333296		4999447	kWh	NPV fuel cost (£) =	240637.274
	Capital costs (£) =	32,555		48215			
	Annual fuel costs (£) =	7,599		116818			
	Annual Maintenance (£) =	652		10023			
	Disposal Cost (£) =	1304		302			
				175357	£		
	Energy cost (p/kWh) =	2.19				Energy cost (p/kWh) =	4.20
System costs	Heat =	2.19	p/kWh				
	Electricity =	4.20	p/kWh	5727000			
	TOTAL =	3.1	p/kWh				
		ENERGY SUPPLY					
		Boiler	Electricity				
	Energy cost (p/kWh)	2.28	8.20				
	CO2 emission factor (kg/kWh)	0.19	0.43				
	Annual heat/electricity load (kWh)	266637	190900				
	Annual Fuel input (kWh)	333,296					
	Annual fuel cost (£)	7599	15654	5.08	p/kWh		
	Annual CO2 emissions (kg)	63326	82087	0.32	kg CO2/kWh		
	Emissions			145413	kg CO2		

Figure 5.8 Boiler costs spreadsheet

b) System costs and emissions

1) Boiler

The annual boiler heat output O_{boiler} is the annual heat demand D_H as previously calculated. The boiler fuel input FI_{boiler} (kWh) therefore is:

$FI_{boiler} = O_{boiler} / \eta_{\text{boiler}} = 266\ 637 / 0.80 = 333\ 296$ kWh

Assuming a gas cost, GC of 2.28 p/kWh in this case, the annual fuel cost FC_{boiler} (£/year) is:

$FC_{boiler} = FI_{boiler} \times GC = 333\ 296 \times 2.28 / 100 =$ £ 7 599 /year

The boiler capital cost is calculated using the equation from Figure 4.10:

$CC_{boiler} = 1058.7 \times S_b^{-0.3314} \times S_b = 1058.7 \times 168^{-0.3314} \times 168 =$ £ 32 555

Annual boiler maintenance cost is:

$MC_{boiler} = CC_{boiler} \times 2\% =$ £ 652 /year

Boiler disposal cost is:

$DC_{boiler} = MC_{boiler} \times 2 =$ £ 1 304

Next, the net present value (NPV) system cost is calculated.

- Assuming a project lifetime, n of 30 years, the lifetime energy output, O_L (kWh) (cell F66 Figure 5.8) is calculated for the boiler using equation 4.10:

$O_{L,boiler} = O_{boiler} \times n = 266\ 637 \times 30 = 7\ 999\ 115$ kWh

- NPV boiler replacement cost $CC_{NPVreplacement}$ (£) is calculated using equation 4.12. In this case the boiler is only replaced once during the project lifetime as the boiler lifetime is 15 years and project lifetime is 30 years. The discount rate is assumed to be 5 % in this case.

$$CC_{NPVreplacement} = CC_{current} \times (1 + DR)^{-n} = 32\ 555 \times (1 + 0.05)^{-15} = £\ 15\ 660$$

- NPV capital cost is calculated using equation 4.11:

$$CC_{NPV} = CC_{current} + CC_{NPVreplacement} = 32\ 555 + 15\ 660 = £\ 48\ 215$$

- Boiler NPV fuel cost using equation 4.13:

$$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 7\ 599 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 116\ 818$$

- Boiler NPV maintenance cost using equation 4.14:

$$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 652 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £10\ 023$$

- Boiler NPV disposal cost using equation 4.15:

$$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n} = 1\ 304 \times (1 + 0.05)^{-30} = £\ 302$$

- The costs are summed up to give a total NPV cost (equation 4.16):

$$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler}$$

$$= 48\ 215 + 116\ 818 + 10\ 023 + 302 = £\ 175\ 357$$

- The boiler energy cost is obtained using equation 4.17:

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{175357}{7999115} \times 100 = 2.19 \text{ p/kWh}$$

2) Grid

- Electricity lifetime output O_{Le} (kWh) is:

O_{Le} = $D_e \times n$ = 190 900 × 30 = 5 727 000 kWh

- Assuming an electricity cost, EC of 8.20 p/kWh in this case, the annual fuel cost FC_e (£/year) is:

$FC_e = D_e \times EC$ = 190 900 × 8.2 / 100 = £ 15 653 /year

- NPV fuel cost $FC_{NPV,e}$ is:

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR = 15653 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 240 637

- Electricity energy cost is:

$$EC_e = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{240637}{5727000} \times 100 = 4.20 \text{ p/kWh}$$

3) System energy cost

System energy cost is calculated using equation 4.18:

$$EC_{system} = \frac{[(EC_{boiler} \times D_h) + (EC_{EGrid} \times D_e)]}{(D_h + D_e)} = \frac{[(2.19 \times 266637) + (4.2 \times 190900)]}{(266637 + 190900)} = 3.1$$
p/kWh

4) Emissions

Assuming an electricity emission factor, EF_e of 0.43 kg CO_2/kWh, and a gas emission factor, EF_g of 0.19 kg CO_2/kWh, the annual CO_2 emissions $E_{CO2,BG}$ (kg CO_2) are calculated using equation 4.9:

$E_{CO2,BG} = (D_e \times EF_e) + (D_g \times EF_g)$ = (190 900 × 0.43) + (333 296 × 0.19) = 145 413 kg CO_2

System CO_2 Emissions per kWh for the boiler and grid option are: $E_{CO2,BG}$ / (D_e + D_h) = 145413 / (190900+266637) = 0.32 kg CO_2/kWh.

5.2.3 Supply of heat and electricity from a CHP, Boiler and Grid

a) System sizing

In this tool it is assumed that the CHP heat to power fraction is 2:1. The overall efficiency of CHP system is usually considered to be 80%.

The tool first checks if there is a demand for at least 4500 hours from the hot water and space heating load profiles. Only when this criterion is met then the CHP sizing is carried out.

For every hour, it is assumed that the CHP is running when there is a heat demand in that hour. The hours the CHP is running are then added up by the tool to give total running hours per year.

The computer tool sizes CHP by using the total heat load profile for the project. The optimum size of CHP in terms of costs and emissions is found by minimising the saved costs of emissions in £/kg CO_2.

Table 5.1 CHP sizing simulation output list

CHP size (kW)	Energy cost (p/kWh)	Emissions (kg CO2/kWh)	£/kg CO2 saved)	CHP hours
11	2.9	0.307	2.5	5670.9
12	2.9	0.307	2.5	5497
13	2.9	0.307	2.5	5292.8
14	2.9	0.307	2.5	5118.9
15	2.9	0.307	2.5	4888.7
16	2.9	0.307	2.5	4810.5
10	2.9	0.307	2.6	5914.2
17	2.9	0.307	2.6	4754.1
9	3	0.307	2.7	6140.4
8	3	0.308	2.8	6335.9
18	2.8	0.308	2.8	4614.9
7	3	0.308	2.9	6561.8
19	2.8	0.309	3	4506.3
6	3	0.309	3.3	6740
5	3	0.311	3.9	7026.9
4	3	0.312	4.7	7187.6
3	3	0.313	6.1	7548.4
2	3.1	0.315	8.8	7961.5
1	3.1	0.317	17	8256.5

Any surplus heat produced could be stored for the next period of the heating cycle where a boiler would supply any deficit in heat generation. In this computer subroutine, the storage capacity is assumed to be 50% of the surplus heat produced by the CHP in a summer day of the month July.

The sizing procedure for the CHP is as follows: The tool records cost of emissions saved (£/kg CO_2 saved) for every kW thermal rating of CHP starting with 1 kW until a CHP size is reached that achieves less than 4500 running hours. From this list, the tool then selects the CHP size achieving the lowest £/kg CO_2 saved. Table 5.1 shows the simulation outputs of the different CHP sizes in this example, which were sorted to find the lowest £/kg CO_2 saved at the top of the table. A CHP of 11kW$_{th}$ was selected to achieve the lowest £/kg CO_2 saved in this example.

OPTION 2 CHP + Boiler + Grid

CHP SIZE

Peak heat demand	134	kW			
CHP size	11	kWth		5.5	kWe
Assume storage	50%	of surplus July day		65	kWh
	5671	CHP hours/year			
		WEEKDAY	21.726		

January (WEEKDAY)

Time	Heat demand (kWh) SH	HW	Total	CHP hours	CHP (kWh) Output	Deficit	Surplus	electricity demand (kWh)	CHP (kWh) Output	Deficit	Surplus
1	11.4	0.4	11.9	1	11	0.9	0.0	7.0	5.5	1.5	0.0
2	19.5	0.1	19.6	1	11	8.6	0.0	9.5	5.5	4.0	0.0
3	26.2	2.1	28.3	1	11	17.3	0.0	11.3	5.5	5.8	0.0
4	20.4	2.6	23.0	1	11	12.0	0.0	11.0	5.5	5.5	0.0
5	26.9	2.6	29.5	1	11	18.5	0.0	11.3	5.5	5.8	0.0
6	18.6	1.4	20.0	1	11	9.0	0.0	11.1	5.5	5.6	0.0
7	130.3	3.7	134.0	1	11	123.0	0.0	14.5	5.5	9.0	0.0
8	113.4	0.4	113.9	1	11	102.9	0.0	22.8	5.5	17.3	0.0
9	110.3	13.9	124.2	1	11	113.2	0.0	28.4	5.5	22.9	0.0
10	41.3	12.6	53.9	1	11	42.9	0.0	30.6	5.5	25.1	0.0
11	46.9	11.6	58.5	1	11	47.5	0.0	34.4	5.5	28.9	0.0
12	45.7	14.6	60.3	1	11	49.3	0.0	34.8	5.5	29.3	0.0
13	40.7	8.7	49.4	1	11	38.4	0.0	33.7	5.5	28.2	0.0
14	57.2	9.8	67.0	1	11	56.0	0.0	36.2	5.5	30.7	0.0
15	47.1	7.7	54.8	1	11	43.8	0.0	36.7	5.5	31.2	0.0
16	68.3	4.7	73.0	1	11	62.0	0.0	36.8	5.5	31.3	0.0
17	62.9	5.7	68.6	1	11	57.6	0.0	39.2	5.5	33.7	0.0
18	113.1	10.8	123.9	1	11	112.9	0.0	42.2	5.5	36.7	0.0
19	89.4	6.8	96.2	1	11	85.2	0.0	46.7	5.5	41.2	0.0
20	101.4	2.2	103.6	1	11	92.6	0.0	49.4	5.5	43.9	0.0
21	87.8	3.4	91.2	1	11	80.2	0.0	45.6	5.5	40.1	0.0
22	57.9	9.1	67.0	1	11	56.0	0.0	45.0	5.5	39.5	0.0
23	33.4	5.0	38.4	1	11	27.4	0.0	37.9	5.5	32.4	0.0
24	39.3	3.7	43.0	1	11	32.0	0.0	33.8	5.5	28.3	0.0
			1553.5		264	1289.5	0.0	709.71	132	577.7	0
						1289.5	0.0			12565.1	

WEEKEND 8.690

January (WEEKEND)

Time	Heat demand (kWh) SH	HW	Total	CHP hours	CHP (kWh) Output	Deficit	Surplus	electricity demand (kWh)	CHP (kWh) Output	Deficit	Surplus
1	11.4	0.6	12.0	1	11	1.0	0	6.7	5.5	1.2	0.0
2	19.4	0.8	20.2	1	11	9.2	0	7.2	5.5	1.7	0.0
3	25.4	0.2	25.6	1	11	14.6	0	8.5	5.5	3.0	0.0
4	19.9	1.4	21.3	1	11	10.3	0	9.0	5.5	3.5	0.0
5	26.4	0.7	27.1	1	11	16.1	0	9.8	5.5	4.3	0.0
6	18.4	0.4	18.8	1	11	7.8	0	10.0	5.5	4.5	0.0
7	126.4	0.8	127.3	1	11	116.3	0	11.1	5.5	5.6	0.0
8	112.4	1.1	113.5	1	11	102.5	0	16.2	5.5	10.7	0.0
9	108.4	0.6	109.0	1	11	98.0	0	19.6	5.5	14.1	0.0
10	41.4	2.7	44.1	1	11	33.1	0	20.0	5.5	14.5	0.0
11	46.4	1.9	48.3	1	11	37.3	0	24.3	5.5	18.8	0.0
12	45.4	10.2	55.6	1	11	44.6	0	24.2	5.5	18.7	0.0
13	40.4	14.8	55.2	1	11	44.2	0	24.1	5.5	18.6	0.0
14	56.4	7.9	64.3	1	11	53.3	0	25.6	5.5	20.1	0.0
15	46.4	1.5	48.0	1	11	37.0	0	24.9	5.5	19.4	0.0
16	67.4	1.3	68.8	1	11	57.8	0	24.7	5.5	19.2	0.0
17	62.4	1.9	64.3	1	11	53.3	0	26.8	5.5	21.3	0.0
18	111.4	7.4	118.8	1	11	107.8	0	29.6	5.5	24.1	0.0
19	89.4	3.9	93.3	1	11	82.3	0	36.1	5.5	30.6	0.0
20	100.4	12.8	113.2	1	11	102.2	0	45.6	5.5	40.1	0.0
21	87.4	8.9	96.3	1	11	85.3	0	46.5	5.5	41.0	0.0
22	57.4	4.1	61.5	1	11	50.5	0	45.6	5.5	40.1	0.0
23	33.4	3.6	37.0	1	11	26.0	0	38.2	5.5	32.7	0.0
24	39.4	5.3	44.7	1	11	33.74	0	34.0	5.5	28.5	0.0
			1488		264	1224	0	568.09	132	436.1	0
						1224.1	0.0			3779.6	

Figure 5.9 Hourly CHP simulations for a typical day in January

Figure 5.9 shows the hourly simulation of the CHP system for a typical January day. This table is repeated for each month of the year to simulate the CHP system throughout the year. The hourly demand and supply of heat and power for the CHP system and CHP running hours for a typical January day are listed. It is assumed that the CHP is running if there is a heat demand. The deficit and surplus heat and electricity are calculated for each hour using equations 4.22 and 4.23. For example, the weekday heat deficit and surplus during 01:00 are:

$$Deficit_{heat} = D_h - O_{CHP} = 11.9 - 11 = 0.9 \text{ kWh}$$

As there is a deficit during this hour, there is no surplus. Therefore,

$$Surplus_{heat} = 0$$

The weekday electricity deficit and surplus at 01:00 are:

$Deficit_e = D_e - O_{CHP} = 7 - 5.5 = 1.5$ kWh

As there is a deficit during this hour, there is no surplus. Therefore,

$Surplus_e = 0$

The surpluses and deficits are calculated in this manner for every hour in the day for a weekday and a weekend day as shown in Figure 5.9.

The total heat deficit for a day is calculated taking into account the heat storage. Equation 4.24 is used in cell G38 in the Excel sheet is:

> If *Surplus* (kWh/day) < *Storage capacity* (kWh/day),
>
> Then *Total Deficit* = *Deficit* – *Surplus*,
>
> Else *Total Deficit* = *Deficit* – *Storage capacity*.

Where, *Total Deficit* is the heat deficit taking into account heat storage (kWh/day), *Deficit* is the heat deficit before taking into account the heat storage (kWh/day) and *Surplus* is the heat surplus (kWh/day).

In this case, *Surplus* = 0, therefore *Total Deficit* = *Deficit* = 1282 kWh for this day in January.

Where there is a surplus, for example on a typical day in May, where *Surplus* = 30.7 kWh, *Deficit* = 207 kWh and *Storage capacity* = 65 kWh, then, since *Surplus* < *Storage capacity*, then: *Total Deficit* = *Deficit* – *Surplus* = 207 - 30.7 = 176.3 kWh

The annual heat and electricity deficits and surpluses of the CHP (Figure 5.10) are calculated by first calculating monthly figures and then adding the monthly figures to obtain yearly ones.

Heat				**Electricity**		
Total deficit		186616	kWh/year	Total deficit	142894	kWh/year
				Total surplus	216	kWh/year
CHP annual output		**96360**	**kWh/year**		**48180**	**kWh/year**
BOILER SIZE				**GRID DEMAND**		
peak heat demand =		123	kW			
boiler efficiency =		0.8				
boiler size =	154	**154**	**kW**			
Hot water storage size	747	**747**	**litres**			
Annual Boiler Load =		**186616**	**kWh/year**	**Annual EGrid Load =**	**142900**	**kWh/year**

Figure 5.10 CHP annual outputs and Boiler + Grid sizing

Equations 4.25 and 4.26 are used to calculated monthly heat deficit and electricity deficit and surplus. For January, weekday heat deficit, $Deficit_{WD,h}$ = 176.3 kWh, and weekend day heat deficit, $Deficit_{WE,h}$ is 1224.1 kWh, therefore monthly heat deficit, $Deficit_{January,h}$ (kWh) is:

$$Deficit_{January,h} = [(Deficit_{WD,h} \times 21.726) + (Deficit_{WE,h} \times 8.69)] = [(1289.5 \times 21.726) + (1224.1 \times 8.69)] = 38\,653 \text{ kWh}$$

For January, weekday electricity deficit, $Deficit_{WD,e}$ = 577.71 kWh, and weekend day electricity deficit, $Deficit_{WE,e}$ is 436.1 kWh, therefore monthly electricity deficit, $Deficit_{January,e}$ (kWh) is:

$$Deficit_{January,e} = [(Deficit_{WD,e} \times 21.726) + (Deficit_{WE,e} \times 8.69)] = [(577.71 \times 21.726) + (436.1 \times 8.69)] = 16\,328 \text{ kWh}$$

There is no weekday or weekend day surplus in January for this example. Therefore $Surplus_{January,e}$ = 0 kWh in this case.

The annual CHP heat output $O_{CHP,h}$ and electricity demand $O_{CHP,e}$ are calculated in the CHP simulation spreadsheet above by calculating monthly figures and adding these up to give an annual heat output, as was the case for the surpluses and deficits.

For January, weekday and weekend day CHP heat outputs ($O_{CHP,WD,h}$ and $O_{CHP,WE,h}$) are 264 kWh and weekday and weekend day CHP electricity outputs ($O_{CHP,WD,e}$ and $O_{CHP,WE,e}$) are 132 kWh, therefore, January CHP heat and electricity outputs ($O_{January,CHP,h}$ and $O_{January,CHP,e}$) are:

$O_{January,CHP,h}$ = [($O_{CHP,WD,h}$ × 21.726) + ($O_{CHP,WE,h}$ × 8.69)] = [(264 × 21.726) + (264 × 8.69)] = 8 030 kWh

$O_{January,CHP,e}$ = [($O_{CHP,WD,e}$ × 21.726) + ($O_{CHP,WE,e}$ × 8.69)] = [(132 × 21.726) + (132 × 8.69)] = 4 015 kWh

Outputs are calculated for every month and are added up to give annual CHP heat and electricity outputs:

$O_{CHP,h}$ = 96 360 kWh/year

$O_{CHP,e}$ = 48 180 kWh/year

Any surplus electricity generated is exported to the grid and the annual electricity demand from the grid is equal to the annual electricity deficit as calculated above ($Surplus_e$ = 261 kWh/year and $Deficit_e$ = 142 894 kWh/year).

The Boiler is sized on the deficit heat demand as in block B1. In this case boiler size:

$S_b = \frac{D_{H,p}}{\eta_b}$ = 123 / 0.8 = 154 kW.

The hot water storage is 1/3 of a July day Deficit heat demand of either weekday or weekend day($Deficit_{JanuaryWD,h}$ or $Deficit_{JanuaryWE,h}$) depending on which demand is largest. In this case, the storage is therefore assumed to be 1289.5 / 3 = 430 litres.

b) System costs and emissions

COSTS					
Project Lifetime (years) =	30				
Discount rate (%) =	5				
Electricity export price (p/kWh) =	3				
Gas cost (p/kWh) =	2.28	Gas emission factor =		0.19	
Electricity cost (p/kWh) =	8.2	Electricity emission factor =		0.43	
System					
System =	**Boiler**				
Lifetime (years) =	15				
Efficiency =	0.80	**PV**			
Annual heat output (kWh) =	186616	5598479			
			5598479	**kWh**	
Fuel input (kWh) =	233270				
Capital costs (£) =	30,715	45489			
Annual fuel costs (£) =	5,319	81759			
Annual Maintenance (£) =	615	9454			
Disposal Cost (£) =	1230	285			
			136987	**£**	
Energy cost (p/kWh) =	**2.45**				
System =	**CHP**				
CHP Lifetime (years) =	20				
Efficiency =	0.8	**PV**			
Annual heat output (kWh) =	96360	2890800			
Annual electricity output (kWh) =	48180	1445400			
Fuel input (kWh) =	180675		**4336200**	**kWh**	
Capital costs (£) =	8929	12294			
Annual fuel costs (£) =	4113	63226			
Annual Maintenance (£) =	179	2752			
Disposal Cost (£) =	358	83			
Electricity export (£) =	-6		**78354**	**£**	
Energy cost (p/kWh) =	**1.81**				
System =	**Grid**				
Annual electricity output (kWh) =	142900				
Life time output (kWh) =	**4287000**				
annual fuel costs (£) =	11717.8				
NPV fuel cost (£) =	**180131.3066**				
Energy cost (p/kWh) =	**4.20**				
System costs Heat =	2.37	p/kWh			
Electricity =	3.60	p/kWh			
TOTAL =	**2.9**	**p/kWh**			
		ENERGY SUPPLY			
	Boiler	Grid	CHP		
Energy cost (p/kWh)	2.28	8.20	2.28		
CO2 emission factor (kg/kWh)	0.19	0.43	0.19		
Annual heat/electricity load (kWh)	186616	142900	144540		
Annual Fuel input (kWh)	233270		180675		
Annual fuel cost (£)	5318.56	11717.80	4112.92	**4.62**	**p/kWh**
Annual CO2 emission (kg)	44321	61447	34328	**0.31**	**kg CO2/kWh**
Emissions saved				**5317**	**kg CO2 saved**
				2.5	**£/kg CO2 saved**
				3.70	**% carbon emissions saved**

Figure 5.11 CHP, Boiler and Grid costs and emissions

The NPV system energy costs are calculated for each technology as in the Boiler and Grid option:

1) <u>boiler</u>

$FI_{boiler} = O_{boiler} / \eta_{CHP} = 186\ 616 / 0.80 = 233\ 270$ kWh

$FC_{boiler} = FI_{boiler} \times GC$ = 233 270 × 2.28 / 100 = £ 5 319 /year

CC_{boiler} = 1058.7 × $S_b^{-0.3314} \times S_b$ = 1058.7 × 154 $^{-0.3314}$ × 154 = £ 30 715

$MC_{boiler} = CC_{boiler}$ × 2% = £ 615 /year

$DC_{boiler} = MC_{boiler}$ × 2 = £ 1 230

$O_{L,boiler} = O_{boiler} \times n$ = 186 616 × 30 = 5 598 479 kWh

$CC_{NPVreplacement,boiler} = CC_{boiler} \times (1 + DR)^{-n}$ = 30 715 × (1 + *0.05*)$^{-15}$ = £ 14 774

$CC_{NPV,\ boiler} = CC_{boiler} + CC_{NPVreplacement,boiler}$ = 30 715 + 14 774 = £ 45 489

$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR$ = 5 319 × [1 – (1 + *0.05*)$^{-30}$] / 0.05 = £ 81 759

$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR$ = 615 × [1 – (1 + *0.05*)$^{-30}$] / 0.05 = £9 454

$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n}$ = 1 230 × (1 + *0.05*)$^{-30}$ = £ 285

$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler}$

= 45 489 + 81 759 + 9 454 + 285 = £ 136 987

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{136987}{5598479} \times 100 = 2.45 \text{ p/kWh}$$

2) <u>CHP</u>

$FI_{CHP} = (O_{CHP,h} + O_{CHP,e}) / \eta_{\mathrm{CHP}}$ = (96 360 + 48 180) / 0.80 = 180 675 kWh

Assuming an electricity export price, EEC of 3p/kWh in this example and CHP electricity export to the grid is FE_{CHP} (kWh/year), annual CHP electricity export cost, $FC_{CHP,export}$ (£) is:

$FC_{CHP,export} = FE_{CHP} \times EEC / 100 = Surplus_e \times EEC = 216 \times 3 / 100 = £\ 6$

$FC_{CHP} = FI_{CHP} \times GC - FC_{CHP,export} = 180\ 675 \times 2.28 / 100 - 6 = £\ 4\ 113$ /year

Using the equation in Figure 4.15, CHP capital cost is:

$CC_{CHP} = 1\ 676 \times S_{CHPth}^{-0.3025} \times S_{CHPth} = 1\ 676 \times 11^{-0.3025} \times 11 = £\ 8\ 929$

Maintenance costs are assumed to be 2% of capital costs of the CHP and disposal costs are double the annual maintenance costs.

$MC_{CHP} = CC_{CHP} \times 2\% = £\ 179$ /year

$DC_{CHP} = MC_{CHP} \times 2 = £\ 358$

$O_{L,CHP} = O_{CHP} \times n = (O_{CHP,h} + O_{CHP,e}) \times n = (96\ 360 + 48\ 180) \times 30 = 4\ 336\ 200$ kWh

$CC_{NPVreplacement,CHP} = CC_{CHP} \times (1 + DR)^{-n} = 8\ 929 \times (1 + 0.05)^{-15} = £\ 3\ 365$

$CC_{NPV,CHP} = CC_{CHP} + CC_{NPVreplacement,CHP} = 8\ 929 + 3\ 365 = £\ 12\ 294$

$FC_{NPV,CHP} = FC_{CHP} \times [1 - (1 + DR)^{-n}] / DR = 4\ 113 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 63\ 226$

$MC_{NPV,CHP} = MC_{CHP} \times [1 - (1 + DR)^{-n}] / DR = 179 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 2\ 752$

$DC_{NPV,CHP} = DC_{CHP} \times (1 + DR)^{-n} = 358 \times (1 + 0.05)^{-30} = £\ 83$

$C_{NPVCHPtotal} = CC_{NPV,CHP} + FC_{NPV,CHP} + MC_{NPV,CHP} + DC_{NPV,CHP} = £\ 78\ 354$

$$EC_{CHP} = \frac{C_{NPVCHP,total}}{O_{LCHP}} \times 100 = \frac{78354}{4336200} \times 100 = 1.81\,\text{p/kWh}$$

3) <u>Grid</u>

$O_{Le} = D_e \times n = 142\ 900 \times 30 = 4\ 287\ 000$ kWh

$FC_e = D_e \times EC = 142\ 900 \times 8.2 / 100 = £\ 11\ 718$ /year

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR = 11\ 718 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 180$
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$$EC_e = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{180131}{4287000} \times 100 = 4.20\,\text{p/kWh}$$

4) <u>System energy cost</u>

System energy cost is therefore calculated using equation 4.18:

$$EC_{system} = \frac{\left[(EC_{CHP} \times (O_{CHP,h} + O_{CHP,e})) + \left(EC_{boiler} \times O_b\right) + \left(EC_{EGrid} \times D_{egrid}\right)\right]}{\left(D_h + D_e\right)}$$
$$= \frac{[(1.81 \times (96360 + 48180)) + (2.45 \times 186616) + (4.2 \times 142900)]}{(266637 + 190900)} = 2.9\,p/kWh$$

5) <u>Emissions and emissions saved</u>

The annual CO_2 emissions $E_{CO2,BG}$ (kg CO_2) are:

$E_{CO2,CBG} = \left(D_{egrid} \times EF_e\right) + \left(D_g \times EF_g\right)$ = (D_{egrid} × EF_e) + [(FI_{CHP} + FI_{boiler}) × EF_g] = (142 900 × 0.43) + [(180 675 + 233 270) × 0.19] = 140 097 kg CO_2

System CO_2 Emissions per kWh for the CHP boiler and grid option are: $E_{CO2,CBG}$ / (D_e + D_h) = 140097 / (190900+266637) = 0.31 kg CO_2/kWh.

Emissions saved, $ES_{CO2,CBG}$ (kg CO_2 saved) for the CHP, Boiler and Grid option is calculated using equation 4.27:

$ES_{CO2,CBG} = E_{CO2,BG} - E_{CO2,CBG}$ = 145 413 – 140 097 = 5 317 kg CO_2 saved

For this option, a 3.7% emissions savings is achieved ($ES_{CO2,CBG}$ / $E_{CO2,BG}$ = 5317 / 145413 = 0.037 = 3.7%).

6) System cost per emissions saved

Cost per emissions savings, *ESC* (£/kg CO_2 saved) is calculated for the CHP, Boiler and Grid option using equation 4.28:

$$ESC = \frac{EC_{system} \times (D_h + D_e)}{100 \times ES_{CO2}} = \frac{2.9 \times (266637 + 190900)}{100 \times 5317} = 2.5£ / kgCO_2 saved$$

5.2.4 Supply of heat and electricity from ST, Boiler and Grid

a) System sizing

No limitation in the sizing procedure was selected in this example. Therefore the tool optimises the solar thermal system to find the collector size to achieve an optimum cost of emission saving in £/kg CO_2 saved.

The table shown in Figure 5.13 lists the hot water demand, D_{HW} and solar irradiation, I_S for each month and totals for the year. The average collector efficiency is calculated from the simulation tables such as the one in Figure 5.12 for the whole year to obtain an average collector efficiency figure for the year. The yearly figures (D_{HW} = 47344 kWh/year, I_S = 11217 kWh/m^2/year and η_{SC} = 27.7 %) are used to estimate a ST size that would supply hot water in the year equal to the yearly hot water demand. Equation 4.31 is used:

$$A_{sc} = \frac{D_{HW}}{I_S \eta_{SC}} = \frac{47344}{1121.7 \times 0.277} = 153m^2$$

This figure is used as a maximum solar collector size in the simulation to find the optimum collector size which achieves the lowest £/kg CO_2 saved. £/kg CO_2 saved figures are recorded for every ST area in intervals of 1 m^2 until 153 m^2 in this case. The size with the lowest £/kg CO_2 saved in this case is 127 m^2.

OPTION 3a: **ST + Boiler + Grid**

Solar thermal hot water collectors

HW temp:	60	degC		collector temperature:	55	degC		
CW temp:	5	degC		deltaT:	55	degC		
	WEEKDAY	WEEKEND		evacuated tube	ST size =	127	m2	
	21.73	8.69			storage =	48	kWh	
July	1.00	1.00						

Time	Weekday Hot water demand (kWh)	Weekend Hot water demand (kWh)	Abient temperature (degC)	Solar irradiance (W/m2)	Collector efficiency	ST output (kWh)	weekday deficit (kWh)		weekday surplus (kWh)	weekend deficit (kWh)		weekend surplus (kWh)	Pump running hours
1	0.4	0.6			0	0	0.4	0.0	0	0.6	0.5	0	0
2	0.1	0.8			0	0	0.1	0.0	0	0.8	0.8	0	0
3	2.1	0.2			0	0	2.1	1.5	0	0.2	0.2	0	0
4	2.6	1.4	12.3	27	0	0	2.6	2.6	0	1.4	1.4	0	0
5	2.6	0.7	13.8	70.5	0	0	2.6	2.6	0	0.7	0.7	0	0
6	1.4	0.4	15.1	143.25	0	0	1.4	1.4	0	0.4	0.4	0	0
7	3.7	0.8	16.4	246	0.18	5.67	0.0	0.0	2.01	0.0	0.0	4.84	1
8	0.4	1.1	17.5	346	0.34	15.03	0.0	0.0	14.58	0.0	0.0	13.94	1
9	13.9	0.6	18.5	429.5	0.42	22.86	0.0	0.0	9.00	0.0	0.0	22.29	1
10	12.6	2.7	19.3	488.75	0.46	28.49	0.0	0.0	15.91	0.0	0.0	25.79	1
11	11.6	1.9	20.0	519.25	0.48	31.49	0.0	0.0	19.94	0.0	0.0	29.63	1
12	14.6	10.2	20.6	519.25	0.48	31.72	0.0	0.0	17.09	0.0	0.0	21.52	1
13	8.7	14.8	20.9	488.75	0.47	29.16	0.0	0.0	20.43	0.0	0.0	14.40	1
14	9.8	7.9	21.1	429.5	0.44	23.95	0.0	0.0	14.14	0.0	0.0	16.06	1
15	7.7	1.5	21.0	346	0.38	16.52	0.0	0.0	8.82	0.0	0.0	14.98	1
16	4.7	1.3	20.8	246	0.24	7.52	0.0	0.0	2.83	0.0	0.0	6.17	1
17	5.7	1.9	20.3	143.25	0	0	5.7	0.0	0.00	1.9	0.0	0.00	0
18	10.8	7.4	19.6	70.5	0	0	10.8	0.0	0.00	7.4	0.0	0.00	0
19	6.8	3.9	18.7	27	0	0	6.8	0.0	0.00	3.9	0.0	0.00	0
20	2.2	12.8			0	0	2.2	0.0	0.00	12.8	0.0	0.00	0
21	3.4	8.9			0	0	3.4	0.0	0.00	8.9	0.0	0.00	0
22	9.1	4.1			0	0	9.1	0.0	0.00	4.1	0.0	0.00	0
23	5.0	3.6			0	0	5.0	0.0	0.00	3.6	0.0	0.00	0
24	3.7	5.3			0	0	3.7	0.0	0.00	5.3	0.0	0.00	0
	143.7	94.6		4540.5			8.2	8.2	124.77	3.9	3.9	169.62	310
									47.91			47.91	

Figure 5.12 ST simulation for a typical July day

ST hot water

Total demand	47344	kWh/year		pump power	795	W
Total deficit	18761	kWh/year				
Total surplus	9883	kWh/year				

ST collector SIZE

10% reduction in carbon emissions

14541	kgCO2	Output:	82656	kWh/year		Area =	266	m2

Sized using maximum area

Max space available =		m2	Output =	0	kWh/year

Sized to meet July demand			Sized to meet yearly demand		
Area =	73	m2		153	m2
			Optimum ST size (in £/kgCO2 saved)		
Limitation =	optimum £/kg CO2 saved			127	m2
			ST size achieving max CO2 saving		
Collector area =	**127**	**m2**		150	m2

	hot water load kWh	solar irradiation kWh/m2	ST collector output kWh
J	3945	41	30
F	3945	60	985
M	3945	88	2153
A	3945	122	4678
M	3945	138	5700
J	3945	131	5471
J	3945	141	6585
A	3945	135	6547
S	3945	105	4349
O	3945	80	2247
N	3945	50	509
D	3945	31	0
	47344	**1121.7**	**39254**

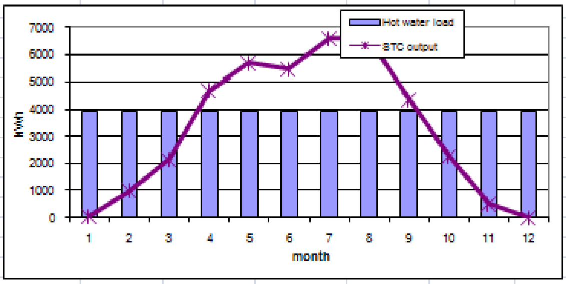


Figure 5.13 ST sizing

Figure 5.12 shows the hourly simulation of the solar thermal system for a typical July day. As previously mentioned, it is assumed that the solar thermal system supplies only domestic hot water and the collector type used in this tool is evacuated tube. The computer tool evaluates the solar collector output on an hourly basis for a typical day for each month as follows:

Typical evacuated solar collector efficiency is calculated on an hourly basis using equation 4.32. The average collector temperature, T_{SCav} is assumed to be 55°C. At 10 am the ambient temperature, T_{Am} is 19.3°C and the incident solar radiation normal to the collector, I_s is 488.75 kW/m^2. The solar collector efficiency (%) 10am therefore is:

$$\eta_{sc} = 0.7 - 3.3\frac{T_{SCav} - T_{Am}}{I_s} = 0.7 - 3.3\frac{55 - 19.3}{488.75} = 0.46 = 46\%$$

The output of the solar thermal system is calculated using equation 4.31. Assuming a collector area, A_{sc} of 137 m^2, then the collector output, Q_{sc} (kW) is:

$$Q_{sc} = A_{sc} I_s \eta_{sc} = 137 \times 488.75 \times 0.46 = 28.5 \text{ kW}$$

Assuming a constant output throughout the hour then Q_{sc} = 28.5 kWh during that hour.

Hourly deficit and surplus values are calculated, as well as the hourly deficit after hot water storage has been taken into account.

For example, there is no hot water deficit, $Deficit_{HW}$ on a weekday at 10:00am in July, because the output of the solar collector is greater than the hot water demand at that hour.

$Deficit_{HW} = 0$

As there is a deficit during this hour, there is no surplus. Therefore,

$Surplus_{heat} = Q_{sc} – D_{HW} = 28.5 – 12.6 = 15.9$ kWh

The surpluses and deficits are calculated in this manner for every hour in the day for a weekday and a weekend day as shown in Figure 5.12.

The hot water storage capacity is assumed to be 1/3 of the daily hot water demand, which in this case is 48 kWh. The heat deficit taking into account the heat storage is calculated for every hour. The daily heat surplus as calculated above is assumed to be stored in the hot water storage. Therefore the surplus hot water available to be used that day is assumed to be the daily hot water surplus or if this is greater than the storage capacity then the storage capacity is taken as the surplus hot water available to be used that day. For example, on the July day shown in Figure 5.12, the hot water surplus on a weekday is 47.9 kWh, which is less than the storage capacity. Therefore this figure is used as the surplus hot water to be used that day. The way the calculation is carried out in the spreadsheet is as follows:

- At 17:00 there is a deficit of 5.7 kWh. However in the hot water storage there is 47.9 kWh stored. The hot water from the storage is utilised during that hour and the deficit after storage is therefore 0 at that hour. This leaves 47.9 – 5.7 = 42.2 kWh in the storage.
- During the next hour: 18:00, there is a deficit of 10.8 kWh, and the deficit after storage is 0 leaving 42.2 – 10.8 = 31.4 kWh in the storage.

This is continued until nothing is left in the storage.

The pump is assumed to be running whenever there is an output from the solar thermal system. The annual pump running hours, H in this example is 2493 hours and the pump power rating, P_p is 0.795 kW. The annual pump power consumption, D_{ep} (kWh) is calculated using equation 4.33:

$$D_{ep} = P_p H = 0.795 \times 2493 = 1982 \text{ kWh}$$

The solar thermal, boiler and grid option electricity demand, D_{eSBG} (kWh) is calculated by adding the electricity demand and the pump electricity demand:

$$D_{eSBG} = D_d + D_{ep} = 190\ 900 + 1\ 982 = 192\ 900 \text{ kWh}$$

Boiler Size

peak heat demand =		134	kW
boiler efficiency =		0.8	
boiler size =	167	**168**	**kW**
Storage size =	747	**747**	**litres**

Grid Demand

pump electricity demand =
1982 kWh/year

January

Time	Weekday Heat Demand (kWh) SH	HW	Total	Weekday Heat Demand (kWh) SH	HW	Total	Week day electricity (kWh)	Weekend electricity (kWh)
1	11.4	0.4	11.9	11.4	0.6	12.0	7.0	6.7
2	19.5	0.1	19.6	19.4	0.8	20.2	9.5	7.2
3	26.2	2.1	28.3	25.4	0.2	25.6	11.3	8.5
4	20.4	2.6	23.0	19.9	1.4	21.3	11.0	9.0
5	26.9	2.6	29.5	26.4	0.7	27.1	11.3	9.8
6	18.6	1.4	20.0	18.4	0.4	18.8	11.1	10.0
7	130.3	3.7	134.0	126.4	0.8	127.3	14.5	11.1
8	113.4	0.4	113.9	112.4	1.1	113.5	22.8	16.2
9	110.3	13.9	124.2	108.4	0.6	109.0	28.4	19.6
10	41.3	12.6	53.9	41.4	2.7	44.1	30.6	20.0
11	46.9	11.2	58.1	46.4	1.5	47.9	34.4	24.3
12	45.7	14.0	59.8	45.4	9.6	55.0	34.8	24.2
13	40.7	8.7	49.4	40.4	14.8	55.2	33.7	24.1
14	57.2	9.8	67.0	56.4	7.9	64.3	36.2	25.6
15	47.1	7.7	54.8	46.4	1.5	48.0	36.7	24.9
16	68.3	4.7	73.0	67.4	1.3	68.8	36.8	24.7
17	62.9	5.7	68.6	62.4	1.9	64.3	39.2	26.8
18	113.1	10.8	123.9	111.4	7.4	118.8	42.2	29.6
19	89.4	6.8	96.2	89.4	3.9	93.3	46.7	36.1
20	101.4	2.2	103.6	100.4	12.8	113.2	49.4	45.6
21	87.8	3.4	91.2	87.4	8.9	96.3	45.6	46.5
22	57.9	9.1	67.0	57.4	4.1	61.5	45.0	45.6
23	33.4	5.0	38.4	33.4	3.6	37.0	37.9	38.2
24	39.3	3.7	43.0	39.4	5.3	44.7	33.8	34.0
			1552.505433			1487.167933	709.7	568.1

Annual heat load = 238054 kWhyear

Annual electricity load = 192900 kWh/year

Figure 5.14 Boiler sizing and grid demand for ST+boiler+grid option

The boiler is sized to supply the deficit hot water calculated above and the total space heating load. The boiler is sized on the January heat demand, as this is usually the greatest. Figure 5.14 shows the spreadsheet. In this case boiler size:

$S_b = \frac{D_{H,p}}{\eta_b}$ = 134 / 0.8 = 168 kW (rounded up to the next kW)

The hot water storage is 1/3 of a July day Deficit heat demand of either weekday or weekend day($Deficit_{JanuaryWD,h}$ or $Deficit_{JanuaryWE,h}$) depending on which demand is largest. In this case, the storage is therefore assumed to be 2241 / 3 = 747 litres.

b) System costs and emissions

Figure 5.15 shows the spreadsheet calculating the system costs and emissions in the same way as for the CHP+Boiler+Grid option. The calculations are as follows:

1) <u>boiler</u>

$FI_{boiler} = O_{boiler} / \eta_{CHP}$ = 238 054 / 0.80 = 297 568 kWh

$FC_{boiler} = FI_{boiler} \times GC$ = 297 568 × 2.28 / 100 = £ 6 785 /year

$CC_{boiler} = 1058.7 \times S_b^{-0.3314} \times S_b = 1058.7 \times 168^{-0.3314} \times 168$ = £ 32 555

$MC_{boiler} = CC_{boiler} \times 2\%$ = £ 652 /year

$DC_{boiler} = MC_{boiler} \times 2$ = £ 1 304

$O_{L,boiler} = O_{boiler} \times n$ = 238 054 × 30 = 7 141 620 kWh

$CC_{NPVreplacement,boiler} = CC_{boiler} \times (1 + DR)^{-n} = 32\,555 \times (1 + 0.05)^{-15}$ = £ 15 660

Costs					
Project Lifetime (years) =	30				
Discount rate (%) =	5				
Gas cost =	2.28	Gas emission factor =	0.19		
Electricity cost =	8.2	lectricity emission factor =	0.43		
System					
System =	**Boiler**				
Lifetime (years) =	15				
Efficiency =	0.8	**PV**			
Annual heat output (kWh) =	238054	7141632			
Fuel input (kWh) =	297568			**7141632**	**kWh**
Capital costs (£) =	32,555	48215			
Annual fuel costs (£) =	6,785	104295			
Annual Maintenance (£) =	652	10023			
Disposal Cost (£) =	1304	302			
				162834	**£**
Energy cost (p/kWh) =	**2.28**				
System =	**ST**				
Lifetime (years) =	30				
m2	127.0				
Output (kWh) =	39255	1177650		**1177650**	**kWh**
Capital costs (£) =	107950	107950			
Annual fuel costs (£) =	163	2498			
Annual Maintenance (£) =	2159	33189			
Disposal Cost (£) =	5398	1249			
				144886	**£**
Energy cost (p/kWh) =	**12.30**				
System =	**Grid**				
Annual electricity output (kWh) =	192900				
Life time output (kWh) =	**5787000**				
annual fuel costs (£) =	15817.8				
NPV fuel cost (£) =	**243158.36**				
Energy cost (p/kWh) =	**4.20**				
System costs Heat =	3.85	p/kWh			
Electricity =	4.20	p/kWh			
TOTAL =	**4.1**	**p/kWh**			

ENERGY SUPPLY

	Boiler	Electricity	ST		
Energy cost (p/kWh)	2.28	8.20	8.20		
CO2 emission factor (kg/kWh)	0.19	0.43	0.43		
Annual heat/electricity load (kWh)	238054	190918			
Annual Fuel input (kWh)	297,568		1982		
Annual fuel cost (£)	6785	15655	163	**4.92**	**p/kWh**
Annual CO2 emissions (kg)	56538	82095	852	**0.30**	**kg CO2/kWh**
Emissions saved				**5928**	**kg CO2 saved**
				3.1	**£/kg CO2 saved**
				4.1	**% carbon emissions saved**

Figure 5.15 Costs and emissions of the ST+Boiler+Grid option

$$CC_{NPV,\ boiler} = CC_{boiler} + CC_{NPVreplacement,boiler} = 32\ 555 + 15\ 660 = £\ 48\ 215$$

$$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 6\ 785 \times [1 - (1 + 0.05)^{-30}] / 0.05$$

$= £\ 104\ 295$

$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 652 \times [1 - (1 + 0.05)^{-30}] / 0.05$ $= £10\ 023$

$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n} = 1\ 304 \times (1 + 0.05)^{-30} = £\ 302$

$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler}$

$= 48\ 215 + 104\ 295 + 10\ 023 + 302 = £\ 162\ 835$

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{162835}{7141620} \times 100 = 2.28\ \text{p/kWh}$$

2) <u>ST</u>

$FI_{ST} = D_{ep} = 1\ 982$ kWh

$FC_{ST} = FI_{ST} \times EC = 1\ 982 \times 8.2 / 100 = £\ 163$ /year

Using a cost figure of £853/m^2:

$CC_{ST} = 853 \times A_{sc} = 853 \times 127 = £\ 107\ 950$

Maintenance costs are assumed to be 2% of capital costs of the ST and disposal costs are double the annual maintenance costs.

$MC_{ST} = CC_{ST} \times 2\% = £\ 2\ 159$ /year

$DC_{ST} = MC_{ST} \times 2 = £\ 5\ 398$

$O_{L,ST} = O_{ST} \times n\ = O_{ST} \times n\ = 39\ 255 \times 30 = 1\ 177\ 650$ kWh

The solar thermal system has lifetime of 30 years in this example. There therefore is no replacement cost and the NPV capital cost is equal to the current capital cost in this example:

$CC_{NPVreplacement,ST}$ = £0

$CC_{NPV,ST} = CC_{ST}$ = £ 107 950

$FC_{NPV,ST} = FC_{ST} \times [1 - (1 + DR)^{-n}] / DR = 163 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 2 498

$MC_{NPV,ST} = MC_{ST} \times [1 - (1 + DR)^{-n}] / DR = 2\ 159 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 33 189

$DC_{NPV,ST} = DC_{ST} \times (1 + DR)^{-n} = 5398 \times (1 + 0.05)^{-30}$ = £ 1249

$C_{NPVSTtotal} = CC_{NPV,ST} + FC_{NPV,ST} + MC_{NPV,ST} + DC_{NPV,ST}$ = £ 144 886

$$EC_{ST} = \frac{C_{NPVCHP,total}}{O_{LCHP}} \times 100 = \frac{144886}{1177650} \times 100 = 12.30 \text{ p/kWh}$$

3) <u>Grid</u>

$O_{Le} = D_{eSBG} \times n = 192\ 900 \times 30 = 5\ 787\ 000$ kWh

$FC_e = D_e \times EC = 192\ 900 \times 8.2 / 100$ = £ 15 818 /year

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR = 15\ 818 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 243 158

$$EC_e = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{243158}{5787000} \times 100 = 4.20 \text{ p/kWh}$$

4) System energy cost

System energy cost is calculated using equation 4.18:

$$EC_{system} = \frac{\left[(EC_{ST} \times O_{ST}) + \left(EC_{boiler} \times O_b\right) + \left(EC_{EGrid} \times D_{egrid}\right)\right]}{\left(D_h + D_e\right)}$$
$$= \frac{[(12.3 \times 39255) + (2.28 \times 238054) + (4.2 \times 192900)]}{(266637 + 192900)} = 4.1p / kWh$$

5) Emissions and emissions saved

The annual CO_2 emissions $E_{CO2,BG}$ (kg CO_2) are:

$E_{CO2,STBG} = \left(D_{egrid} \times EF_e\right) + \left(D_g \times EF_g\right)$ = ($D_{egrid} \times EF_e$) + ($FI_{boiler} \times EF_g$) = (192 900 × 0.43) + (297 568 × 0.19) = 139 485 kg CO_2

System CO_2 Emissions per kWh for the ST, boiler and grid option are: $E_{CO2,SBG}$ / (D_e + D_h) = 139485 / (192900+266637) = 0.30 kg CO_2/kWh.

Emissions saved, $ES_{CO2,CBG}$ (kg CO_2 saved) for the ST, Boiler and Grid option is:

$ES_{CO2,STBG} = E_{CO2,BG} - E_{CO2,STBG}$ = 145 413 – 139 485 = 5 928 kg CO_2 saved

For this option, a 3.7% emissions savings is achieved ($ES_{CO2,CBG} / E_{CO2,BG}$ = 5928 / 145413 = 0.041 = 4.1%).

6) System cost per emissions saved

Cost per emissions savings, *ESC* (£/kg CO_2 saved) is calculated for the ST, Boiler and Grid option:

$$ESC = \frac{EC_{system} \times (D_h + D_e)}{100 \times ES_{CO2}} = \frac{4.1 \times (266637 + 192900)}{100 \times 5928} = 3.1 £ / kgCO_2 saved$$

5.2.5 Supply of heat and electricity from a ST, CHP, Boiler and Grid

a) System sizing

Table 5.2 Extract of optimisation table of ST with CHP

ST area m^2	CHP kW_{th}	p/kWh	% carbon emissions saved	£/kg CO2 saved
38	17	3	9.2	1
9	17	2.7	7.7	1.1
10	17	2.7	7.8	1.1
11	16	2.8	7.8	1.1
12	16	2.8	7.9	1.1
13	16	2.8	8	1.1
14	16	2.8	8	1.1
15	15	2.8	8	1.1
16	15	2.8	8	1.1
17	15	2.8	8	1.1
18	15	2.8	8.1	1.1
19	15	2.9	8.2	1.1
20	15	2.9	8.2	1.1
21	15	2.9	8.2	1.1
22	15	2.9	8.3	1.1
23	15	2.9	8.3	1.1
24	14	2.9	8.2	1.1
25	14	2.9	8.3	1.1
26	14	2.9	8.3	1.1
27	14	2.9	8.4	1.1
28	14	2.9	8.4	1.1
29	14	3	8.5	1.1
30	14	3	8.6	1.1

Since no sizing limitation was selected in this example. The tool therefore calculates the optimum CHP size, in the manner described in the CHP+Boiler+Grid option, for different ST collector sizes. This data is listed and the sorted to find an optimum combination of ST and CHP in terms of £/kgCO_2 saved. Table 5.2 shows the first few lines of this data table in the tool. In this example the optimum combination of ST with CHP is found to be 38 m^2 of ST collectors with a CHP size with a heat rating of 17 kW_{th}.

July	1.00	1.00											
Time	Weekday Hot water demand (kWh)	Weekend Hot water demand (kWh)	Abient temperature (degC)	Solar irradiance (W/m2)	Collector efficiency	ST output (kWh)	weekday deficit (kWh)	WD deficit after storage (kWh)	weekday surplus (kWh)	weekend deficit (kWh)	WE deficit after storage (kWh)	weekend surplus (kWh)	Pump running hours
1	0.4	0.6			0	0	0.4	0.4	0	0.6	0.6	0	0
2	0.1	0.8			0	0	0.1	0.1	0	0.8	0.8	0	0
3	2.1	0.2			0	0	2.1	2.1	0	0.2	0.2	0	0
4	2.6	1.4	12.3	27	0	0	2.6	2.6	0	1.4	1.4	0	0
5	2.6	0.7	13.8	70.5	0	0	2.6	2.6	0	0.7	0.7	0	0
6	1.4	0.4	15.1	143.25	0	0	1.4	1.4	0	0.4	0.4	0	0
7	3.7	0.8	16.4	246	0.18	1.70	2.0	2.0	0	0.0	0.0	0.86	1
8	0.4	1.1	17.5	346	0.34	4.50	0.0	0.0	4.05	0.0	0.0	3.41	1
9	13.9	0.6	18.5	429.5	0.42	6.84	7.0	7.0	0	0.0	0.0	6.26	1
10	12.6	2.7	19.3	488.75	0.46	8.52	4.1	4.1	0	0.0	0.0	5.83	1
11	11.6	1.9	20.0	519.25	0.48	9.42	2.1	2.1	0	0.0	0.0	7.56	1
12	14.6	10.2	20.6	519.25	0.48	9.49	5.1	5.1	0	0.7	0.7	0.00	1
13	8.7	14.8	20.9	488.75	0.47	8.72	0.0	0.0	0	6.0	6.0	0.00	1
14	9.8	7.9	21.1	429.5	0.44	7.17	2.7	2.7	0	0.7	0.7	0.00	1
15	7.7	1.5	21.0	346	0.38	4.94	2.8	2.8	0	0.0	0.0	3.40	1
16	4.7	1.3	20.8	246	0.24	2.25	2.4	2.4	0	0.0	0.0	0.90	1
17	5.7	1.9	20.3	143.25	0	0	5.7	1.7	0	1.9	0.0	0	0
18	10.8	7.4	19.6	70.5	0	0	10.8	10.8	0	7.4	0.0	0	0
19	6.8	3.9	18.7	27	0	0	6.8	6.8	0	3.9	0.0	0	0
20	2.2	12.8			0	0	2.2	2.2	0	12.8	0.0	0	0
21	3.4	8.9			0	0	3.4	3.4	0	8.9	6.5	0	0
22	9.1	4.1			0	0	9.1	9.1	0	4.1	4.1	0	0
23	5.0	3.6			0	0	5.0	5.0	0	3.6	3.6	0	0
24	3.7	5.3			0	0	3.7	3.7	0	5.3	5.3	0	0
	143.7	94.6		4540.5			80.2	80.2	4.05	31.1	31.1	28.23	310
									4.05			28.23	

Figure 5.16 July day simulation of ST system

Figure 5.16 works in the same way as Figure 5.12 in simulating the solar thermal system for every hour on a July day and Figure 5.17 works in the same way as Figure 5.9 in simulating the CHP system for every hour on a July day. The hourly CHP heat demand is calculated by adding the hourly space heating demand to the hourly solar thermal hot water deficit from Figure 5.16. There is no space heating demand, D_{SH} during July. The CHP heat demand, $D_{H,CHP}$ therefore for a weekday at 17:00 would be:

$$D_{H,CHP} = Deficit_{ST} + D_{SH} = 1.7 + 0 = 1.7 \text{ kWh}$$

The boiler is sized to supply the deficit hot water and space heating demands calculated above. The boiler is sized on the January heat demand (the peak deficit calculated in the CHP spreadsheet for the month of January). Figure 5.18 shows the spreadsheet.

July						0.62			
Time	Weekday heat demand	CHP running hours	CHP (kWh) Output	Deficit	Surplus	Electricity demand	CHP (kWh) Output	Deficit	Surplus
1	0.4	1	17	0.0	16.6	4.4	8.5	0.0	4.1
2	0.1	1	17	0.0	16.9	5.9	8.5	0.0	2.6
3	2.1	1	17	0.0	14.9	7.0	8.5	0.0	1.5
4	2.6	1	17	0.0	14.4	6.9	8.5	0.0	1.6
5	2.6	1	17	0.0	14.4	7.0	8.5	0.0	1.5
6	1.4	1	17	0.0	15.6	6.9	8.5	0.0	1.6
7	2.0	1	17	0.0	15.0	9.1	8.5	0.6	0.0
8	0.0	0	0	0.0	0.0	14.2	0	14.2	0.0
9	7.0	1	17	0.0	10.0	17.7	8.5	9.2	0.0
10	4.1	1	17	0.0	12.9	19.1	8.5	10.6	0.0
11	2.1	1	17	0.0	14.9	21.4	8.5	12.9	0.0
12	5.1	1	17	0.0	11.9	21.7	8.5	13.2	0.0
13	0.0	1	17	0.0	17.0	21.1	8.5	12.6	0.0
14	2.7	1	17	0.0	14.3	22.6	8.5	14.1	0.0
15	2.8	1	17	0.0	14.2	22.9	8.5	14.4	0.0
16	2.4	1	17	0.0	14.6	23.0	8.5	14.5	0.0
17	1.7	1	17	0.0	15.3	24.4	8.5	15.9	0.0
18	10.8	1	17	0.0	6.2	26.3	8.5	17.8	0.0
19	6.8	1	17	0.0	10.2	29.1	8.5	20.6	0.0
20	2.2	1	17	0.0	14.8	30.8	8.5	22.3	0.0
21	3.4	1	17	0.0	13.6	28.5	8.5	20.0	0.0
22	9.1	1	17	0.0	7.9	28.1	8.5	19.6	0.0
23	5.0	1	17	0.0	12.0	23.6	8.5	15.1	0.0
24	3.7	1	17	0.0	13.3	21.1	8.5	12.6	0.0
	80.2		391.0	0.0	310.8	442.9	195.5	260.2	12.8
				0.0				5654.1	

July						0.62			
Time	Weekend day heat demand	CHP running hours	CHP (kWh) Output	Deficit	Surplus	Electricity demand	CHP (kWh) Output	Deficit	Surplus
1	0.6	1	17	0.0	16.4	4.2	8.5	0.0	4.3
2	0.8	1	17	0.0	16.2	4.5	8.5	0.0	4.0
3	0.2	1	17	0.0	16.8	5.3	8.5	0.0	3.2
4	1.4	1	17	0.0	15.6	5.6	8.5	0.0	2.9
5	0.7	1	17	0.0	16.3	6.1	8.5	0.0	2.4
6	0.4	1	17	0.0	16.6	6.3	8.5	0.0	2.2
7	0.0	0	0	0.0	0.0	6.9	0	6.9	0.0
8	0.0	0	0	0.0	0.0	10.1	0	10.1	0.0
9	0.0	0	0	0.0	0.0	12.2	0	12.2	0.0
10	0.0	0	0	0.0	0.0	12.5	0	12.5	0.0
11	0.0	0	0	0.0	0.0	15.2	0	15.2	0.0
12	0.7	1	17	0.0	16.3	15.1	8.5	6.6	0.0
13	6.0	1	17	0.0	11.0	15.0	8.5	6.5	0.0
14	0.7	1	17	0.0	16.3	16.0	8.5	7.5	0.0
15	0.0	0	0	0.0	0.0	15.5	0	15.5	0.0
16	0.0	0	0	0.0	0.0	15.4	0	15.4	0.0
17	0.0	0	0	0.0	0.0	16.7	0	16.7	0.0
18	0.0	0	0	0.0	0.0	18.5	0	18.5	0.0
19	0.0	0	0	0.0	0.0	22.5	0	22.5	0.0
20	0.0	0	0	0.0	0.0	28.4	0	28.4	0.0
21	6.5	1	17	0.0	10.5	29.0	8.5	20.5	0.0
22	4.1	1	17	0.0	12.9	28.4	8.5	19.9	0.0
23	3.6	1	17	0.0	13.4	23.8	8.5	15.3	0.0
24	5.3	1	17	0.0	11.7	21.2	8.5	12.7	0.0
	31.1		221.0	0.0	189.9	354.5	110.5	263.1	19.0
				0.0				2286.2	

Figure 5.17 July day hourly CHP simulation for ST+CHP+Boiler+Grid option

In this case boiler size:

$$S_b = \frac{D_{H,p}}{\eta_b} = 117 / 0.8 = 147 \text{ kW (rounded up to the next kW)}$$

The hot water storage is 1/3 of a July day Deficit heat demand of either weekday or weekend day($Deficit_{JanuaryWD,h}$ or $Deficit_{JanuaryWE,h}$) depending on which demand is largest. In this case, the storage is therefore assumed to be 1149 / 3 = 384 litres.

Boiler Size				Grid Demand		
peak heat demand =		117	kW	pump electricity demand =		
boiler efficiency =		0.8		761	kWh/year	
boiler size =	146	147	kW			
Hot water storage size =	383	384	litres			
Annual Boiler Load =		119747	kWh/year	Annual EGrid Load =	124100	kWh/year

Figure 5.18 Boiler and grid sizing for ST+CHP+Boiler+Grid option

b) System costs and emissions

Costs				
Project Lifetime (years) =	30			
Discount rate (%) =	5			
Electricity export price (p/kWh) =	3			
Gas cost (p/kWh) =	2.28	Gas emission factor =	0.19	
Electricity cost (kWh) =	8.2	tricity emission factor =	0.43	
System				
System =	**Boiler**			
Lifetime (years) =	15			
Efficiency =	0.8	**PV**		
Annual heat output (kWh) =	119747	3592400		
Fuel input (kWh) =	149683		**3592400**	**kWh**
Capital costs (£) =	29,775	44097		
Annual fuel costs (£) =	3,413	52463		
Annual Maintenance (£) =	596	9162		
Disposal Cost (£) =	1192	276		
			105998	**£**
Energy cost (p/kWh) =	**2.95**			
System =	**ST**			
Lifetime (years) =	30			
m2	38.0			
Output (kWh) =	11746	352380	**352380**	**kWh**
Capital costs (£) =	32300	32300		
Annual Maintenance (£) =	646	9931		
Disposal Cost (£) =	1615	374		
Annual fuel costs (£) =	62.402	959	**43564**	**£**
Energy cost (p/kWh) =	**12.36**			
System =	**CHP**			
CHP Lifetime (years) =	20			
Efficiency =	0.8			
Annual heat output (kWh) =	141016	4230480		
Annual electricity output (kWh) =	70508	2115240	**6345721**	**kWh**
Fuel input (kWh) =	264405			
Capital costs (£) =	12097	16656		
Annual fuel costs (£) =	5941	91320		
Annual Maintenance (£) =	242	3720		
Disposal Cost (£) =	484	112		
Electricity export (£) =	-88		**111809**	**£**
Energy cost (p/kWh) =	**1.76**			
System =	**Grid**			
Annual electricity output (kWh) =	124100			
Life time output (kWh) =	**3723000**			
annual fuel costs (£) =	10176.2			
NPV fuel cost (£) =	**156433**			
Energy cost (p/kWh) =	**4.20**			
System costs Heat =	2.80	p/kWh		
Electricity =	3.34	p/kWh		
TOTAL =	**3.1**	**p/kWh**		

ENERGY SUPPLY	Boiler	Electricity	ST	CHP		
Energy cost (p/kWh)	2.28	8.20	8.20	2.28		
CO2 emission factor (kg/kWh)	0.19	0.43	0.43	0.19		
Annual heat/electricity load (kWh)	119747	123339		211524		
Annual Fuel input (kWh)	149,683		761	264405		
Annual fuel cost (£)	3413	10114	62	5941	**4.26**	**p/kWh**
Annual CO2 emissions (kg)	28440	53036	327	50237	**0.29**	**kg CO2/kWh**
Emissions saved					**13374**	**kg CO2 saved**
					1.1	**£/kg CO2 saved**
					9.2	**% carbon emissions saved**

Figure 5.19 Costs and emissions for ST+CHP+Boiler+Grid option

1) <u>boiler</u>

$FI_{boiler} = O_{boiler} / \eta_{CHP}$ = 119 747 / 0.80 = 149 683 kWh

$FC_{boiler} = FI_{boiler} \times GC$ = 149 683 × 2.28 / 100 = £ 3 413 /year

$CC_{boiler} = 1058.7 \times S_b^{-0.3314} \times S_b = 1058.7 \times 147^{-0.3314} \times 147$ = £ 29 775

$MC_{boiler} = CC_{boiler} \times 2\%$ = £ 596 /year

$DC_{boiler} = MC_{boiler} \times 2$ = £ 1 192

$O_{L,boiler} = O_{boiler} \times n$ = 119 747 × 30 = 3 592 400 kWh

$CC_{NPVreplacement,boiler} = CC_{boiler} \times (1 + DR)^{-n} = 29\ 775 \times (1 + 0.05)^{-15}$ = £ 14 322

$CC_{NPV,\ boiler} = CC_{boiler} + CC_{NPVreplacement,boiler}$ = 29 775 + 14 322 = £ 44 097

$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 3\ 413 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 52 463

$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 596 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £9 162

$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n} = 1\ 192 \times (1 + 0.05)^{-30}$ = £ 276

$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler}$

= 44 097 + 52 463 + 9 162 + 276 = £ 105 998

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{105998}{3592400} \times 100 = 2.95 \text{ p/kWh}$$

2) <u>ST</u>

$FI_{ST} = D_{ep}$ = 761 kWh

$FC_{ST} = FI_{ST} \times EC$ = 761 × 8.2 / 100 = £ 62 /year

Using a cost figure of £853/m^2:

CC_{ST} = 853 × A_{sc} = 853 × 38 = £ 32 300

Maintenance costs are assumed to be 2% of capital costs of the ST and disposal costs are double the annual maintenance costs.

$MC_{ST} = CC_{ST}$ × 2% = £ 646 /year

$DC_{ST} = MC_{CHP}$ × 2 = £ 1 615

$O_{L,ST} = O_{ST} \times n = O_{ST} \times n$ = 11 746 × 30 = 352 380 kWh

The solar thermal system has lifetime of 30 years in this example. There therefore is no replacement cost and the NPV capital cost is equal to the current capital cost in this example:

$CC_{NPVreplacement,ST}$ = £0

$CC_{NPV,ST} = CC_{ST}$ = £ 32 300

$FC_{NPV,ST} = FC_{ST} \times [1 - (1 + DR)^{-n}] / DR = 62 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 969

$MC_{NPV,ST} = MC_{ST} \times [1 - (1 + DR)^{-n}] / DR = 646 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 9 931

$DC_{NPV,ST} = DC_{ST} \times (1 + DR)^{-n} = 1\ 615 \times (1 + 0.05)^{-30}$ = £ 374

$C_{NPVSTtotal}$ = $CC_{NPV,ST}$ + $FC_{NPV,ST}$ + $MC_{NPV,ST}$ + $DC_{NPV,ST}$ = £ 43 564

$$EC_{ST} = \frac{C_{NPVCHP,total}}{O_{LCHP}} \times 100 = \frac{43564}{352380} \times 100 = 12.36\,\text{p/kWh}$$

3) <u>CHP</u>

FI_{CHP} = ($O_{CHP,h}$ + $O_{CHP,e}$) / η_{CHP} = (141 016 + 70 508) / 0.80 = 264 405 kWh

$FC_{CHP,export}$ = FE_{CHP} × EEC / 100= $Surplus_e$ × EEC = 2 931× 3 /100 = £ 88

FC_{CHP} = FI_{CHP} × GC - $FC_{CHP,export}$ = 264 405 × 2.28 / 100 – 88 = £ 5 941 /year

CC_{CHP} = 1 676 × $S_{CHPth}^{-0.3025}$ × S_{CHPth} = 1 676 × 17 $^{-0.3025}$ × 17 = £ 12 097

MC_{CHP} = CC_{CHP}× 2% = £ 242 /year

DC_{CHP} = MC_{CHP} × 2 = £ 484

$O_{L,CHP}$ = O_{CHP} × n = ($O_{CHP,h}$ + $O_{CHP,e}$) × n = (141 016 + 70 508) × 30 = 6 345 721 kWh

$CC_{NPVreplacement,CHP}$ = CC_{CHP} × (1 + DR)$^{-n}$ = 12 097 × (1 + 0.05)$^{-15}$ = £ 4 559

$CC_{NPV,CHP}$ = CC_{CHP} + $CC_{NPVreplacement,CHP}$ = 12 097 + 4 559 = £ 16 656

$FC_{NPV,CHP}$ = FC_{CHP} × [1 – (1 + DR)$^{-n}$] / DR = 5 941 × [1 – (1 + 0.05)$^{-30}$] / 0.05 = £ 91 320

$MC_{NPV,CHP}$ = MC_{CHP} × [1 – (1 + DR)$^{-n}$] / DR = 242 × [1 – (1 + 0.05)$^{-30}$] / 0.05 = £ 3 720

$DC_{NPV,CHP} = DC_{CHP} \times (1 + DR)^{-n} = 484 \times (1 + 0.05)^{-30} = £\ 112$

$C_{NPVCHPtotal} = CC_{NPV,CHP} + FC_{NPV,CHP} + MC_{NPV,CHP} + DC_{NPV,CHP} = £\ 111\ 809$

$$EC_{CHP} = \frac{C_{NPVCHP,total}}{O_{LCHP}} \times 100 = \frac{111809}{6345721} \times 100 = 1.76\ \text{p/kWh}$$

4) <u>Grid</u>

$O_{Le} = D_{eSCBG} \times n = 124\ 100 \times 30 = 3\ 723\ 000$ kWh

$FC_e = D_{eSCBG} \times EC = 124\ 100 \times 8.2 / 100 = £\ 10\ 176$ /year

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR = 10\ 176 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 156$

433

$$EC_{EGrid} = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{156433}{3723000} \times 100 = 4.20\ \text{p/kWh}$$

4) <u>System energy cost</u>

$$EC_{system,SCBG} = \frac{\lfloor (EC_{ST} \times O_{ST}) + (EC_{CHP} \times (O_{CHP,h} + O_{CHP,e})) + (EC_{boiler} \times O_b) + (EC_{EGrid} \times D_{eSCBG}) \rfloor}{(D_h + D_e)}$$

$$= \frac{[(12.36 \times 11746) + (1.76 \times (141016 + 70508)) + (2.95 \times 119747) + (4.2 \times 124100)]}{(266637 + 192900)} = 3.1 p / kWh$$

5) <u>Emissions and emissions saved</u>

The annual CO_2 emissions $E_{CO2,SCBG}$ (kg CO_2) are:

$E_{CO2,SCBG} = (D_{egrid} \times EF_e) + (D_g \times EF_g) = (D_{egrid} \times EF_e) + ((FI_{boiler} + FI_{CHP}) \times EF_g) =$

$(124\ 100 \times 0.43) + ((149\ 683 + 264\ 405) \times 0.19) = 132\ 040$ kg CO_2

System CO_2 Emissions per kWh for the ST, CHP, boiler and grid option are: $E_{CO2,SCBG}$ / (D_e + D_h) = 132040 / (192900+266637) = 0.29 kg CO_2/kWh.

Emissions saved, $ES_{CO2,CSBG}$ (kg CO_2 saved) for the ST, CHP, Boiler and Grid option is:

$ES_{CO2,SCBG} = E_{CO2,BG} - E_{CO2,STBG}$ = 145 413 – 132 040 = 13 374 kg CO_2 saved

For this option, a 9.2% emissions savings is achieved ($ES_{CO2,SCBG}$ / $E_{CO2,BG}$ = 13374 / 145413 = 0.092 = 9.2%).

6) System cost per emissions saved

$$ESC_{SCBG} = \frac{EC_{system,SCBG} \times (D_h + D_e)}{100 \times ES_{CO2,SCBG}} = \frac{3.1 \times (266637 + 192900)}{100 \times 13374} = 1.1\text{£} / kgCO_2 saved$$

5.2.6 Supply of heat and electricity from PV, Boiler and Grid

a) System sizing

In this case it was assumed that there select is no restriction on the amount of roof area and capital cost and the PV panel are sized to provide the optimum annual electricity demand.

Monthly electricity demands and monthly irradiation values are listed in the table in Figure 5.21. The maximum PV area assumed in the optimisation is a PV size with a monthly output equal to the demand in the month of July. In July, the electricity demand, D_e is 12 703 kWh, the incident solar irradiation, I_s is 140.8 kWh/m^2, the efficiency of the PV cells, η_{PV} is 14%, and the efficiency of the power conditioner (inverter, controller), transformer and interconnection (1- *L)* is (1 - 0.25) = 75%. Equation 4.29 is used to calculate the PV area with an output equal to the demand in July:

$$S_{PV} = \frac{D_e}{I_s(1-L)\eta_{PV}} = \frac{12703}{140.8 \times (1-0.25) \times 0.14} = 860m^2$$

Table 5.3 Extract of PV size optimisation table

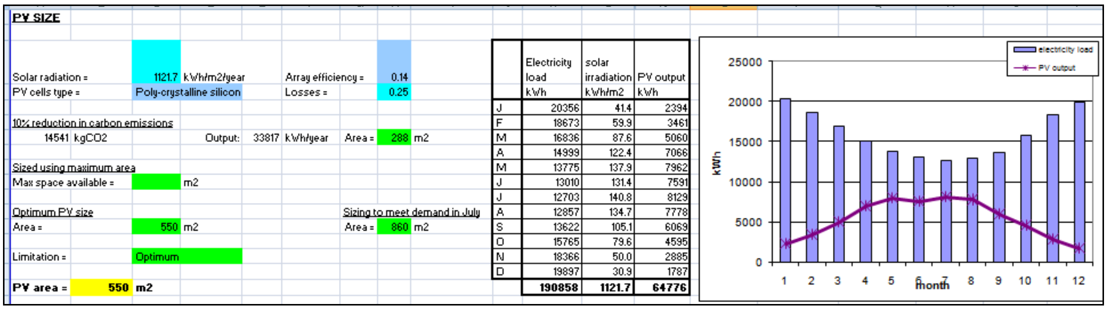
PV size (m2)	Energy cost (p/kWh)	Emissions (kg CO2/kWh)	(£/kg CO2 saved)
550	4.2	0.266	0.8
552	4.2	0.266	0.8
553	4.2	0.266	0.8
554	4.2	0.266	0.8
555	4.2	0.266	0.8
556	4.2	0.266	0.8
557	4.2	0.266	0.8
558	4.2	0.266	0.8
559	4.2	0.266	0.8
560	4.2	0.266	0.8
561	4.2	0.266	0.8
562	4.2	0.266	0.8
563	4.2	0.266	0.8
564	4.2	0.266	0.8
565	4.2	0.266	0.8
566	4.2	0.266	0.8
567	4.2	0.266	0.8
568	4.3	0.265	0.8
569	4.3	0.265	0.8
570	4.3	0.265	0.8
571	4.3	0.265	0.8
572	4.3	0.265	0.8
573	4.3	0.265	0.8
574	4.3	0.265	0.8
575	4.3	0.265	0.8
576	4.3	0.265	0.8
577	4.3	0.265	0.8
578	4.3	0.265	0.8
579	4.3	0.265	0.8
580	4.3	0.265	0.8

Different PV sizes are therefore simulated in the PV spreadsheet as described below in intervals of 1m^2 up to 860m^2. This data is listed and then sorted to find an optimum PV size in terms of £/kgCO_2 saved. Table 5.3 shows the first few lines of this data table in the tool. In this example the optimum PV size, S_{PV} is found to be 550 m^2.

Figure 5.20 shows the hourly simulation of the PV system for a typical January day. The system is simulated for a typical day in each month, to get an understanding of the yearly performance of the system.

OPTION 3a:	**PV + Boiler + Grid**							
PV								
January	WEEKDAY	21.73	WEEKEND	8.69		PV size =	550	m2
Time	Electricity demand kWh	Electricity demand kWh	Solar irradiance (W/m2)	PV output (kWh)	weekday deficit (kWh)	weekday surplus (kWh)	weekend deficit (kWh)	weekend surplus (kWh)
1	7.0	6.7		0	7.0	0	6.7	0
2	9.5	7.2		0	9.5	0	7.2	0
3	11.3	8.5		0	11.3	0	8.5	0
4	11.0	9.0		0	11.0	0	9.0	0
5	11.3	9.8		0	11.3	0	9.8	0
6	11.1	10.0		0	11.1	0	10.0	0
7	14.5	11.1		0	14.5	0	11.1	0
8	22.8	16.2	76	4.39	18.4	0	11.8	0
9	28.4	19.6	155	8.95	19.5	0	10.6	0
10	30.6	20.0	209.25	12.08	18.5	0	7.9	0
11	34.4	24.3	236.5	13.66	20.7	0	10.6	0
12	34.8	24.2	236.5	13.66	21.1	0	10.6	0
13	33.7	24.1	209.25	12.08	21.7	0	12.0	0
14	36.2	25.6	155	8.95	27.2	0	16.6	0
15	36.7	24.9	59.5	3.44	33.3	0	21.4	0
16	36.8	24.7		0	36.8	0	24.7	0
17	39.2	26.8		0	39.2	0	26.8	0
18	42.2	29.6		0	42.2	0	29.6	0
19	46.7	36.1		0	46.7	0	36.1	0
20	49.4	45.6		0	49.4	0	45.6	0
21	45.6	46.5		0	45.6	0	46.5	0
22	45.0	45.6		0	45.0	0	45.6	0
23	37.9	38.2		0	37.9	0	38.2	0
24	33.8	34.0		0	33.8	0	34.0	0
	709.71	568.09	1337					

Figure 5.20 Hourly PV simulation for a typical January day



	Electricity load kWh	solar irradiation kWh/m2	PV output kWh
J	20356	41.4	2394
F	18673	59.9	3461
M	16836	87.6	5060
A	14999	122.4	7066
M	13775	137.9	7962
J	13010	131.4	7591
J	12703	140.8	8129
A	12857	134.7	7778
S	13622	105.1	6069
O	15765	79.6	4595
N	18366	50.0	2885
D	19897	30.9	1787
	190858	**1121.7**	**64776**

Figure 5.21 PV sizing

Hourly PV output, O_{PV} (kW) is calculated using equation 4.30. For example, at 10am, the incident solar radiation I_s is 0.20925 kW/m^2, the efficiency of the PV cells η_{PV} is 14%, and the efficiency of the power conditioner (inverter, controller), transformer and interconnection, (1- L) is (1 - 0.25). The output during this hour therefore is:

$$O_{PV} = S_{PV} I_S (1 - L)\eta_{PV} = 550 \times 209.25 \times 0.14 \times (1 - 0.25) = 12.085 \text{ kW}$$

Assuming a constant output for the PV during each hour, O_{PV} can also have kWh units, as is shown in Table 4.8.

Deficit and surplus are also calculated for each hour for a weekday and a weekend day using equations 4.22 and 4.23. For example at 10am on a weekday:

$$Deficit = D - O_{PV} = 30.6 - 12.085 = 18.5$$

$$Surplus = 0$$

Monthly surplus and deficit figures are also calculated using equations 4.25 and 4.26. For January:

$$Deficit_{monthly} = [(Deficit_{WD} \times 21.726) + (Deficit_{WE} \times 8.69)]$$

$$= [(632.5 \times 21.726) + (490.9 \times 8.69)] = 18\ 008\ \text{kWh}$$

$$Surplus_{monthly} = [(Surplus_{WD} \times 21.726) + (Surplus_{WE} \times 8.69)] = 0\ \text{kWh}$$

The monthly figures are then added up to calculate yearly surplus and deficit figures. In this example:

$Deficit_{yearly} = 135\ 489$ kWh

$Surplus_{yearly} = 9\ 324$ kWh

It is assumed here that any surplus is exported to the grid and any deficit is imported from the grid.

Boiler Size

peak space heat demand =		134	kW
boiler efficiency =		0.8	
boiler size =	167	168	kW
Storage size =	747	747	litres

Grid Demand

January

Time	Weekday Heat Demand (kWh) SH	HW	Total	Weekday Heat Demand (kWh) SH	HW	Total	Week day electricity (kWh)	Weekend electricity (kWh)
1	11.4	0.4	11.9	11.4	0.6	12.0	7.0	6.7
2	19.5	0.1	19.6	19.4	0.8	20.2	9.5	7.2
3	26.2	2.1	28.3	25.4	0.2	25.6	11.3	8.5
4	20.4	2.6	23.0	19.9	1.4	21.3	11.0	9.0
5	26.9	2.6	29.5	26.4	0.7	27.1	11.3	9.8
6	18.6	1.4	20.0	18.4	0.4	18.8	11.1	10.0
7	130.3	3.7	134.0	126.4	0.8	127.3	14.5	11.1
8	113.4	0.4	113.9	112.4	1.1	113.5	22.8	16.2
9	110.3	13.9	124.2	108.4	0.6	109.0	28.4	19.6
10	41.3	12.6	53.9	41.4	2.7	44.1	30.6	20.0
11	46.9	11.6	58.5	46.4	1.9	48.3	34.4	24.3
12	45.7	14.6	60.3	45.4	10.2	55.6	34.8	24.2
13	40.7	8.7	49.4	40.4	14.8	55.2	33.7	24.1
14	57.2	9.8	67.0	56.4	7.9	64.3	36.2	25.6
15	47.1	7.7	54.8	46.4	1.5	48.0	36.7	24.9
16	68.3	4.7	73.0	67.4	1.3	68.8	36.8	24.7
17	62.9	5.7	68.6	62.4	1.9	64.3	39.2	26.8
18	113.1	10.8	123.9	111.4	7.4	118.8	42.2	29.6
19	89.4	6.8	96.2	89.4	3.9	93.3	46.7	36.1
20	101.4	2.2	103.6	100.4	12.8	113.2	49.4	45.6
21	87.8	3.4	91.2	87.4	8.9	96.3	45.6	46.5
22	57.9	9.1	67.0	57.4	4.1	61.5	45.0	45.6
23	33.4	5.0	38.4	33.4	3.6	37.0	37.9	38.2
24	39.3	3.7	43.0	39.4	5.3	44.7	33.8	34.0
			1553.48			1488.15	709.7	568.1

Annual heat load = 266637 kWh/year

Annual electricity load = 135500 kWh/year

Figure 5.22 Boiler Sizing for PV+Boiler+Grid option

The sizing of the boiler system is exactly as for the Boiler and Grid option, as the boiler supplies all the heat in this technology combination option. Therefore:

$S_b = \frac{D_{H,p}}{\eta_b}$ = 134 / 0.8 = 168 kW (rounded up to the nearest kW)

and the hot water storage is 2240 / 3 = 747 litres.

b) System costs and emissions

1) Boiler

$FI_{boiler} = O_{boiler} / \eta_{boiler}$ = 266 637 / 0.80 = 333 296 kWh

$FC_{boiler} = FI_{boiler} \times GC$ = 333 296 × 2.28 / 100 = £ 7 599 /year

$CC_{boiler} = 1058.7 \times S_b^{-0.3314} \times S_b = 1058.7 \times 168^{-0.3314} \times 168$ = £ 32 555

$MC_{boiler} = CC_{boiler} \times 2\%$ = £ 652 /year

$DC_{boiler} = MC_{boiler} \times 2$ = £ 1 304

$O_{L,boiler} = O_{boiler} \times n$ = 266 637 × 30 = 7 999 115 kWh

$CC_{NPVreplacement} = CC_{current} \times (1 + DR)^{-n} = 32\,555 \times (1 + 0.05)^{-15}$ = £ 15 660

$CC_{NPV} = CC_{current} + CC_{NPVreplacement}$ = 32 555 + 15 660 = £ 48 215

$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 7\,599 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 116 818

$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 652 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £10 023

$$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n} = 1\,304 \times (1 + 0.05)^{-30} = £\ 302$$

$$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler} = £\ 175\,357$$

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{175357}{7999115} \times 100 = 2.19\ \text{p/kWh}$$

Costs						
	Project Lifetime (years) =	30				
	Discount rate (%) =	5				
	Electricity export price =	3.0	p/kWh			
	Gas cost =	2.28		Gas emission factor =	0.19	
	Electricity cost =	8.2		Electricity emission factor =	0.43	
System						
	System =	**Boiler**				
	Lifetime (years) =	15				
	Efficiency =	0.8	**PV**			
	Annual heat output (kWh) =	266637	7999115			
	Fuel input (kWh) =	333296.45		**7999115**	**kWh**	
	Capital costs (£) =	32,555	48215			
	Annual fuel costs (£) =	7,599	116818			
	Annual Maintenance (£) =	652	10023			
	Disposal Cost (£) =	1304	302			
				175357	**£**	
	Energy cost (p/kWh) =	**2.19**				
	System =	**PV**				
	Lifetime (years) =	30				
	kWp	55.0				
	Output (kWh) =	776322	23289660	**23289660**	**kWh**	
	Capital costs (£) =	201756	201756			
	Annual Maintenance (£) =	2018	31022			
	Disposal Cost (£) =	4036	934			
	Export (£) =	-280	0			
				233711	**£**	
	Energy cost (p/kWh) =	**1.003499**				
	System =	**Grid**				
	Annual electricity output (kWh) =	135500				
	Life time output (kWh) =	**4065000**				
	annual fuel costs (£) =	11111				
	NPV fuel cost (£) =	**170803.3**				
	Energy cost (p/kWh) =	**4.20**				
System costs	Heat =	2.19	p/kWh			
	Electricity =	6.92	p/kWh			
	TOTAL =	**4.2**	**p/kWh**			
		ENERGY SUPPLY				
		Boiler	Electricity	PV		
	Energy cost (p/kWh)	2.28	7.00	0		
	CO2 emission factor (kg/kWh)	0.19	0.43	0		
	Annual heat/electricity load (kWh)	266637	135500	55369		
	Annual Fuel input (kWh)	333,296				
	Annual fuel cost (£)	7599	9485	-280	**3.67**	**p/kWh**
	Annual CO2 emissions (kg)	63326	58265	0	**0.2660**	**kg CO2/kWh**
	Emissions saved				**23822**	**kg CO2 saved**
					0.8	**£/kg CO2 saved**
					16.4	**% carbon emissions saved**

Figure 5.23 Costs and emissions for PV+Boiler+Grid option

2) PV

FI_{PV} = 0 kWh

Assuming an electricity export price, *EEC* of 3p/kWh in this example and PV electricity export to the grid is FE_{PV} (kWh/year), annual PV electricity export cost, $FC_{PV,export}$ (£) is:

$FC_{PV,export} = FE_{PV} \times EEC$ / 100= $Surplus_e \times EEC$ = 9 324 × 3 /100 = £ 280 /year

$FC_{PV} = FC_{PV,export}$ = £ -280 /year

Using the equation in Figure 4.25, PV capital cost is:

$CC_{PV} = 525.61 \times S_{PV}^{-0.057} \times S_{PV} = 525.61 \times 550^{-0.057} \times 550$ = £ 201 756

PV maintenance and disposal costs are assumed to be 1% and 2% respectively of the capital costs.

$MC_{PV} = CC_{PV} \times 1\%$ = £ 2 018 /year

$DC_{PV} = CC_{PV} \times 2\%$ = £ 4 036

$O_{L,PV} = O_{PV} \times n$ = 776 322 × 30 = 23 289 660 kWh

The PV system lifetime is the same as the project lifetime in this case. There therefore is no replacement cost for the PV system in this example.

$CC_{NPVreplacement,PV}$ = £ 0

$CC_{NPV,PV} = CC_{PV}$ = £ 201 756

$FC_{NPV,PV} = FC_{PV} \times [1 - (1 + DR)^{-n}] / DR$ = £ 0

$MC_{NPV,PV} = MC_{PV} \times [1 - (1 + DR)^{-n}] / DR = 2\ 018 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 31\ 022$

$DC_{NPV,PV} = DC_{PV} \times (1 + DR)^{-n} = 4\ 036 \times (1 + 0.05)^{-30} = £\ 934$

$C_{NPV,PV,total} = CC_{NPV,PV} + FC_{NPV,PV} + MC_{NPV,PV} + DC_{NPV,PV} = £\ 233\ 711$

$$EC_{PV} = \frac{C_{NPV,PV,total}}{O_{LPV}} \times 100 = \frac{233711}{776322} \times 100 = 1.00 \text{ p/kWh}$$

3) <u>Grid</u>

$O_{Le} = D_e \times n = 135\ 500 \times 30 = 4\ 065\ 000$ kWh

$FC_e = D_e \times EC = 135\ 500 \times 8.2 / 100 = £\ 11\ 111$ /year

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR = 11\ 111 \times [1 - (1 + 0.05)^{-30}] / 0.05 = £\ 170\ 803$

$$EC_e = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{170803}{4065000} \times 100 = 4.20 \text{ p/kWh}$$

4) <u>System energy cost</u>

System energy cost is therefore calculated using equation 4.18:

$$EC_{system} = \frac{\left[\left(EC_{boiler} \times O_b\right) + (EC_{PV} \times O_{PV}) + \left(EC_{EGrid} \times D_{egrid}\right)\right]}{\left(D_h + D_e\right)}$$
$$= \frac{[(2.19 \times 266637) + (1.00 \times 776322) + (4.2 \times 135500)]}{(266637 + 190900)} = 4.2\, p / kWh$$

5) Emissions and emissions saved

The annual CO_2 emissions $E_{CO2,PBG}$ (kg CO_2) are:

$E_{CO2,PBG} = \left(D_{egrid} \times EF_e\right) + \left(D_g \times EF_g\right)$ = ($D_{egrid} \times EF_e$) + ($FI_{boiler} \times \mathrm{EF_g}$) = (135 500 × 0.43) + (333 296 × 0.19) = 121 591 kg CO_2

System CO_2 Emissions per kWh for the PV, boiler and grid option are: $E_{CO2,PBG}$ / (D_e + D_h) = 121591 / (190900+266637) = 0.27 kg CO_2/kWh.

Emissions saved, $ES_{CO2,PBG}$ (kg CO_2 saved) for the PV, Boiler and Grid option is calculated using equation 4.27:

$ES_{CO2,PBG} = E_{CO2,BG} – E_{CO2,PBG}$ = 145 413 – 121 591 = 23 822 kg CO_2 saved

For this option, a 16.4% emissions saving is achieved ($ES_{CO2,PBG} / E_{CO2,BG}$ = 23822 / 145413 = 0.164 = 16.4%).

6) System cost per emissions saved

Cost per emissions savings, ESC (£/kg CO_2 saved) is calculated for the PV, Boiler and Grid option using equation 4.28:

$$ESC = \frac{EC_{system} \times (D_h + D_e)}{100 \times ES_{CO2}} = \frac{4.2 \times (266637 + 190900)}{100 \times 23822} = 0.8£ / kgCO_2 saved$$

5.2.7 Supply of heat and electricity from a CHP, PV, Boiler and Grid

a) System sizing

In the CHP+PV+Boiler+Grid option, the CHP is sized first. The CHP size is therefore exactly the same as in the CHP+Boiler+Grid option (see section 5.2.2). The PV is sized on the remaining electricity demand to provide a minimum £/kg CO_2 saved figure in the same manner as in the PV+Boiler+Grid option (section 5.2.5). In this example the optimum PV size was found to be 376m^2 (Figure 5.25).

		PV system					
		PV size =	376	m2			
weekday CHP elctricity Deficit	weekend day CHP elctricity Deficit	Solar irradiance (W/m2)	PV output (kWh)	weekday deficit (kWh)	weekday surplus (kWh)	weekend deficit (kWh)	weekend surplus (kWh)
1.5	1.2		0	1.5	0	1.2	0
4.0	1.7		0	4.0	0	1.7	0
5.8	3.0		0	5.8	0	3.0	0
5.5	3.5		0	5.5	0	3.5	0
5.8	4.3		0	5.8	0	4.3	0
5.6	4.5		0	5.6	0	4.5	0
9.0	5.6		0	9.0	0	5.6	0
17.3	10.7	67.25	2.65503	14.6	0	8.0	0
22.9	14.1	136.5	5.38902	17.5	0	8.7	0
25.1	14.5	184.25	7.27419	17.8	0	7.2	0
28.9	18.8	208.75	8.24145	20.6	0	10.6	0
29.3	18.7	208.75	8.24145	21.1	0	10.5	0
28.2	18.6	184.25	7.27419	21.0	0	11.3	0
30.7	20.1	136.5	5.38902	25.3	0	14.7	0
31.2	19.4	67.25	2.65503	28.6	0	16.7	0
31.3	19.2		0	31.3	0	19.2	0
33.7	21.3		0	33.7	0	21.3	0
36.7	24.1		0	36.7	0	24.1	0
41.2	30.6		0	41.2	0	30.6	0
43.9	40.1		0	43.9	0	40.1	0
40.1	41.0		0	40.1	0	41.0	0
39.5	40.1		0	39.5	0	40.1	0
32.4	32.7		0	32.4	0	32.7	0
28.3	28.5		0	28.3	0	28.5	0
577.7053448	436.090345	1193.5		530.6	0.0	389.0	0.0
12551.3	3789.8						

Figure 5.24 Hourly PV simulation for a typical January day

PV SIZE						
Solar radiation =	1126.43	kWh/m2/year		Array efficiency =	0.14	
PV cells type =	Poly-crystalline silicon			Losses =	0.25	
10% reduction in carbon emissions						
9161	kgCO2	Output:	21305	kWh/year	Area =	181 m2
Sized using maximum area						
Max space available =	0	m2		Output	0	kWh/year
Optimum PV size				Sized to meet July demand		
Area =	376	m2		Area =	545	m2
Limitation =	Optimum					
PV area =	**376**	**m2**				

	Electricity load kWh	solar irradiation kWh/m2
J	16341.2	37.0
F	14657.6	54.6
M	12820.9	83.7
A	10998.7	123.5
M	9790.7	148.3
J	9036.2	143.5
J	8735.3	152.8
A	8885.7	139.9
S	9639.7	101.7
O	11754.4	72.6
N	14351.5	42.6
D	15882.0	26.2
	142894	**1126.4**

Figure 5.25 PV sizing for CHP+PV+Boiler+Grid option

The annual CHP heat and electricity outputs are the same as in section 5.2.2:

$O_{CHP,h}$ = 96 360 kWh/year

$O_{CHP,e}$ = 48 180 kWh/year

Again, hourly electricity deficits and surpluses are calculated after the PV as shown in Figure 5.24 to calculate daily, monthly and yearly deficits and surpluses,

As in section 5.2.5, hourly PV outputs are calculated using equation 4.30 and hourly deficits and surpluses are calculated for each hour for a weekday and a weekend day using equations 4.22 and 4.23.

Monthly surplus and deficit figures are also calculated using equations 4.25 and 4.26. For January:

$$Deficit_{monthly} = [(Deficit_{WD} \times 21.726) + (Deficit_{WE} \times 8.69)]$$

$$= [(530.6 \times 21.726) + (389 \times 8.69)] = 14\,908 \text{ kWh}$$

$$Surplus_{monthly} = [(Surplus_{WD} \times 21.726) + (Surplus_{WE} \times 8.69)] = 0 \text{ kWh}$$

The monthly figures are then added up to calculate yearly surplus and deficit figures. In this example:

$Deficit_{yearly}$ = 106 462 kWh

$Surplus_{yearly}$ = 7 961 kWh

It is assumed here that any surplus is exported to the grid and any deficit is imported from the grid.

The Boiler size is also the same as in section 5.2.2 (Figure 5.26):

S_b = 154 kW and the hot water storage is 430 litres.

BOILER SIZE						**GRID DEMAND**			
peak space heat demand =			123	kW					
boiler efficiency =			0.8						
boiler size =		154	**154**	**kW**					
Storage size =		430	**430**	**litres**					
	Annual Boiler Load =		**186616**	**kWh/year**			**Annual EGrid Load =**	**106500**	**kWh/year**

Figure 5.26 Boiler and grid sizes for CHP+PV+Boiler+Grid option

b) System costs and emissions

The NPV system energy costs are calculated for each technology:

1) <u>boiler</u>

$FI_{boiler} = O_{boiler} / \eta_{CHP}$ = 186 616 / 0.80 = 233 270 kWh

$FC_{boiler} = FI_{boiler} \times GC$ = 233 270 × 2.28 / 100 = £ 5 319 /year

$CC_{boiler} = 1058.7 \times S_b^{-0.3314} \times S_b = 1058.7 \times 154^{-0.3314} \times 154$ = £ 30 715

$MC_{boiler} = CC_{boiler} \times 2\% =$ £ 615 /year

$DC_{boiler} = MC_{boiler} \times 2 =$ £ 1 230

$O_{L,boiler} = O_{boiler} \times n = 186\ 616 \times 30 = 5\ 598\ 479$ kWh

$CC_{NPVreplacement,boiler} = CC_{boiler} \times (1 + DR)^{-n} = 30\ 715 \times (1 + 0.05)^{-15} =$ £ 14 774

$CC_{NPV,\ boiler} = CC_{boiler} + CC_{NPVreplacement,boiler} = 30\ 715 + 14\ 774 =$ £ 45 489

$FC_{NPV,boiler} = FC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 5\ 319 \times [1 - (1 + 0.05)^{-30}] / 0.05 =$ £ 81 759

$MC_{NPV,boiler} = MC_{boiler} \times [1 - (1 + DR)^{-n}] / DR = 615 \times [1 - (1 + 0.05)^{-30}] / 0.05 =$ £9 454

$DC_{NPV,boiler} = DC_{boiler} \times (1 + DR)^{-n} = 1\ 230 \times (1 + 0.05)^{-30} =$ £ 285

$C_{NPVboiler,total} = CC_{NPV,boiler} + FC_{NPV,boiler} + MC_{NPV,boiler} + DC_{NPV,boiler}$

$= 45\ 489 + 81\ 759 + 9\ 454 + 285 =$ £ 136 987

$$EC_{boiler} = \frac{C_{NPVboiler,total}}{O_{Lboiler}} \times 100 = \frac{136987}{5598479} \times 100 = 2.45 \text{ p/kWh}$$

2) <u>PV</u>

$FC_{PV,export} = FE_{PV} \times EEC / 100 = Surplus_e \times EEC = 7\ 961 \times 3 / 100 =$ £ 239 /year

$FC_{PV} = FC_{PV,export} =$ £ -239 /year

COSTS					
	Project Lifetime (years) =	30			
	Discount rate (%) =	5			
	Electricity export price =	3.0	p/kWh		
	Gas cost =	2.28		Gas emission factor =	0.19
	Electricity cost =	8.2		Electricity emission factor =	0.43
System					
	System =	**Boiler**			
	Lifetime (years) =	15			
	Efficiency =	0.8	**PW**		
	Annual heat output (kWh) =	186616	5598479		
	Fuel input (kWh) =	233270		**5598479**	**kWh**
	Capital costs (£) =	30,715	45489		
	Annual fuel costs (£) =	5,319	81759		
	Annual Maintenance (£) =	615	9454		
	Disposal Cost (£) =	1230	285		
				136987	**£**
	Energy cost (p/kWh) =	**2.45**			
	System =	**PV**			
	Lifetime (years) =	30			
	kWp	37.6			
	Output (kWh) =	532713	15981390	**15981390**	**kWh**
	Capital costs (£) =	140951	140951		
	Annual Maintenance (£) =	1410	21675		
	Disposal Cost (£) =	2820	652		
	Export (£) =	-239			
				163279	**£**
	Energy cost (p/kWh) =	**1.02**			
	System =	**CHP**			
	CHP Lifetime (years) =	20			
	Efficiency =	0.80	**PW**		
	Annual heat output (kWh) =	96360	2890800		
	Annual electricity output (kWh) =	48180	1445400		
	Fuel input (kWh) =	180675		**4336200**	**kWh**
	Capital costs (£) =	8929	12294		
	Annual fuel costs (£) =	4113	63226		
	Annual Maintenance (£) =	179	2752		
	Disposal Cost (£) =	358	83		
	Electricity export (£) =	-6		**78354**	**£**
	Energy cost (p/kWh) =	**1.81**			
	System =	**Grid**			
	Annual electricity output (kWh) =	106500			
	Life time output (kWh) =	**3195000**			
	annual fuel costs (£) =	8733			
	NPV fuel cost (£) =	**134248**			
	Energy cost (p/kWh) =	**4.20**			
System costs	Heat =	2.37	p/kWh		
	Electricity =	5.52	p/kWh		
	TOTAL =	3.7	**p/kWh**		

	ENERGY SUPPLY					
	Boiler	Electricity	CHP	PV		
Energy cost (p/kWh)	2.28	8.20	2.28	0		
CO2 emission factor (kg/kWh)	0.19	0.43	0.19	0		
Annual heat/electricity load (kWh)	186616	106500	144540	36432		
Annual Fuel input (kWh)	233,270		180675			
Annual fuel cost (£)	5319	8733	4113	-239	**3.92**	**p/kWh**
Annual CO2 emissions (kg)	44321	45795	34328	0	**0.27**	**kg CO2/kWh**
Emissions saved					**20969**	**kg CO2 saved**
					0.9	**£/kg CO2 saved**
					14.5	**% carbon emissions saved**

Figure 5.27 Costs and emissions for CHP+PV+Boiler+Grid option

$$CC_{PV} = 525.61 \times S_{PV}^{-0.057} \times S_{PV} = 525.61 \times 376^{-0.057} \times 376 = £\ 140\ 951$$

$$MC_{PV} = CC_{PV} \times 1\% = £\ 1\ 410\ /\text{year}$$

$$DC_{PV} = CC_{PV} \times 2\% = £\ 2\ 820$$

$O_{L,PV} = O_{PV} \times n$ = 532 713 × 30 = 15 981 390 kWh

$CC_{NPVreplacement,PV}$ = £ 0

$CC_{NPV,PV} = CC_{PV}$ = £ 140 951

$FC_{NPV,PV} = FC_{PV} \times [1 - (1 + DR)^{-n}] / DR$ = £ 0

$MC_{NPV,PV} = MC_{PV} \times [1 - (1 + DR)^{-n}] / DR = 1\ 410 \times [1 - (1 + 0.05)^{-30}] / 0.05$ = £ 21 675

$DC_{NPV,PV} = DC_{PV} \times (1 + DR)^{-n} = 2\ 820 \times (1 + 0.05)^{-30}$ = £ 652

$C_{NPV,PV,total} = CC_{NPV,PV} + FC_{NPV,PV} + MC_{NPV,PV} + DC_{NPV,PV}$ = £ 163 279

$$EC_{PV} = \frac{C_{NPV,PV,total}}{O_{LPV}} \times 100 = \frac{163279}{15981390} \times 100 = 1.02 \text{ p/kWh}$$

3) <u>CHP</u>

$FI_{CHP} = (O_{CHP,h} + O_{CHP,e}) / \eta_{CHP}$ = (96 360 + 48 180) / 0.80 = 180 675 kWh

$FC_{CHP,export} = FE_{CHP} \times EEC / 100 = Surplus_e \times EEC$ = 216 × 3 /100 = £ 6

$FC_{CHP} = FI_{CHP} \times GC - FC_{CHP,export}$ = 180 675 × 2.28 / 100 – 6 = £ 4 113 /year

$CC_{CHP} = 1\ 676 \times S_{CHPth}^{-0.3025} \times S_{CHPth} = 1\ 676 \times 11^{-0.3025} \times 11$ = £ 8 929

$MC_{CHP} = CC_{CHP} \times 2\%$ = £ 179 /year

$DC_{CHP} = MC_{CHP} \times 2$ = £ 358

$O_{L,CHP} = O_{CHP} \times n = (O_{CHP,h} + O_{CHP,e}) \times n$ = (96 360 + 48 180) × 30 = 4 336 200 kWh

$CC_{NPVreplacement,CHP} = CC_{CHP} \times (1 + DR)^{-n}$ = 8 929 × (1 + *0.05*)$^{-15}$ = £ 3 365

$CC_{NPV,CHP} = CC_{CHP} + CC_{NPVreplacement,CHP}$ = 8 929 + 3 365 = £ 12 294

$FC_{NPV,CHP} = FC_{CHP} \times [1 - (1 + DR)^{-n}] / DR$ = 4 113 × [1 – (1 + *0.05*)$^{-30}$] / 0.05 = £ 63 226

$MC_{NPV,CHP} = MC_{CHP} \times [1 - (1 + DR)^{-n}] / DR$ = 179 × [1 – (1 + *0.05*)$^{-30}$] / 0.05 = £ 2 752

$DC_{NPV,CHP} = DC_{CHP} \times (1 + DR)^{-n}$ = 358 × (1 + *0.05*)$^{-30}$ = £ 83

$C_{NPVCHPtotal} = CC_{NPV,CHP} + FC_{NPV,CHP} + MC_{NPV,CHP} + DC_{NPV,CHP}$ = £ 78 354

$$EC_{CHP} = \frac{C_{NPVCHP,total}}{O_{LCHP}} \times 100 = \frac{78354}{4336200} \times 100 = 1.81 \text{ p/kWh}$$

4) <u>Grid</u>

$O_{Le} = D_e \times n$ = 106 500 × 30 = 3 195 000 kWh

$FC_e = D_e \times EC$ = 106 500 × 8.2 / 100 = £ 8 733 /year

$FC_{NPV,e} = FC_e \times [1 - (1 + DR)^{-n}] / DR$ = 8 733 × [1 – (1 + *0.05*)$^{-30}$] / 0.05 = £ 134 248

$$EC_e = \frac{FC_{NPVe}}{O_{Le}} \times 100 = \frac{134248}{3195000} \times 100 = 4.20 \text{ p/kWh}$$

4) System energy cost

System energy cost is therefore calculated using equation 4.18:

$$EC_{system} = \frac{\left[(EC_{CHP} \times (O_{CHP,h} + O_{CHP,e})) + (EC_{PV} \times O_{PV}) + \left(EC_{boiler} \times O_b\right) + \left(EC_{EGrid} \times D_{egrid}\right)\right]}{\left(D_h + D_e\right)}$$

$$= \frac{[(1.81 \times (96360 + 48180)) + (1.02 \times 532713) + (2.45 \times 186616) + (4.2 \times 106500)]}{(266637 + 190900)} = 3.7\, p / kWh$$

5) Emissions and emissions saved

The annual CO_2 emissions $E_{CO2,CPBG}$ (kg CO_2) are:

$E_{CO2,CPBG} = \left(D_{egrid} \times EF_e\right) + \left(D_g \times EF_g\right)$ = ($D_{egrid} \times EF_e$) + [(FI_{CHP} + FI_{boiler}) × EF_g] = (106 500 × 0.43) + [(180 675 + 233 270) × 0.19] = 124 445 kg CO_2

System CO_2 Emissions per kWh for the CHP, PV, boiler and grid option are: $E_{CO2,CPBG}$ / (D_e + D_h) = 124445 / (190900+266637) = 0.27 kg CO_2/kWh.

Emissions saved, $ES_{CO2,CPBG}$ (kg CO_2 saved) for the CHP, PV, Boiler and Grid option is calculated using equation 4.27:

$ES_{CO2,CBG} = E_{CO2,BG} - E_{CO2,CBG}$ = 145 413 – 124 445 = 20 969 kg CO_2 saved

For this option, a 14.5% emissions savings is achieved ($ES_{CO2,CPBG}$ / $E_{CO2,BG}$ = 20969 / 145413 = 0.145 = 14.5%).

6) System cost per emissions saved

Cost per emissions savings, *ESC* (£/kg CO_2 saved) is calculated for the CHP, PV, Boiler and Grid option using equation 4.28:

$$ESC = \frac{EC_{system} \times (D_h + D_e)}{100 \times ES_{CO2}} = \frac{3.7 \times (266637 + 190900)}{100 \times 20969} = 0.9£ / kgCO_2 saved$$

5.2.8 Summary of outputs

Table 5.4 Summary of Outputs

	Boiler + Grid	CHP + Boiler + Grid	ST + Boiler + Grid	PV + Boiler + Grid	ST + CHP + Boiler + Grid	CHP + PV + Boiler + Grid
Boiler size (kW)	168	154	168	168	147	154
Grid demand (kWh)	190 900	142 894	192 900	135 500	124 100	106 462
CHP size ($kW_{thermal}$)	-	11	-	-	17	11
ST/PV collector area (m^2)	-	-	127	550	38	376
System cost (p/kWh)	3.1	2.9	4.1	4.2	3.1	3.7
Emissions ($kgCO_2$ / kWh)	0.32	0.31	0.30	0.27	0.29	0.27
Cost per emissions saved (£/ $kgCO_2$ saved)	-	2.5	3.1	0.8	1.1	0.9
Reduction in emissions (%)	-	3.7	4.1	16.4	9.2	14.5

Section 1.01 5.3 TOOL EVALUATION PROCEDURE

The procedure for evaluating the viability of renewable energy technologies and CHP schemes for a new or refurbished building project using the tool, as in this example, is carried out as described below.

When starting the computer tool the user may choose between starting a new project or working and modifying an existing project as shown in Figure 5.28. In this case, a new project is initiated to build up the building loads profile.

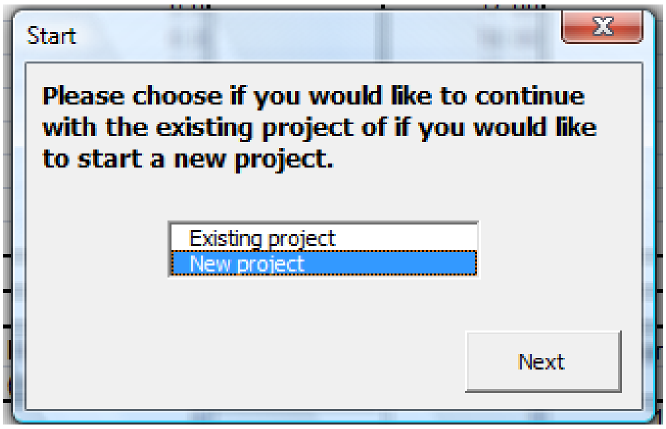


Figure 5.28 Start interface

5.3.1 The Building loads

This is carried out in the following order.

a) Entering the building details

In this step the building specifications (type, floor area, occupancy, etc) are entered for all building types.

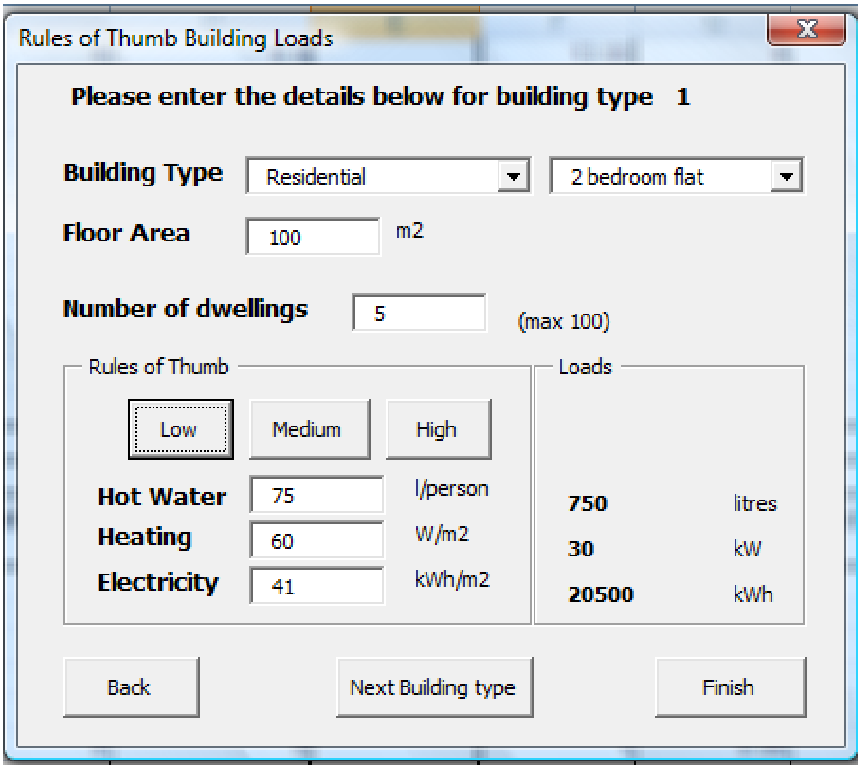


Figure 5.29a Entering details for 2 bedroom flats residential building

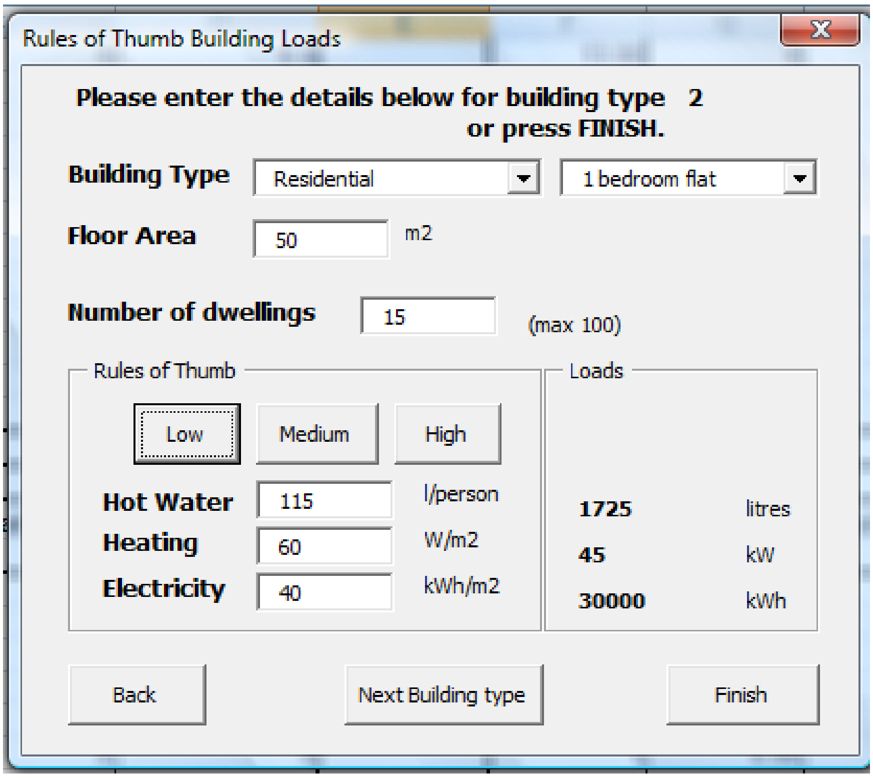


Figure 5.29b Entering details for 1 bedroom flats residential building

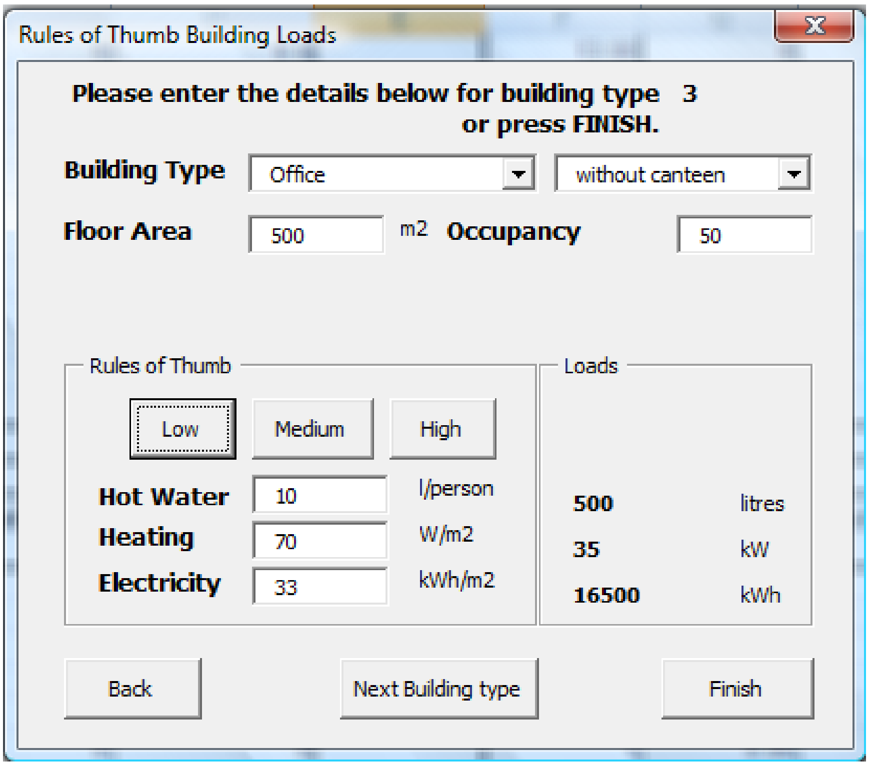


Figure 5.29c Entering details for office type building

This case study involves three types of buildings with different floor areas and types of occupancy, namely, 2-bedroom flats, 1-bedroom flats, and office space. Energy requirements for each type of building cluster are obtained from rule of thumb data in the tools database. Physical details and rules of thumb for energy consumption of these buildings are given in the user interface windows of Figure 5.29a, Figure 5.29b and Figure 5.29c respectively.

b) Choosing to use own load profiles or using the computer tool database of load profiles

Users have the choice to enter their own load profiles for the building by selecting "input" or as in this particular example, the database of load profiles was selected as shown in Figure 5.30.

Figure 5.30 User interface window for load profile selection

c) Building loads summary

In this step, a building requirement for heat, hot water and power is then calculated as shown in Figure 5.31.

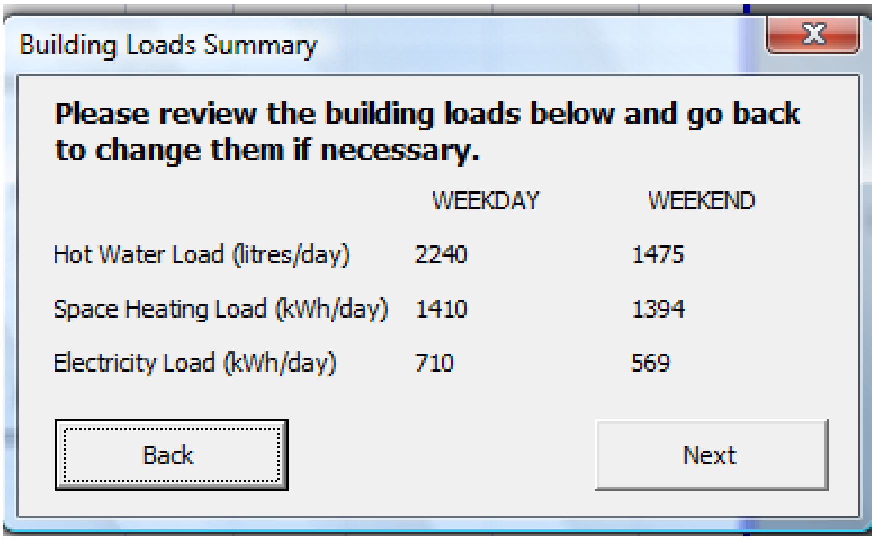


Figure 5.31 Calculation of building Loads

5.3.2 Evaluation of a combination of Grid, boiler, CHP and solar thermal collector systems using ST tool

a) Supply of heat and power from a Boiler and Grid

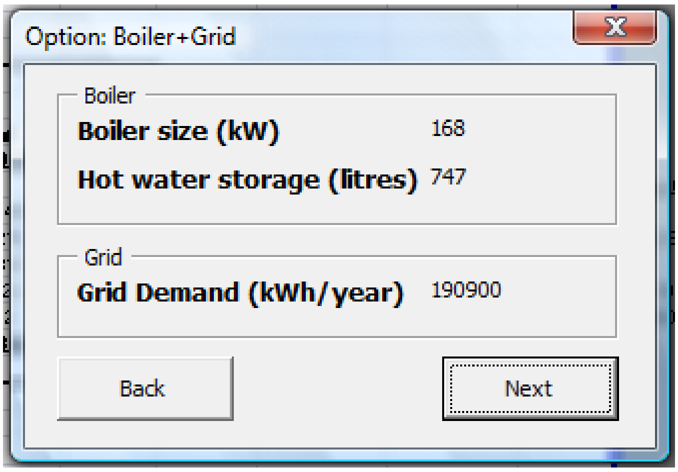


Figure 5.32 Boiler+EGrid sizes

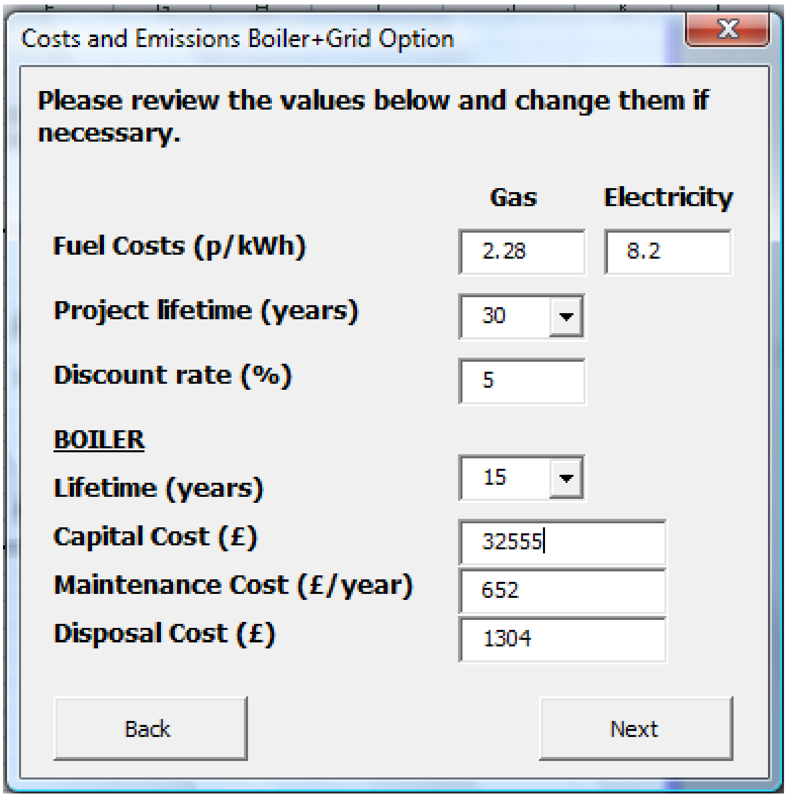


Figure 5.33 Costs for Boiler+Grid option

This is the baseline calculation in which the boiler heat rate and associated hot water storage capacity is calculated. A yearly power consumption of the building is also evaluated. Figure 5.32 shows estimated loads for this example.

To determine the economic feasibility of different combinations of technologies, the energy tariffs, life time, capital and maintenance cost are then entered as shown in Figure 5.33. In this example, the costs related to the boiler installation are calculated from rule of thumb estimates which can be changed to real quotes by the project manager.

b) Supply of heat and power from a combination of CHP, Boiler and Grid

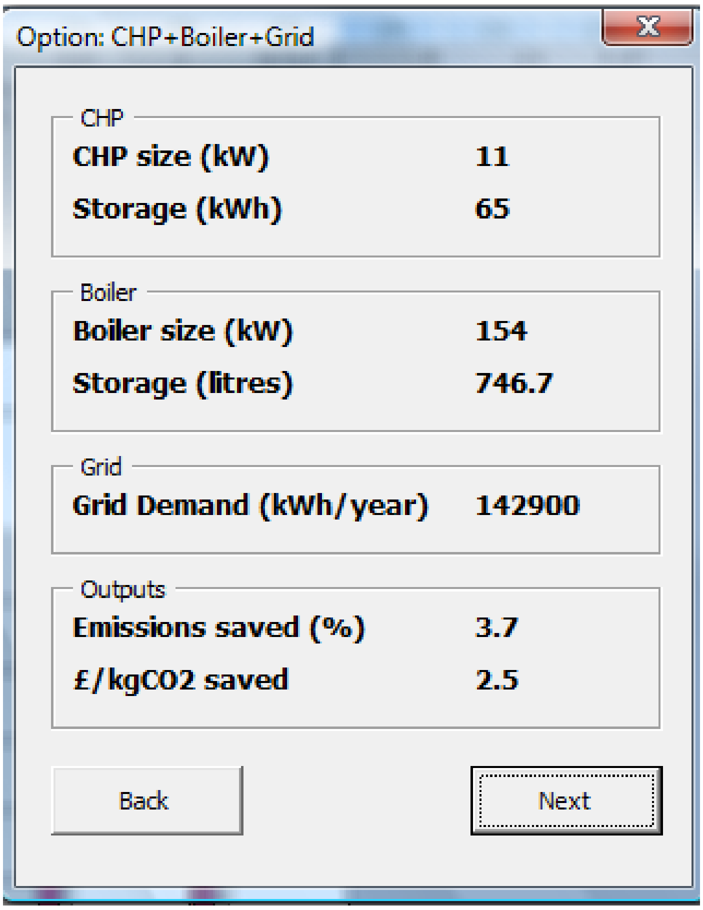


Figure 5.34 CHP+Boiler+EGrid case

The computer tool evaluates the size of the CHP and its heat storage system, backup boiler and hot water storage, and calculates the power needed to be met (i.e., imported) from the grid. In addition, the cost of saved CO_2 from such a combination of technologies is determined as shown in Figure 5.34 and Figure 5.35.

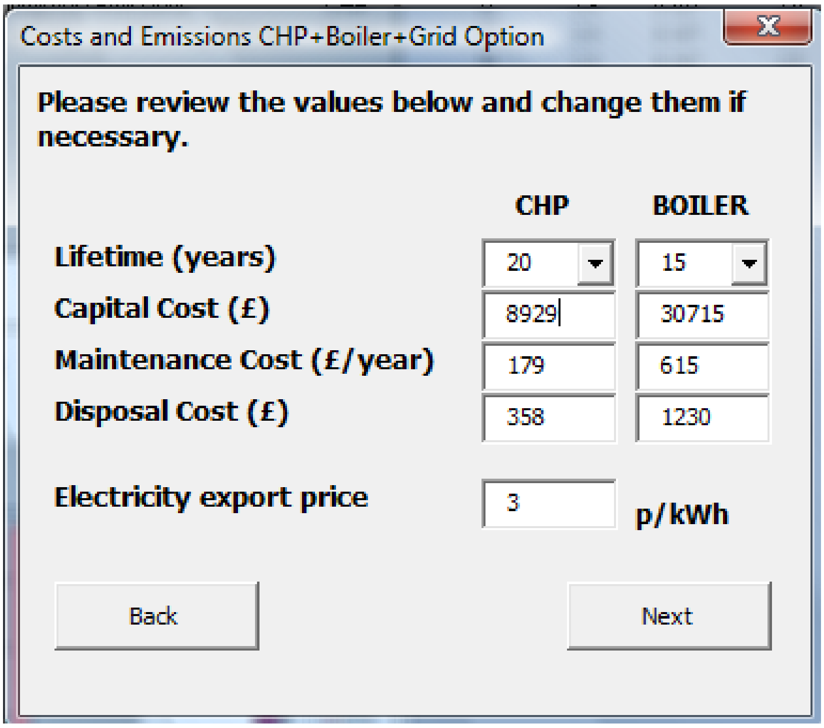


Figure 5.35 Costs for CHP+Boiler+Grid case

c) Supply of heat and power from a combination of Boiler, Solar collector and Grid

First the tool user is asked whether there is a size limitation on the solar collector that can be installed (e.g., available roof area) as shown in Figure 5.36. However, in this case no limitation factor is considered and the merit of using a solar collector will be evaluated by the computer tool simply to find the optimum size that would save CO_2 emission in a cost effective way.

Next capital, maintenance and disposal costs of the solar collector and boiler are calculated from rules of thumb built into the computer tool but again these could be modified by the user as given Figure 5.37.

Figure 5.38 shows optimum power and heat outputs for the solar thermal collector, boiler and hot water storage and grid mains that would generate a reduction in CO2 emissions of 2.1% compared to the baseline option of a grid and boiler only.

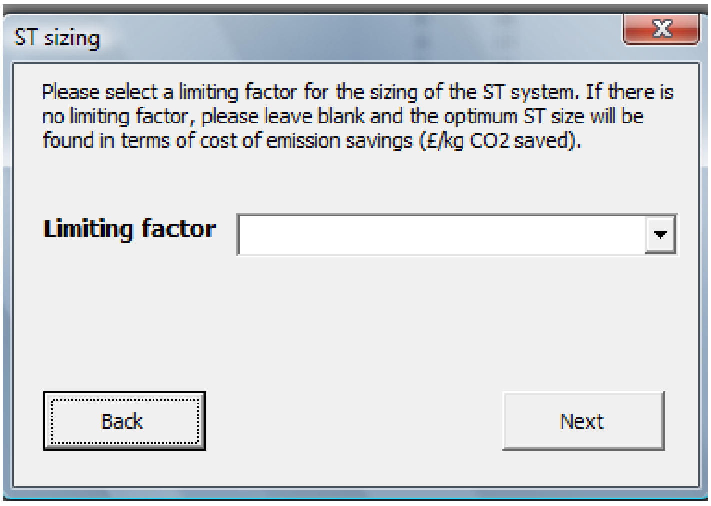


Figure 5.36 selecting a limiting factor in the sizing of solar thermal collectors

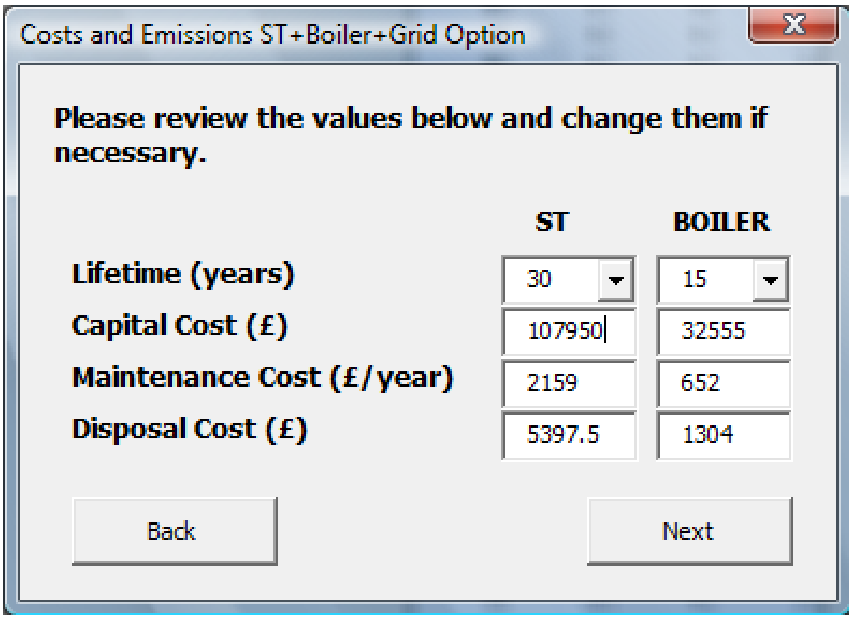


Figure 5.37 Costs for ST+Boiler+Grid option

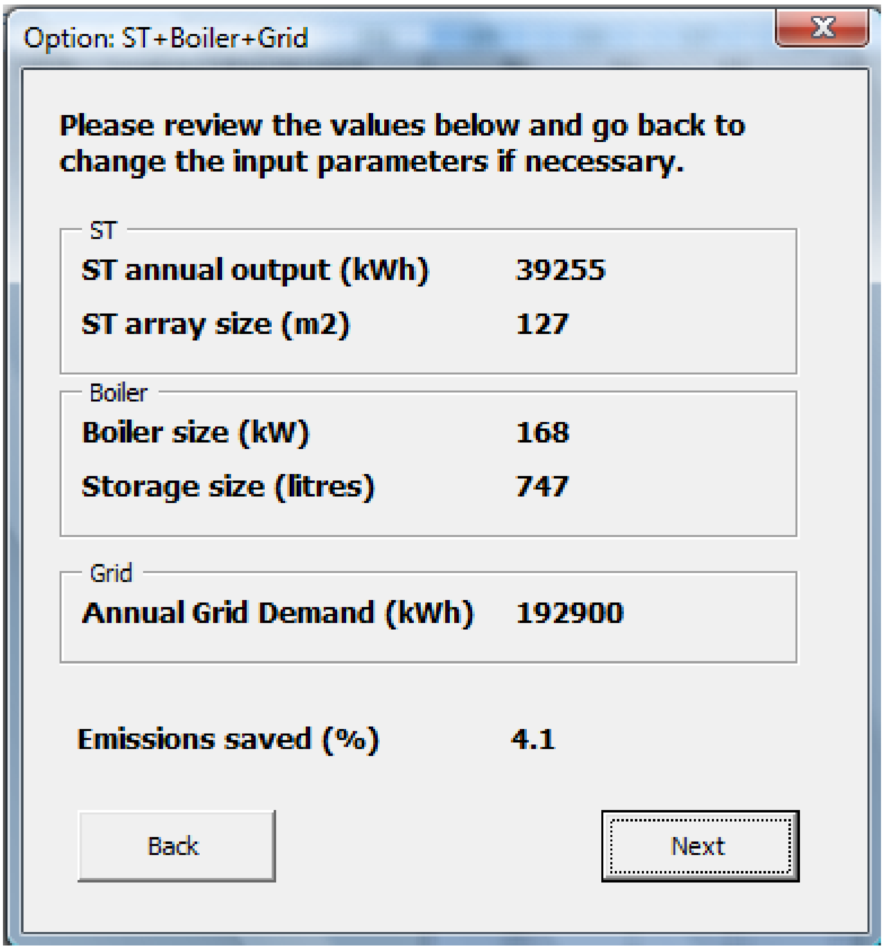


Figure 5.38 Technology sizes for ST+Boiler+Grid option

d) Supply of heat and power from a combination of CHP, Boiler, Solar collector and Grid

In this case, the CHP and Solar thermal systems are sized to provide as much heat and power as practical. The solar thermal collector capacity is not limited by the area available for installation and the CHP runs for a minimum of 4500 hours a year. Modelling operating parameters and results of this option as show in Figure 5.39 and Figure 5.40 respectively and give an estimate of 4.1% savings of CO_2 emission.

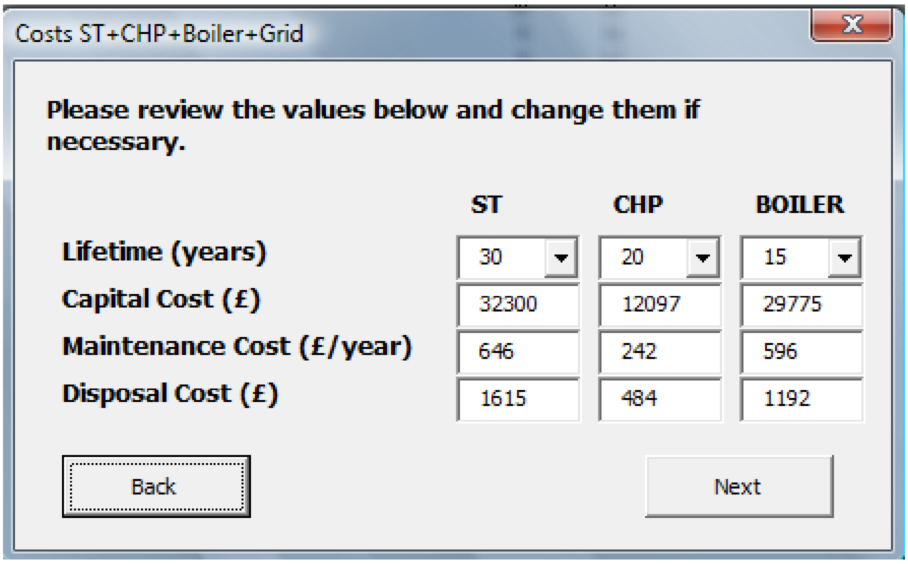


Figure 5.39 Costs for ST+CHP+Boiler+Grid option

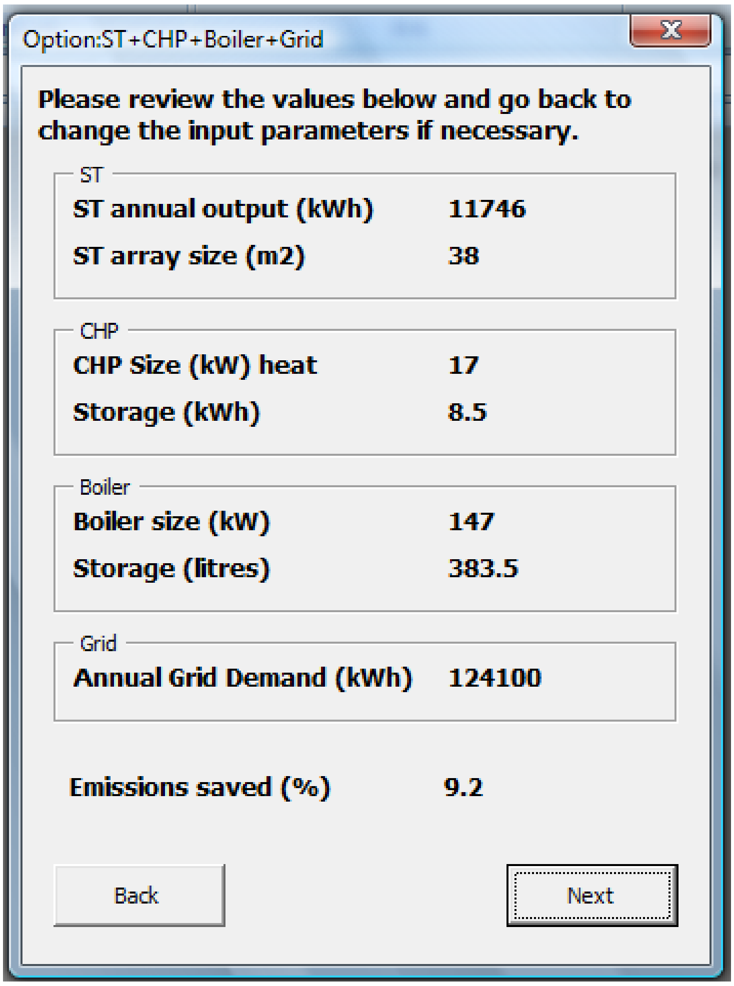


Figure 5.40 Sizes of technologies for ST+CHP+Boiler+Grid

e) Optimum size selection and comparison of technology combinations of the ST tool using the Monte Carlo method.

The final step in obtaining optimum heat and power output for different technologies is to apply the Monte Carlo method which performs an iterative process using building load profiles that are stored in the database of the computer tool. In this modelling case for instance the computer tool performs 100 iterations for randomly selected load profiles. The most frequently occurring outputs for the different technology combinations are summarised in the bar charts Figures 5.41 to 5.44 which also indicate the ranges of all the outputs.

Figure 5.41 shows a bar chart of the most frequently occurring energy costs of the different technology combinations against their base cases. The technology combination with the lowest system energy cost for this example is the CHP+Boiler+EGrid option with 2.9p/kWh. The Boiler+EGrid and the ST+CHP+Boiler+EGrid options have a slightly higher energy cost of 3.1p/kWh. The ST+Boiler+EGrid option has a much higher energy cost of 4p/kWh. However all options have a lower cost than the cost of electricity.

Figure 5.42 shows that the ST+CHP+Boiler+EGrid option provides the minimum CO_2 emissions of 0.302 kg per kWh of energy consumption. When compared to the baseline case of boiler and grid only, the ST+CHP+Boiler+EGrid combination offers maximum CO_2 emission reduction of 8.6%, as illustrated by Figure 5.43.

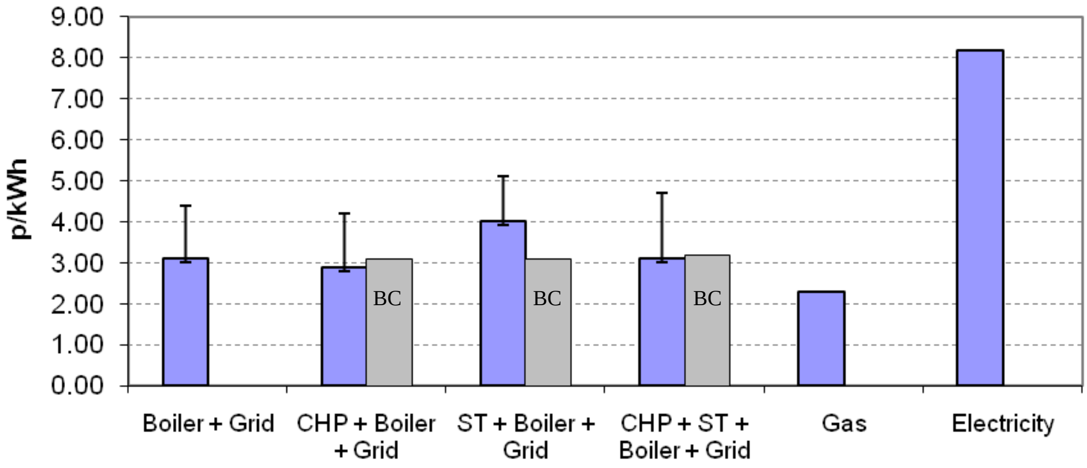


Figure 5.41 System energy costs for each technology combination

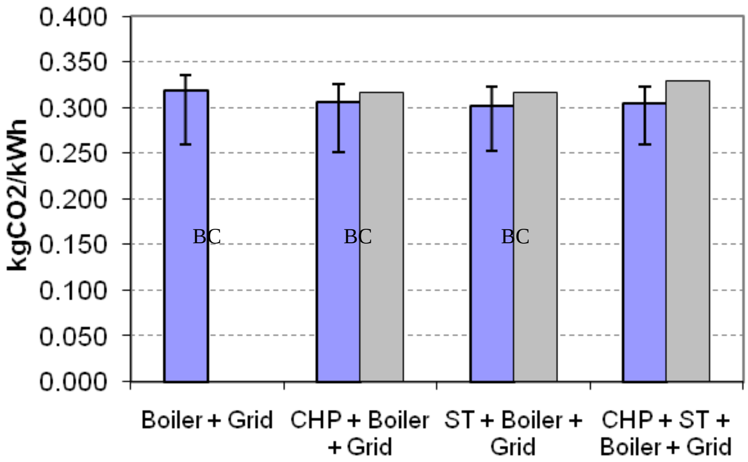


Figure 5.42 Emissions for each technology combination

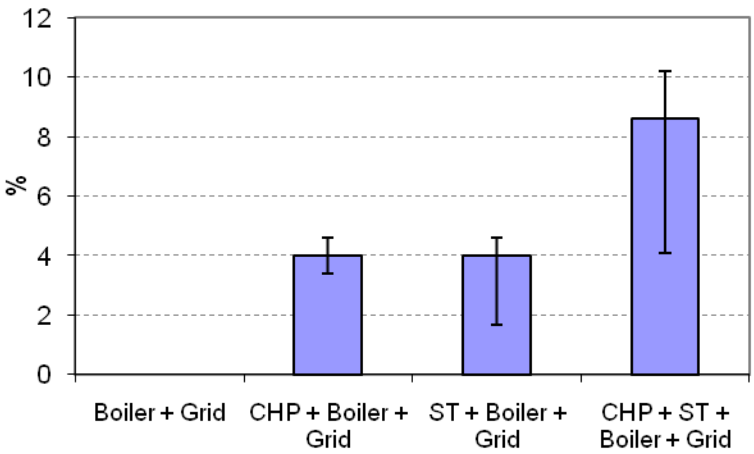


Figure 5.43 Emissions reduction for each technology combination

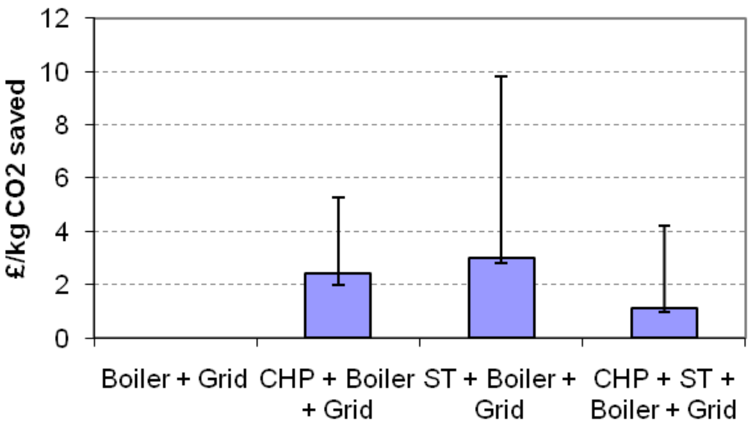
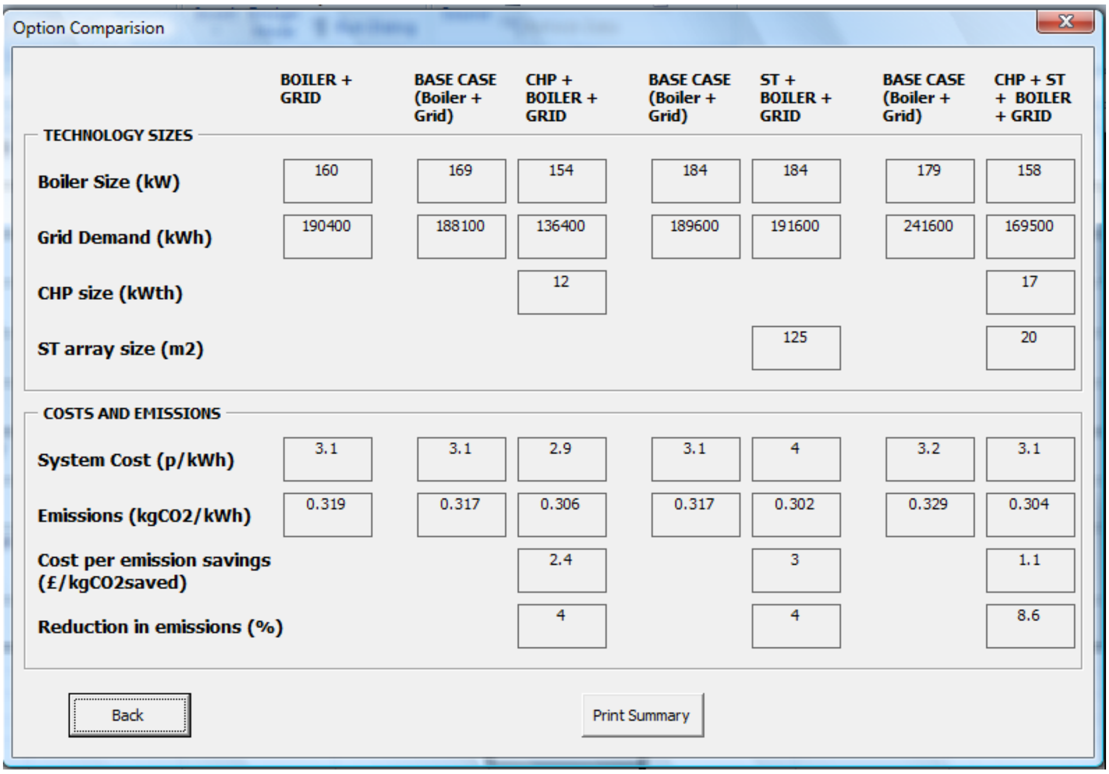


Figure 5.44 Cost of emission savings for each technology combination


Option Comparision

	BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + BOILER + GRID	BASE CASE (Boiler + Grid)	ST + BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + ST + BOILER + GRID
TECHNOLOGY SIZES							
Boiler Size (kW)	160	169	154	184	184	179	158
Grid Demand (kWh)	190400	188100	136400	189600	191600	241600	169500
CHP size (kWth)			12				17
ST array size (m2)					125		20
COSTS AND EMISSIONS							
System Cost (p/kWh)	3.1	3.1	2.9	3.1	4	3.2	3.1
Emissions (kgCO2/kWh)	0.319	0.317	0.306	0.317	0.302	0.329	0.304
Cost per emission savings (£/kgCO2saved)			2.4		3		1.1
Reduction in emissions (%)			4		4		8.6

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Figure 5.45 Summary of outputs and option comparison with MCM

Equally important, the lowest cost per CO2 emission savings is achieved by the ST+CHP+Boiler+EGrid option which is estimated to be 1.1£/kgCO_2 saved as shown in Figure 5.44. It can also be seen that ST+Boiler+EGrid option has the highest cost of emissions savings with 3£/ kgCO_2.

Figure 5.45 gives a summary of the most probable and cost effective solution for each technology combination. Therefore, the computer tool could constitute a valuable instrument for the user in planning and decision making when considering investment in energy abatement technologies.

f) Optimum size selection and comparison of technology combinations of the ST tool using one set of load profiles only.

In order to compare the outputs of the tool with the sample calculation outputs in section 5.2, the tool was also run for one set of load profiles, without the Monte Carlo method being applied. Figure 5.46 shows the summary of outputs of the ST tool when one set of load profiles is used and therefore the Monte Carlo method is not applied. These outputs coincide with the outputs of the sample calculation (Table 5.4) carried out in section 5.2.

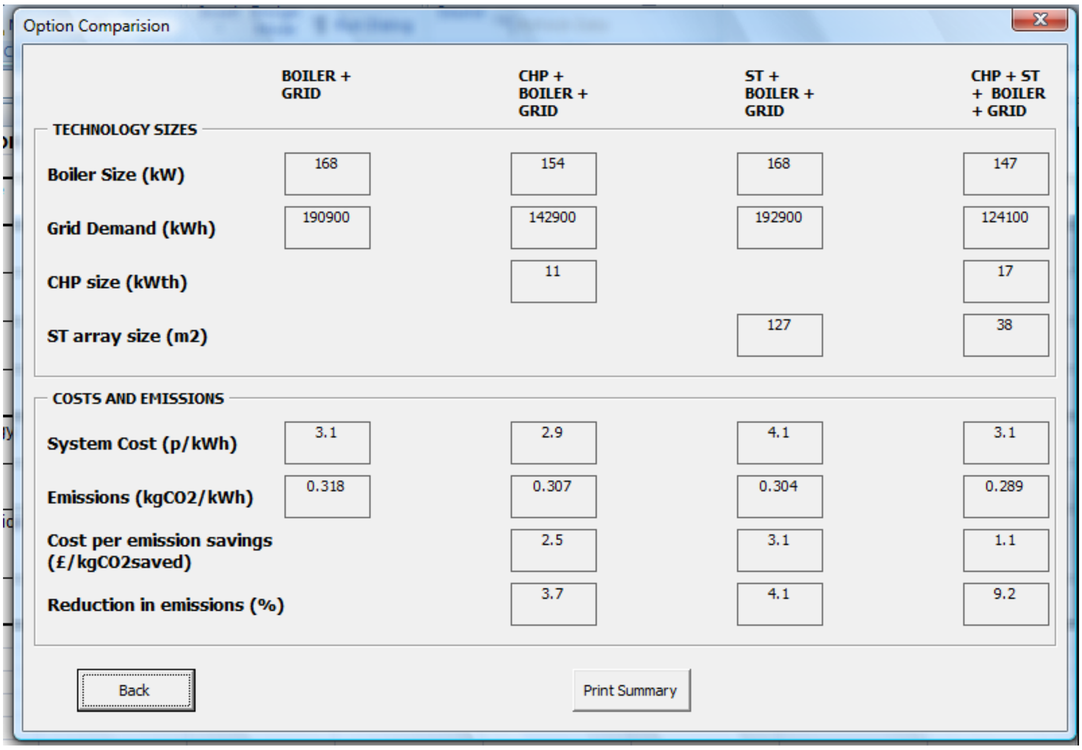


Figure 5.46 Summary of outputs and option comparison without MCM

5.3.3 Evaluation of a combination of Grid, Boiler, CHP and Photovoltaic panels using the PV tool

The procedure for evaluating the PV tool for a combination of technologies including Grid, Boiler, CHP and PV panels is similar to the ST tool described above and the same operating data is used.

a) Supply of heat and power from a combination of Boiler, Grid and PV panel

Like in the sizing of the solar thermal collector, the user may select a limiting factor for the size of the panel as given in Figure 5.47. If, however, no constraints on the size of the panel are entered then the tool evaluates the optimum size of the panel that would reduce CO_2 emission cheaply.

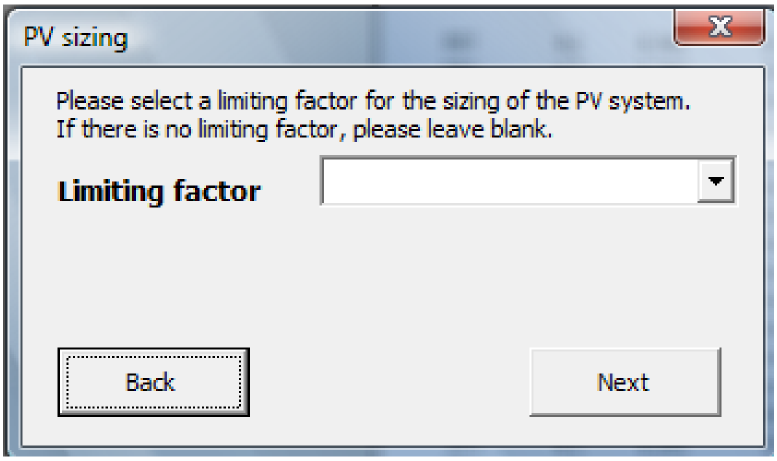


Figure 5.47 Selecting a limiting factor for sizing PV

Operating parameters, energy outputs and emissions savings of grid, boiler and PV combination are given in Figure 5.48 and Figure 5.49 respectively. Figure 5.49 shows that the PV, boiler and grid combination would save 16.4% in CO_2 emission compared to the baseline case of grid and boiler only. This however would require a PV panel area of 550 m^2.

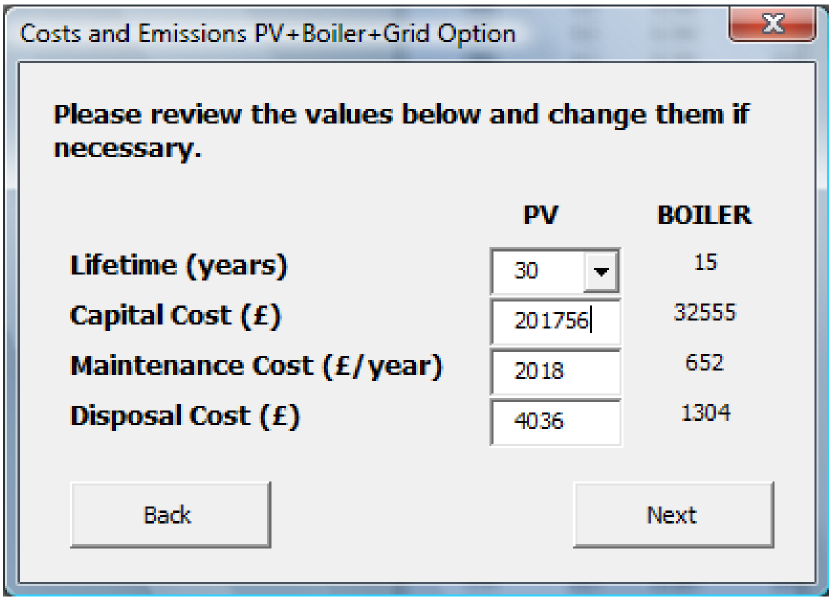


Figure 5.48 Operating Costs for PV+Boiler+EGrid option

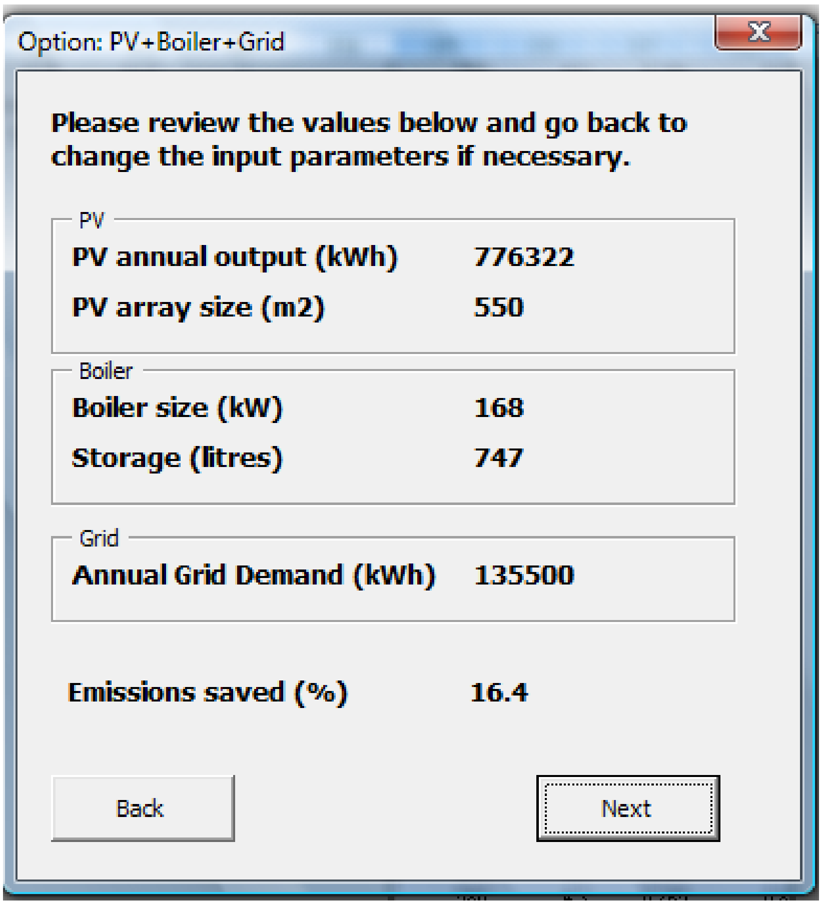


Figure 5.49 Sizes of technologies for PV+Boiler+EGrid option

b) Supply of heat and power from a combination of PV, CHP, Boiler and Grid

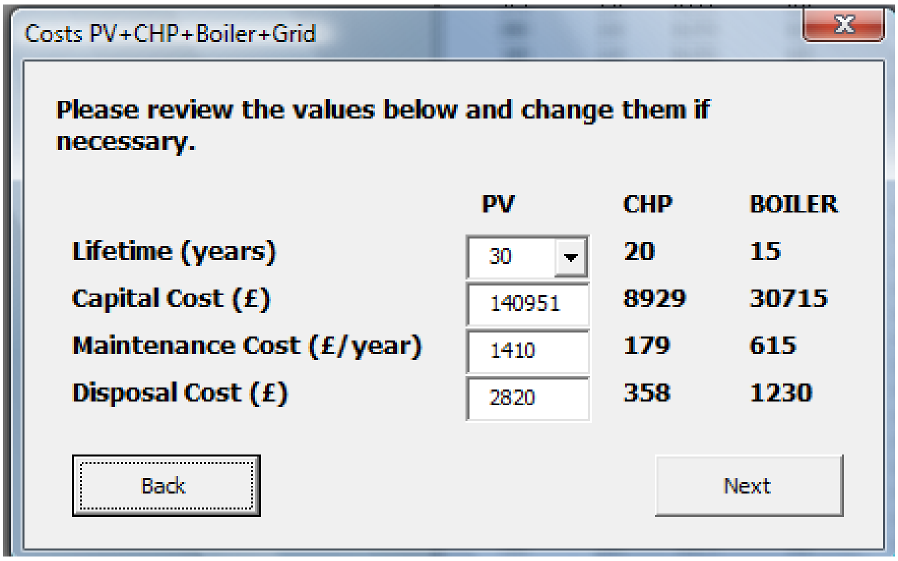


Figure 5.50 Costs for PV+CHP+Boiler+EGrid option

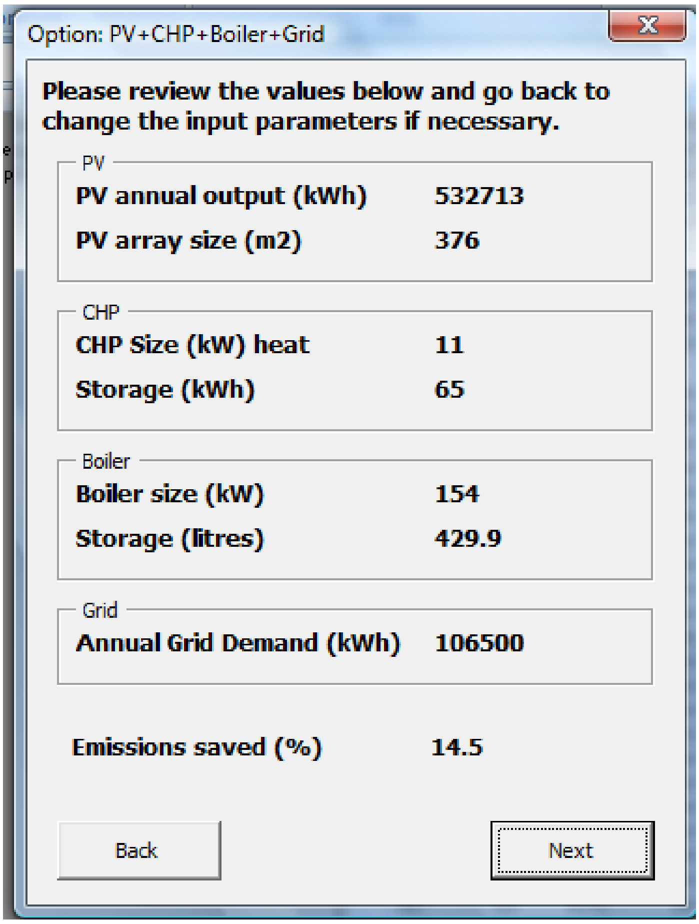


Figure 5.51 Sizes of technologies for PV+CHP+Boiler+EGrid option

In this case, the CHP system and PV panel are optimally sized to provide the maximum heat and power to satisfy the building load. The CHP would run for a minimum of 4500 hours a year and the PV panel capacity, not being limited by the area available for installation, is optimally sized to provide additional electricity. The boiler and grid supply the peak heat and power loads. The computer model operating parameters and results of this option are shown in Figure 5.50 and Figure 5.51 respectively.

c) Optimum size selection and comparison of technology combinations of the PV tool using the Monte Carlo method.

As for the ST tool the optimum heat and power output for different technologies, is obtained by applying the Monte Carlo Method. This iterative process uses building load profiles stored in the database and records the most frequently occurring outputs for the different technology combinations and also indicates the ranges of all the outputs. Figure 5.52 shows a bar chart of the most occurring energy costs of the different technology combinations. The technology combination with the lowest system energy cost for this example is again the CHP+Boiler+EGrid option with 2.9p/kWh. The PV+Boiler+EGrid option has the highest energy cost of 4.2p/kWh.

Figure 5.53 and Figure 5.54 show that the PV+Boiler+EGrid option achieves the lowest emissions of 0.268kgCO_2/kWh which represents emissions savings of 16.3% compared to the boiler and grid only option. Figure 5.54 shows that the PV+Boiler+EGrid option and the CHP+PV+Boiler+EGrid option achieved the lowest cost per emission savings of £0.8/kgCO_2 saved. The CHP had the highest cost per emission savings with £2.5/kg CO_2 saved.

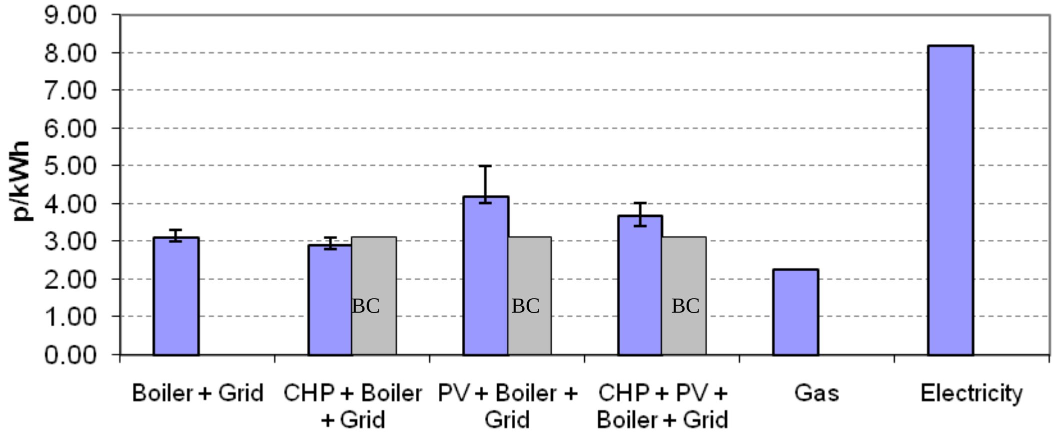


Figure 5.52 System energy costs for each technology combination

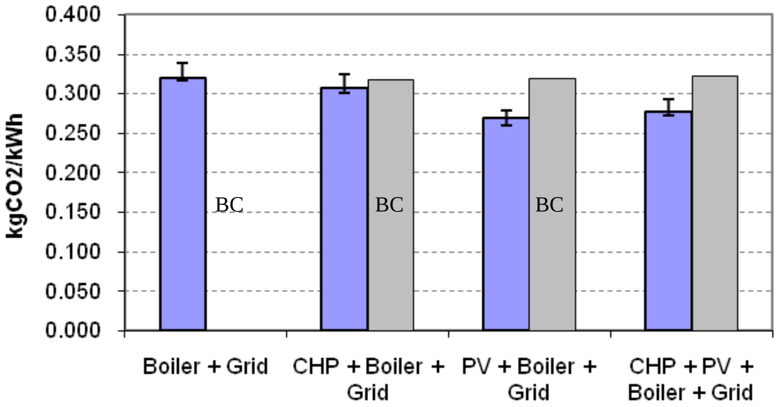


Figure 5.53 Emissions for each technology combination

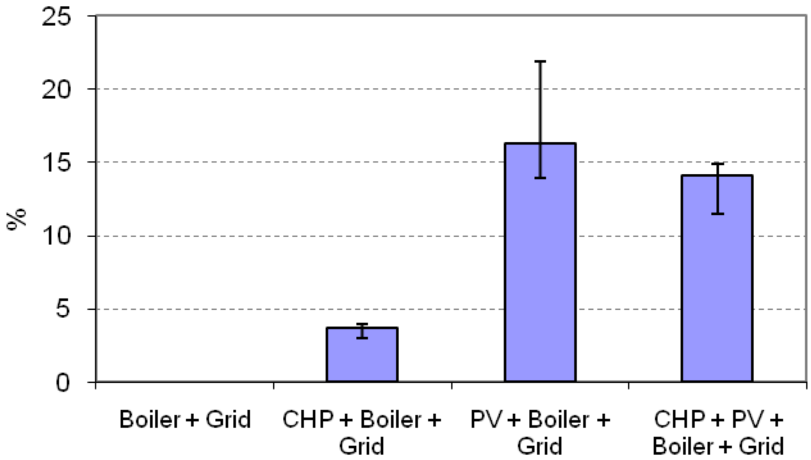


Figure 5.54 Emissions reduction for each technology combination

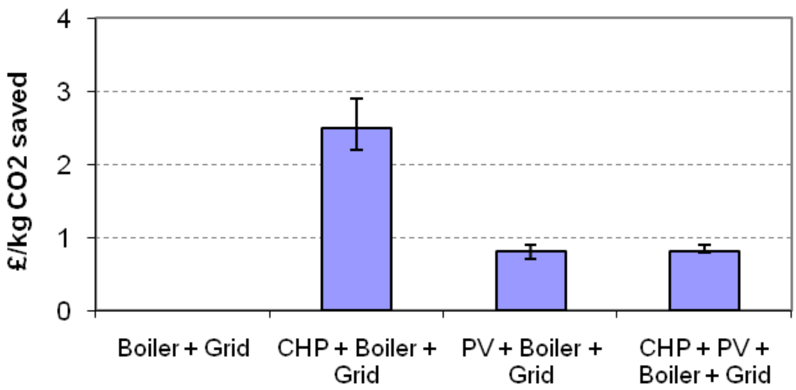
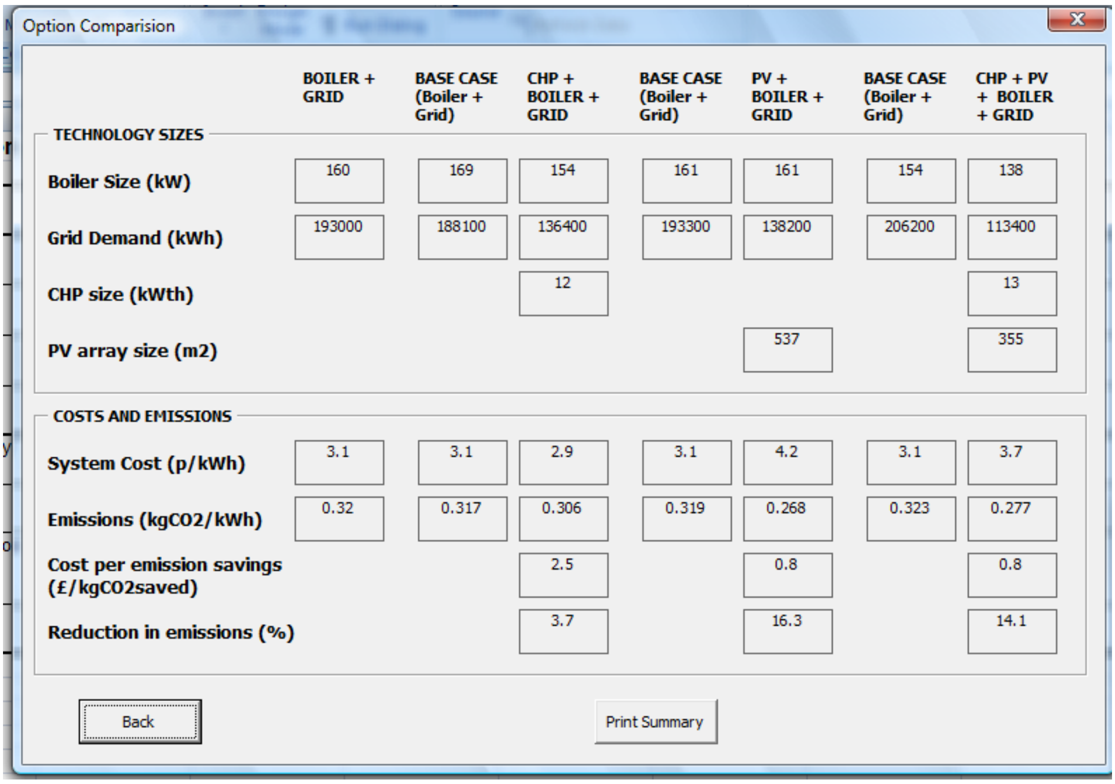


Figure 5.55 Cost of emission savings for each technology combination

Figure 5.56 gives a summary of the optimum solutions for each technology combination and the computer tool makes it easier to select a technology combination that provides the best results.



Option Comparision

	BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + BOILER + GRID	BASE CASE (Boiler + Grid)	PV + BOILER + GRID	BASE CASE (Boiler + Grid)	CHP + PV + BOILER + GRID
TECHNOLOGY SIZES							
Boiler Size (kW)	160	169	154	161	161	154	138
Grid Demand (kWh)	193000	188100	136400	193300	138200	206200	113400
CHP size (kWth)			12				13
PV array size (m2)					537		355
COSTS AND EMISSIONS							
System Cost (p/kWh)	3.1	3.1	2.9	3.1	4.2	3.1	3.7
Emissions (kgCO2/kWh)	0.32	0.317	0.306	0.319	0.268	0.323	0.277
Cost per emission savings (£/kgCO2saved)			2.5		0.8		0.8
Reduction in emissions (%)			3.7		16.3		14.1

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Figure 5.56 Summary of outputs and option comparison

d) Optimum size selection and comparison of technology combinations of the ST tool using one set of load profiles only.

In order to compare the outputs of the tool with the sample calculation outputs in section 5.2, the tool was also run for one set of load profiles, without the Monte Carlo method being applied. Figure 5.57 shows the summary of outputs of the PV tool when one set of load profiles is used and therefore the Monte Carlo method is not applied. These outputs coincide with the outputs of the sample calculation (Table 5.4) carried out in section 5.2.

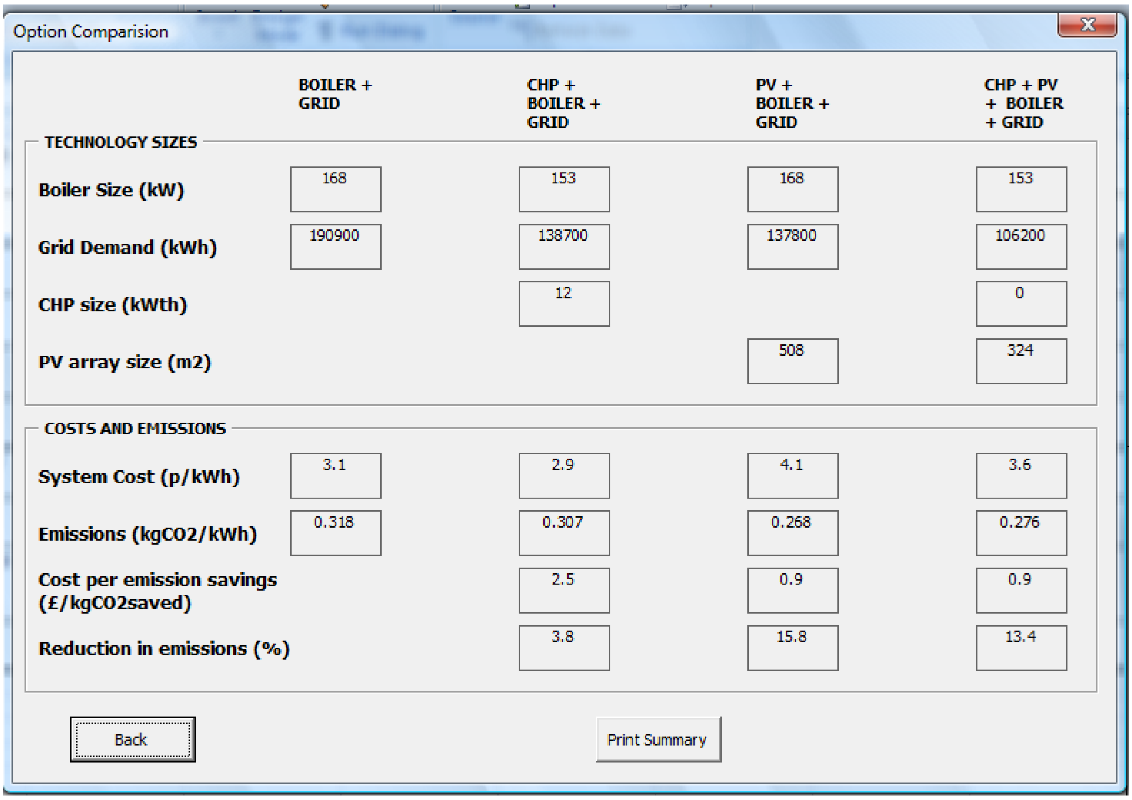

Figure 5.57 Summary of outputs and option comparison

5.4 LIMITATIONS OF THE COMPUTER TOOL

The accuracy of the computer tool outputs depends greatly on the assumptions made in the tool development. For instance the solar radiation and ambient temperature data used in the model are those for the London area. Hence, the calculation procedures could be further improved by incorporating global data to make the computer tool applicable to anywhere in the world.

The optimum heat and power rating of a technology obtained from the computer tool may not always exist as a commercial product. For example, the range of available heat and power equipments (i.e., boilers, CHP systems, PV and solar thermal collectors) are limited to those commercialised by manufacturers and hence the computer tool could include suggestion notes on the best nearest equipment ratings available and the effect this would have on the overall cost and emissions. In addition, for accurate and quick cost analysis, an up-to-date database of heating and power equipments properties and costs could be listed with the name of the manufacturer.

Furthermore, the load profiles database does not statistically represent the whole of UK building stock and this in turn affects the accuracy of the tool. As part of this thesis some load profiles for domestic hot water have been collected in a survey. However, more load profiles would be required to represent the UK building stock. As more load profiles are added to the database, the accuracy of the tool would improve.

The accuracy of the computer tool is also affected by the number of iterations the tool performance in order to obtain a converging solution. A high number of iterations may take a long time and require large computer physical memory to execute. In the current example, the number of iterations using the Monte Carlo method is 100 iterations which take a long time to execute depending on the types of load profiles to process. Hence, speeding up the program execution could be achieved by using faster computer processors or reducing the number of iterations at the expense of the accuracy of the tool's outputs.

The computer tool is also made up of two separate sub-tools that run independently: the ST tool and the PV tool. The ST tool sizes technologies that combine with solar thermal collectors, whereas the PV tool sizes technologies that combine with PV panels. Therefore, the two sub-tools could be combined seamlessly into one tool which is capable of sizing a whole host of combination of technologies including micro-wind turbines and ground source heat pumps. In this way the most optimal energy mix required for the reduction of emissions could be determined.

5.5 DISCUSSION AND CONCLUSION

The tool developed in this study addresses the uncertainty of load profiles in the sizing of renewable energy and CHP technologies and compares different combinations of technologies to find the option with the lowest cost of emissions reduction (£/kgCO_2 saved). As discussed in Chapter 2, there is currently no computer tool available which investigates the use of a combination of renewable energy and CHP technologies to provide heat and power in buildings and at the same time takes into account the uncertainty of building energy load profiles by using the Monte Carlo Method.

The aim in developing this computer tool is to address the needs of an energy project manager which uses historical buildings load profiles in new schemes with a high level of confidence when planning the installation of CHP systems, PV panels and solar thermal collectors individually or in combination with one or more technologies together. In this way, CO_2 emissions in buildings can be reduced as required by existing Building Regulations (Part L2) for England and Wales.

A conventional gas-fired CHP system is not a renewable energy technology, but, given that it uses fuel energy content more efficiently, it is usually considered as an energy saving option, which can ultimately provide a cost effective energy supply, mainly to commercial buildings, where cost-effectiveness is usually a priority in the decision-making process. Renewable energy technologies for buildings, however, are usually more expensive and are rarely considered for application where the cost of reducing CO_2 emission from the building is the overriding priority as the exorbitant capital and installation cost can only be justified if there is some financial incentive to do so. It can however be concluded from the results obtained in this case study that a combination of renewable energy systems and CHP could be a viable option to provide a cost-effective and environmentally friendly supply of energy to buildings.

Finally, the computer tool allows the user to make quick decisions when selecting a technology or combination of technologies to be installed in new or refurbished buildings. In this respect it can be seen from this case study, that if the project is driven by the cost of energy generation (p/kWh), then CHP+Boiler+EGrid option would make better investment returns. On the other hand, if the reduction of CO_2 emissions is more important, then the option of incorporating renewables with or without CHP would be a more attractive proposition. The option of incorporating renewables and CHP (i.e., CHP+ST+Boiler+EGrid and CHP+PV+Boiler+EGrid options) would offer a better solution if both cost of energy generation (p/kWh) and CO_2 emissions are important.

Chapter 6:

Conclusion and Suggestions for Future Work

6.1 GENERAL CONCLUSIONS

This thesis demonstrates the need for better knowledge and the necessary tools to integrate effectively renewable energy and energy efficient technologies to supply energy to buildings. The ever increasing building regulations standards (Part L1 and L2) and the government's ambitious plan to make all new buildings zero CO_2 emissions by 2016 could only be achieved if on-site heat and power generation using renewables and energy efficient technologies are deployed effectively.

The computer tool developed in this study compares different combinations of photovoltaic (PV) panels, solar thermal collectors and Combined Heat and Power (CHP) technologies for building applications to find the option with the lowest cost of emissions reduction (£/kgCO_2 saved). The tool could enable the selection of more appropriate technologies for the supply of electricity, hot water and space heating for buildings by optimising the integration of the combined technologies for different building types. The tool aims to facilitate the decision-making process of the designers, by identifying workable solutions for a project, as well as streamlining the number of options from which a reliable decision could be made.

The computer tool developed in this thesis addresses the uncertainty of building energy load profiles in the sizing of renewable energy and CHP technologies by applying the Monte Carlo method. A database of historical building energy load profiles was collated for this purpose. A survey was also conducted to collect hot water load profiles for residential buildings for the computer tool load profile database.

The Monte Carlo Method is used to take into account the uncertainties of building energy load profiles in order to provide a most probable output from the tool. One of the specific outputs of the tool is the techno-economic analysis and carbon savings from which selected renewable energy/CHP combinations can be compared and which provides the decision-makers with the required information.

A case study was used to validate the computer tool and its accuracy. Although renewable energy and CHP technologies are not usually considered together for building applications, it was concluded, from the results obtained in this case study, that a combination of renewable energy systems and CHP could be a viable option to provide a cost-effective and environmentally friendly supply of energy to buildings.

6.1.1 Complexity of building load profiles/patterns

Building energy load profiles are especially useful for the design of renewable energy technologies and CHP systems, and are, therefore, vital data used in the tool developed in this study. Energy load profiles for buildings depend on many factors, such as the type of building, occupancy, climate and occupancy behaviour, which make them difficult to predict.

Past energy use of a building will give the most accurate predictions for future energy requirements. However for a new-build or some refurbishments this data might not be available. In these cases typical load profiles are estimated, by taking the monitored load profile of a similar building, an average of several, or by simulating a typical profile.

Real load profiles were collected to form a database for the tool. Load profiles were collected and collated from the literature and a domestic hot water demand survey. The Monte Carlo Method is used to take into account the uncertainty of the load profiles in the sizing of the technologies.

6.1.2 Hot water demand profiles

A literature search identified a lack of reliable residential hourly domestic hot water demand profile data for the UK. Therefore, as part of this work, a survey was conducted to collect hot water load profiles for residential buildings in the UK. The survey consisted of a questionnaire and a monitoring survey.

The questionnaire consists of two parts: a general questionnaire about the dwelling and a diary study. The questionnaire enabled the load profiles collected to be classified into different building type categories and in the diary study the hot water consumption patterns were recorded.

The monitoring study was carried out in conjunction with the survey questionnaire and was carried out using temperature sensors attached to the hot water pipes of the different appliances within the dwellings. When hot water was used, the temperature recorded by the sensor increased. This enabled the identification of when and from which appliance hot water was used throughout the day in the dwellings. Although the use of sensors to collect the data, of collecting the data is more precise as it doesn’t rely on participants remembering to record their hot water consumption, the questionnaire nevertheless enabled more data to be collected. The data collected by both methods was used to form hourly hot water load profiles to be loaded into the tool.

Typical hot water usages of appliances were calculated using typical flow rates and usage time periods recorded by a clamp-on flow meter. The typical hot water usages for the appliances were combined with the survey questionnaire data and the data collected from the temperature sensors to form hot water load profiles. This data was loaded into the tool load profile database with the other load profile data collected from the literature.

6.1.3 The computer Tool

The computer tool developed in this study provides the user with an aid to selecting renewable energy technologies with CHP systems for the supply of energy to buildings, whilst taking into account the uncertainty of building energy load profiles. The tool optimally sizes combinations of technologies to find the options with the lowest cost of emissions reduction (£/kgCO_2 saved) and allows the user to make quick decisions when selecting a technology or combination of technologies to be installed in buildings.

Visual Basic for Application (VBA) was used to develop the computer tool. The tool was developed in two Excel files each combining a different renewable energy technology (Photovoltaics and Solar Thermal) with CHP. Each tool consists of the following main stages:

D. The building loads and load profiles are processed.

E. Sizing and selection of technical parameters of technologies followed by a financial and environmental analysis are carried out.

F. If load profiles are not known to the tool user, the Monte Carlo Method is used to account for the uncertainty of building energy load profiles by sizing each of the combination options for 100 different load profiles.

G. For each combination the most likely technology sizes, costs and emissions are obtained and a comparison and evaluation analysis of technologies or combination of technologies is given that would facilitate the selection of the appropriate option.

6.1.4 The case study

The validation of the computer tool was carried out to select and optimise renewable energy technologies for a mixed-use office and residential building located in the UK. A building, with a total floor area of 1750m^2, consisting of three clusters of 5 two-bedroom flats of 100m^2 each, 15 one-bedroom flats of 50m^2 each, and 500m^2 of office space with occupancy capacity of 50 people was used for the validation. In this analysis, it is assumed that the building loads and load profiles are not known in advance and hence the tool uses load profiles from its database of load profiles to match each cluster building. Three different technologies are evaluated in different combinations: combined heat and power, solar thermal collectors for hot water and photovoltaic panels for electricity generation.

It can be seen from this case study, that if the project is driven by the cost of energy generation (p/kWh), then CHP+Boiler+EGrid option would make better investment returns. On the other hand, if the reduction of CO_2 emissions is more important, then the option of incorporating renewables with or without CHP would be a more attractive proposition. The option of incorporating renewables and CHP (i.e., CHP+ST+Boiler+EGrid and CHP+PV+Boiler+EGrid options) would offer a better solution if both cost of energy generation (p/kWh) and CO_2 emissions are important.

6.2 CONTRIBUTION TO KNOWLEDGE AND ORIGINALITY

In this work a computer tool was developed and a hot water demand survey was carried out as described above. The main original points of this research include:

- Development of a computer tool with the built-in capability to determine optimal power ratings, cost and environmental impact of integrated renewable energy and energy efficient technologies to provide heat and power in buildings.
- The computer tool uses a large database of load profiles for different types of buildings.
- An interactive procedure using the Monte Carlo method was employed to take into account the uncertainty of load profiles.
- A case study was used to validate the computer tool and its accuracy.
- A survey was carried out to collect hot water consumption profiles for residential buildings in the UK.

6.3 RECOMMENDATIONS FOR FUTURE WORK

As discussed in Chapter 5, the computer tool developed in this study could be improved further by addressing the following:

- The accuracy of the computer model outputs depends greatly on the assumptions made in the tool development. The calculation procedures of the computer tool could therefore be further improved, by for example incorporating weather data for different locations in the world so that the tool could be used by a wider audience.
- For accurate and quick cost analysis, an up-to-date database of heating and power equipment properties and costs could be listed with the name of the manufacturer.
- The optimum heat and power rating of a technology obtained from the computer tool may not always exist as a commercial product as the range of available heat and power equipment is limited to those commercialised by manufacturers. The computer tool could include suggestion notes on the best nearest equipment ratings available and the effect this would have on the overall cost and emissions.
- The accuracy of the computer tool could be improved by adding more building energy load profiles to the tools database. Although some load profiles for domestic hot water have been collected in a survey as part of this thesis, more load profiles would be required to represent the UK building stock.
- The running time of the computer tool could be reduced to make the tool more user-friendly. In the current example, the number of iterations using the Monte

Carlo method is 100 iterations. This takes a long time to execute depending on the types of load profiles to process.

- The two sub-tools (ST tool and the PV tool) could be combined seamlessly into one tool.
- The computer tool could be further widened to include cooling and air conditioning technologies such as vapour compression, absorption chillers, and heat pumps, and other distributed power generation systems such as micro-wind turbines.

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Appendix

Domestic Hot Water and Heating Demand Survey

This questionnaire aims to establish typical residential hot water consumption patterns.
Please tick or complete the relevant boxes in the sections below.
Thank you very much for your time.

GENERAL

City/County of residence ☐

Property type: Flat ☐ Bedsit ☐ Terraced ☐ Semi ☐ Detached ☐ Other (please specifiy) ☐

Year of build: <1900 ☐ 1900-40 ☐ 1941-60 ☐ 1960s ☐ 1970s ☐ 1980s ☐ 1990s ☐ 2000s ☐ Don't know ☐

No of bedrooms: 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5+ ☐

No of showers: 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4+ ☐

No of baths: 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4+ ☐

Dwelling size (m^2): 0-50 ☐ 51-100 ☐ 101-150 ☐ 151-200 ☐ >200 ☐

Adult occupancy: 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5+ ☐

Children occupancy: 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4+ ☐

On average, how many days in the week is your house occupied during the day (9am – 5pm)? 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐

APPLIANCES

Oven fuel: Electricity ☐ Mains gas ☐ Other (please specify) ☐

Hob fuel: Electricity ☐ Mains gas ☐ Other (please specify) ☐

Washing machine water supply: Hot & cold supply ☐ Cold supply only ☐ Don't know ☐ Don't have one ☐

Dishwasher water supply: Hot & cold supply ☐ Cold supply only ☐ Don't know ☐ Don't have one ☐

HEATING SYSTEM

Main Heating System	Conventional boiler ☐	Combination boiler ☐	Don’t know ☐
	Other (please specify) ________		None ☐
Distribution system	Radiators ☐	Under-floor heating ☐	Don’t know ☐
	Other (please specify) ________		
Main Heating Fuel	Electricity ☐	Natural Gas ☐	Oil ☐ Coal ☐
	Other (please specify) ________		Don’t know ☐

Heating period (please tick months you usually heat your house)

January ☐	February ☐	March ☐	April ☐
May ☐	June ☐	July ☐	August ☐
September ☐	October ☐	November ☐	December ☐

Is your heating controlled by a timer or a thermostat? Timer ☐ Thermostat ☐ Don’t know ☐

Do you have a fireplace? Yes ☐ No ☐

Fireplace fuel Gas ☐ Wood ☐ Coal ☐
Other (please specify) ________

HOT WATER SYSTEM

What hot water system do you have? Same as for heating ☐ Other (please specify) ________

Fuel Same as for heating ☐ Other (please specify) ________

Is your hot water supply controlled by a timer or is it instantaneous? Timer ☐ Instantaneous ☐ Don’t know ☐

COMMENTS

1 - Weekly consumption pattern

Week ____ (1-52) Date ____

	reading at the start of the week	reading at the end of the week
Gas reading		
Electricity reading		
Water reading		

Heating Thermostat setting *Please tick your thermostat setting for every day of the week*

°C

Day	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Monday																					
Tuesday																					
Wednesday																					
Thursday																					
Friday																					
Saturday																					
Sunday																					

Day	1	2	3	4	5
Monday					
Tuesday					
Wednesday					
Thursday					
Friday					
Saturday					
Sunday					

Or Timer settings

ON 1 ____ °C OFF 1 ____ °C

ON 2 ____ °C OFF 2 ____ °C

Hot water Timer settings

ON 1 ____ °C OFF 1 ____ °C

ON 2 ____ °C OFF 2 ____ °C

2a - Weekly Bathroom DHW consumption

Week [ ] (1-52) Date [ ]

Please tick when the bath, shower, wash handbassin, and other hot water is used in the bathroom.

BATH

Time	*Example*	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00								
01:00								
02:00								
03:00								
04:00								
05:00								
06:00								
07:00								
08:00								
09:00								
10:00								
11:00								
12:00								
13:00								
14:00								
15:00								
16:00	*V*							
17:00								
18:00								
19:00								
20:00								
21:00								
22:00								
23:00								

SHOWER

Time	*Example*	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00								
01:00								
02:00								
03:00								
04:00								
05:00								
06:00								
07:00	*V*							
08:00								
09:00								
10:00								
11:00								
12:00								
13:00								
14:00								
15:00								
16:00								
17:00								
18:00								
19:00								
20:00								
21:00								
22:00								
23:00								

WASH HANDBASSIN

Time	*Example*	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00								
01:00								
02:00								
03:00								
04:00								
05:00								
06:00								
07:00								
08:00	*v*							
09:00								
10:00								
11:00								
12:00								
13:00	*v*							
14:00								
15:00								
16:00								
17:00	*v*							
18:00								
19:00	*v*							
20:00								
21:00	*v*							
22:00								
23:00								

OTHER (please specify) [ ]

Time	*Example*	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00								
01:00								
02:00								
03:00								
04:00								
05:00								
06:00								
07:00								
08:00								
09:00								
10:00								
11:00								
12:00								
13:00								
14:00								
15:00								
16:00								
17:00								
18:00								
19:00								
20:00								
21:00								
22:00								
23:00								

2b - Weekly Kitchen DHW consumption

Week [ ] (1-52) Date [ ]

Please tick when the sink, dishwasher, washing machine, and other hot water is used in the kitchen.

SINK (washing dishes)

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
13:00							
14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

DISHWASHER

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
13:00							
14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

WASHING MASHINE

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
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14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

OTHER (please specify) [ ]

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
13:00							
14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

2c – Weekly other DHW consumption

Week ____ (1-52)   Date ____

Please tick when hot water is used in this room. Please also indicate its use.

USE (please specify) ____

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
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14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

USE (please specify) ____

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
13:00							
14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

USE (please specify) ____

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
11:00							
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14:00							
15:00							
16:00							
17:00							
18:00							
19:00							
20:00							
21:00							
22:00							
23:00							

USE (please specify) ____

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00							
06:00							
07:00							
08:00							
09:00							
10:00							
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23:00							