Highlights

1. An in-depth technoeconomic study of the feasibility of using a range of biomass CHP technologies within a community residential context has been carried.
2. Daily and seasonal impacts of load variation on economics have been assessed.
3. The role of thermal storage in terms of system economics is analysed

A Techno-economic Analysis of Small-Scale, Biomass-Fuelled Combined Heat and Power for Community Housing

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Abstract: This paper presents the results of a techno-economic study into the feasibility of a number of biomass fuelled CHP (BCHP) systems when operated in a community housing/mixed use context. Six systems comprising differing technologies have been analysed, with the assumption that the systems operate within an ESCO (energy services company) supply scenario. Actual demand data was obtained for a representative community housing scheme, along with technical performance and cost data on the various biomass CHP systems. Subsequently, an economic modelling tool was developed and a number of operational scenarios were analysed to determine the viability of specific systems and the sensitivity of the results to a range of technical and economic parameters. The impact of thermal storage was also considered in order to optimise heat usage as far as possible. The results indicate that within specific realistic ESCO operating scenarios, biomass CHP can demonstrate positive net present values without the need for capital subsidies. Optimal system design and implementation is critical for profitable operation and it is found that the best economic performance occurs for high load factors when the maximum quantity of both electricity and heat sold onsite is maximised. The results are also found to be very sensitive to a number of the model inputs.

Keywords: Biomass, combined heat and power, economics, community housing, load profiles.

1. INTRODUCTION

1.1 Background

With the current global focus on routes towards low and zero carbon economies, on-site community scale renewable heat and power generation is gaining increasing attention. Of the candidate renewable energy technologies, small-scale wind, photovoltaics (PV), and solar thermal solutions provide both variable and site-specific energy yields, and the relatively low energy densities of such sources means that providing the entire energy needs of a whole community from these technologies is often impractical. In the absence of an available hydro or geothermal resource, non-intermittent on-site renewable energy solutions are limited to heat pump and biomass solutions in most locations, with the latter offering the potential for combined electrical and thermal co-generation capability. Hence there is a significant current interest in small-scale (defined here as 30kW$_e$ to 1MW$_e$) biomass-fuelled combined heat and power (BCHP) technologies. Such BCHP systems can operate using liquid, gaseous or solid fuels, including various waste streams, of which there is a considerable and underused resource base available [1].

Previous research into the techno-economic viability of BCHP includes an early study of various biomass to electricity systems [2]. This showed direct relationships between delivered feedstock cost and cost of electricity generated at each output level and conversion technology, whilst all systems were relatively sensitive to changes in overall capital cost and conversion efficiencies. A 2002 study [3]of biomass gasification CHP of 0.5-3.0MW$_e$ showed that feedstock moisture content had a significant impact on cost of electricity (COE), with a lowest COE of 8.67c/kWh for a biomass cost of €30/dtand that for every €10/dt increase in biomass cast, the cost of electricity increased by around 0.9c/kWh. Another study focussed on Eastern Greece [4], which showed that system viability was enhanced when a capital subsidy was available, the annual operating hours of the unit were relatively high, the self-consumption level (or the on-site electrical loads) supplied is high and the cost of fuel is reasonable and stays relatively stable. A more recent study evaluated biomass trigeneration (TG) versus CHP and power only (PO) generation within a commercial context and found that [5] the high capital cost of the TG plant reduces the economic viability for small scale systems, whilst the PO configuration suffers as the heat energy of the system is not recovered. The TG system economic performance was also better in a building with a higher cooling load spread over a 12 month period. The study also indicated a relatively small variation in breakeven electricity selling price from one fuel to another. An integrated study of bioelectricity options [6] explored key lifecycle impacts for 250kW to 25MW systems and found that carbon savings per unit of electricity generated varied little for the candidate systems with only small distinctions from one system to the next. Stakeholder analysis also indicated that small and medium scale heat and CHP are preferable to large-scale electricity supply, as a use for local wood resources. These uses were believed to be better performing environmentally and socially. It should be noted that the current study differs from previous work in its focus on demand analysis, operating conditions and thermal storage aspects.

In the present study, the the focus is primarily on solid wood fuel in the form of woodchip which can be produced from sources such as clean industrial and commercial wood waste, tree surgery waste and forestry residues to name a few examples. However, where such biomass waste streams are utilised, consideration should be given to factors such as legislative constraints on usage, environmental impact and effects on equipment. A range of regulations and directives control how and where biomass derived fuels and conversion technologies can be used, and these need to be understood before a biomass heat or power generation project is initiated. For example, whilst the EU's Waste Incineration Directive [7] specifies comprehensive and relatively costly post-combustion gas treatment, untreated wood waste and residues from agriculture and forestry are excluded from its scope. Consideration also needs to be given to the potential impacts of poor fuel quality on equipment operation and control; provided appropriate fuel quality control measures are implemented, effects on plant are manageable [8]. With increasing use of biomass for energy production, questions have arisen about the sustainability of differing types of bioenergy. In terms of life-cycle impacts, a recent UK study [9] on wood-fuelled boilers indicated an embodied energy and carbon payback period ranging from 4-10 months, with direct combustion emissions being of the most significant environmental impact, and a correlation being evident between plant load and lifecycle emissions of specific gas species. It should be noted that considerations of lifecycle carbon emissions are likely to become a significant factor in assessing the sustainability of bioenergy systems, and as such those platforms that offer the highest overall operational efficiencies, especially when offsetting highly carbon intensive fossil energy supplies may have an advantage in applications that include full life-cycle analyses.

1.2 Aims and Objectives

Since the steam-cycle technology traditionally used in large-scale biomass CHP systems proves to be inefficient and relatively expensive when applied at small-scales, alternative systems have been developed to serve small-to-medium scale applications in developments such as housing complexes, leisure centres and industrial units. This study considers a number of commercially available systems based on organic Rankine cycle (ORC), gas turbine, Stirling engine and internal combustion platforms, with either direct combustion or gasification fuel conversion methods. Additional previous studies [10],[11] have assessed the feasibility of small-scale CHP in general terms for the purposes of aiding decision making and supporting technology development. In contrast, this study focuses on a specific application, namely a community housing development typical of a type and scale where biomass CHP may be considered, and explores in detail the technical and economic performance of the systems within this context. The analysis is performed from the perspective of an Energy Services Company (ESCO) responsible for the installation and maintenance of the system and the sale of heat and electricity to the residents of the housing development. This model of energy supply is gaining increasing attention internationally, and is often preferable for stakeholders such as developers or local authorities who wish to manage technical and financial risks associated with installing and operating schemes based on relatively new technologies and supply chains [12]. Additionally, within a community energy context, it is possible that preferential electricity and heat tariffs could help alleviate energy poverty for low income clients. In this case, an ESCO would sell locally generated heat and power at discounted tariffs compared to mainstream utility companies; however, any shortfall would need to be imported which may be at a loss depending on relative tariff structures. For this reason correct plant sizing is very important, along with the capability for any surplus electricity to be sold back to a utility via the grid. If additional benefits such as feed-in-tariffs, capital grants or levy exemptions can be earned on electrical or thermal generation, this can provide an additional income stream and helps to improve system viability. Residential developments offer a potentially attractive proposition to ESCOs, as domestic energy tariffs are typically higher than commercial rates, and so a higher price can be charged than would be the case at an industrial complex or leisure centre, for example.

2. METHODOLOGY

2.1 Technology Platforms

In contrast to standard natural gas fuelled CHP systems which almost invariably use internal combustion engines at small scale, BCHP systems vary widely in the technologies used and consequently in their performance characteristics. This is particularly true of systems using solid fuel as it must be converted to a form suitable for combustion in a gas engine, or otherwise unconventional prime movers must be used to generate electricity. Heat exchangers are then used to recover the waste heat. A range of systems with electrical outputs ranging from 35 to 400 kWe have been analysed and are described briefly here. All systems can be operated on waste derived fuel, and the solid fuel systems can all operate on woodchip feedstock.

2.1.1 Gasifier and Internal Combustion Engine (ICE)
Solid biomass in the form of woodchip is converted to combustible gases by heating in a reduced oxygen environment in a downdraft gasifier. The gas is cleaned and combusted in a modified spark ignition or compression ignition engine.

2.1.2 Organic Rankine Cycle (ORC)
Solid biomass is combusted directly and the heat used to generate electricity in a closed Rankine cycle, similar to a traditional steam turbine system. However instead of using steam, which is inefficient and uneconomic at small scales, an organic fluid such as silicone oil or an alkylbenzene [13] is used in conjunction with a small turbine to increase the electrical efficiency of small systems.

2.1.3 Indirectly Fired Gas Turbine (IFGT)
Solid biomass is combusted directly. Electricity is generated via a small turbine operating in an open cycle. The heat from combustion is transferred via a heat exchanger to the working fluid, in this case compressed air, which is expanded through the turbine to generate electricity [14].

2.1.4 Stirling Engine Systems
The Stirling Engine is a reciprocating external combustion engine. Any source of heat can be used, so systems using direct combustion of biomass or burning product gas from an updraft gasifier have been developed. The use of a gasifier results in higher electrical efficiencies, and the updraft gasifier is inherently more efficient than the downdraft type. Problems associated with high levels or tars in the product gas are less of an issue than when the gas is burned in an ICE as the gas does not come into contact with the inner workings of the Stirling Engine.

2.1.5 Vegetable Oil-Fired Internal Combustion Engine
Provided rigorous feedstock quality control is implemented, refined used cooking oil (UCO) from the food industry can be combusted in a modified internal combustion engine. There is competition for this feedstock from the biodiesel industry and as such the resource is limited [15], but UCO can be used more efficiently in a CHP unit and is not subject to the same level of sector-specific taxation as it is when used as a transport fuel. Fuel prices are higher than solid fuel, but it has a higher energy density and capital costs are significantly lower than solid fuel systems.

2.2 System Data
For each of the above technologies, systems were chosen from manufacturers in the EU and USA that specialise in a particular technology and have systems in commercial operation where possible. Technical and capital cost data for all candidate systems are given in Table 1 whilst table 2 shows other baseline economic parameters, including energy purchase . Capital and operational cost and energy sale price data were obtained from communications with individual manufacturers of each technology platform and systems integrators, along with reference to published sources from the EU and US and communications with utility companies [16],[17],[18],[19]. Reference was also made to the Chemical Engineering Plant Cost Index, with sub-system capital costs (including heat distribution infrastructure) included to assess the total capital cost needed to provide an operational system. For the current study, the installation of a single module was assumed in order to assess optimal development sizes for this single module scenario. Were multiple module installation to be considered, incremental capital and operational cost reductions accruing from the increased scale of installation should be considered as described in previous studies [20], [21].

With regards cost of feedstock, recent (2007-2010) cost estimates of bulk UK biomass feedstock (including uncontaminated forestry waste) range from €20 – 80 per tonne [22],[23],[24]. However, although not included in the current study, consideration should also be given where relevant to costs related to the establishment of dedicated supply chains and processing equipment that sources such as forestry residue, straw and short rotation coppice (SRC) may require.

For the external combustion engine platforms, electrical efficiencies are generally lower than those using internal combustion, and the technology is less mature in terms of numbers of commercially installed operational units. However, external combustion allows less stringent controls on impurities in combustion products and feedstock requirements, and has the potential for better reliability and lower maintenance requirements. Overall efficiencies are also slightly higher due to the lack of an intermediate conversion stage and associated losses. For comparative analysis across platforms, modelling was carried out for a single BCHP unit of each type within a community housing context. In reality, multiple BCHP units may be deployed in a modular fashion, depending on the thermal and electrical outputs of the generator and the scale of the housing development.

Table 1: Biomass CHP System Information. Key: ORC = Organic Rankine Cycle; IFGT = Indirectly Fired Gas Turbine; ICE = Internal Combustion Engine

Table 2: Baseline Input Financial Parameters

2.3 Model Development

A numerical cashflow model was developed in order to assess the economic performance of the candidate BCHP platforms, using both system and demand data as inputs. Assessment of economic viability was carried out using a net present value (NPV) analysis for each platform. NPV is a measure that expresses the initial capital investment and all subsequent cash flows arising from imported energy costs and sales of generated energy as an equivalent amount at time zero. This approach is particularly appropriate when the cash flows associated with a single project or several competing alternatives vary over time, as is the case with a typical BCHP investment. The net present value of a cash flow at time *t* is given by:

$$NPV = \sum_{t=0}^{n} \frac{A_t}{\left(1+d\right)^t} \qquad (1)$$

where A_t is the project's cash flow (revenues minus costs) in time *t*, with *t* taking values from year 0 to year *n* and *d* is the discount rate (an interest rate used to calculate the present value of future cash flows). When the calculated NPV is positive, the investment results in a rate of return greater than our minimum rate *d*, and in the absence of alternatives this would be a profitable investment. However, when the NPV is negative, the investment would not give a return at the minimum rate *d*, and indicates a non-profitable investment.

The cashflow model allows the operation of the system to be adjusted hour by hour and allows many different scenarios to be evaluated, as described below in Section 3.4.

Although only community housing was considered in this study, the model allows demand profiles for any development to be analysed if suitable data is available. Likewise, other base case assumptions may be adjusted depending on the specific context in which the model is applied.

3. RESULTS AND DISCUSSION

A techno-economic iterative analysis for each system was carried in which a sequence of improving approximate solutions (i.e. improved net present value) was analysed in conjunction with technical aspects, as a scenario that may appear economically attractive may not be technically feasible, and vice-versa. Initially, the analysis assumed no thermal energy storage capacity is available to address generation/load mismatch. Subsequently, the impact of short term (diurnal) thermal storage is assessed.

3.1 Demand Profiles

To simulate a typical social housing development, heat and electrical load profiles were generated using real data. Electrical profile data were obtained from an International Energy Agency programme [25] which has the specific remit of producing such profiles for simulating performance of CHP systems, and is ideally suited to this study. The data used is 5-minute averaged electricity demand data for 69 social housing properties in the UK. The data was manipulated to give hourly average data for use in the model.

The heat demand profiles are based on real hourly average data from a 1,000 home community housing development, obtained from an independent study [26]. Since the two profiles were from different sources and concerned developments of differing sizes, the profiles were scaled to give an electric to heat ratio equal to the national average for UK social housing of 0.28, based on total yearly energy consumption [27]. The resulting electrical and heat profiles for a 100 dwelling development are shown in Fig. 1 and 2 respectively. Based on these studies, and in order to guage the annual energy requirements of the community, thermal and electrical energy use per dwelling were calculated as approximately 16,500kWh/yr and 4,600kWh/yr respectively.

An average dwelling size of 75m^2 was assumed based on the average size of the properties in the electrical demand study [25]. Using this dataset, various development sizes can be modelled with the profiles being scaled accordingly.

Figure 1. Daily electrical demand profiles used in the analysis.

Figure 2. Daily thermal demand profiles used in the analysis.

3.2 Scenarios
Developments ranging in size from 50 to 1,000 dwellings were considered. Five modes of operation of the CHP plant were analysed:

- On continuously.
- On between 06:00 and 24:00 every day.
- On between September and May, off in summer.
- Electrically led.
- Heat led.

For the electrically and heat led scenarios only, BCHP operation was controlled using the demand scenarios described above, and the BCHP plant was set to modulate to match the hourly electrical or heat demand, or provide rated output when demand exceeds maximum output. The analysis is optimistic as it is assumed that efficiency is constant at partial load, whereas some reduction in part-load efficiency may be expected in reality. For the continuous and time-controlled modes, BCHP operation was not matched to demand scenarios, whilst electrical energy deficits were supplied via import from the grid. Revenues resulting from on-site electrical and heat energy sales were based upon relevant demand profiles, along with temporal calculations for excess heat generation. It should be noted at the outset that specific non-heat or electrically led scenarios may offer improved economic feasibility but at the expense of lower system efficiencies as a significant proportion of generated heat is surplus to requirements. The model was used to determine the economic performance of each system for each mode of operation and development size. In all cases it has been assumed that surplus electricity can be exported via a Utility Power Purchase Agreement (PPA) or similar arrangement [29].

3.3 Development Size and Operation Mode
A sample analysis showing the effect of operating mode for the downdraft gasifier ICE platform is shown in fig. 3, which is typical of all platforms except the oil fired ICE system. For all solid fuel systems the most financially attractive operational mode is found to be continuously on, day and night, all year round. This is the case for all development sizes. The reason for this is the relatively low price of wood fuel compared with imported gas and electricity, and the relatively high net electrical export price using base case assumptions. The fuel price must climb considerably higher than the base case figure of €62/ODT before it becomes preferable to switch the unit off in times of low demand. However, high fuel prices result in systems that are invariably uneconomic regardless of how they are operated as seen in fig. 4. This is the case assuming electricity can be exported; without export the effect is to render the larger systems uneconomic, highlighting the importance of having a grid connection and a PPA or similar arrangement. Running continuously is also consistent with the best way to operate the system from a technical viewpoint. This is however at the expense of lower overall system efficiencies as a higher proportion of generated heat is rejected.

Figure 3. Effect of operational mode for a downdraft gasifier based system.

Figure 4. Effect of feedstock price on BCHP economics.

The exception is the vegetable oil fuelled system, for which the fuel price is higher than the gas import price. This means it is preferable to follow the heat demand for a development of up to 900 dwellings, and above that to follow the electrical demand. The system performs optimally for a 1,000 dwelling development, so should be electrically led for optimum economic performance. However, using base case assumptions, the NPV is negative for all modes of operation though the performance of this system is very sensitive to specific parameters, such as the on-site sale price as a proportion of import price and feedstock fuel prices.

Figure 5. Effect of community development size on BCHP economics.

3.4 Economic Analysis: Base Case Results
The results of the economic analysis using initial base case assumptions (Table 2) can be seen in Fig. 5. The economic performance of each system is presented in terms of the Net Present Value (NPV) based on a 15 year project life. Given no capital grant availability, none of the systems are predicted to have a positive NPV when installed in any size development, though all the solid fuel systems come close to break even in specific circumstances. The vegetable oil-fuelled system performs particularly poorly. It is apparent that the various systems perform optimally at differing development sizes. It should be noted that the results indicated in Fig. 5 only apply under the base case conditions.

There are many variables which, when adjusted, may significantly affect the economic performance, hence results presented here are indicative only and should not be considered in isolation. Subsequent analyses consider some of these variables in detail.

The optimum development size and operating modes for each system are shown in Table 3. All subsequent analysis is based on the optimum operating conditions for each system in Table 3.

Table 3. Optimal community development size and operational modes for candidate BCHP systems.

3.5 Thermal Storage

Thermal storage can be used to smooth peaks and troughs in demand from hour to hour, resulting in more efficient operation. A simple assessment of the impact of thermal storage on the economics and efficiency of biomass CHP has been performed; assuming all excess heat on a particular day is stored with an efficiency of 90%, and released where demand exceeds supply.

3.6 Impact of Capital Grants and Tax Relief

It is not the aim of this study to analyse capital funding and other support measures in detail. However, where capital subsidies or tax allowances (such as enhanced capital allowances, where up to 100% of the capital cost of sustainable energy equipment may be written off against corporate tax liabilities) are available, significant impacts on viability are apparent. For example, a 100% corporation tax relief on the investment would typically lead to an effective reduction of 7 – 8% on the capital cost. In this study, the impact of a 50% capital grant on the economic viability is presented below in Fig. 6. In this case, all the solid-fuel systems return a positive NPV for specific ranges of development sizes.

Figure 6. Effect of a 50% capital grant on BCHP economics.

3.7 Impact of Feedstock Price

The maximum fuel prices that return a positive NPV under base case conditions are shown for each system in Table 4. It comes as no surprise that the economic performance is sensitive to the fuel price. All the solid fuel systems considered in this study operate on woodchip. Although feedstock prices can be very volatile, if prices of around €40 per ODT or less are available (which probably limits feedstock to bulk waste-derived biomass and could require enhanced fuel quality assessment procedures), this will enable solid fuel systems to return a positive NPV without any additional support [28]. With the 50% capital grant particularly higher fuel prices are necessary before the economic performance becomes unfavourable, which has the advantage of reducing the risks associated with fluctuating fuel prices in an immature market. The fact that systems can operate profitably even on relatively expensive feedstock should be seen as an incentive for the wider expansion of wood fuel producers to help stimulate the biomass CHP market. Long term, fixed price fuel contracts would do much to reduce the financial risks and encourage investment.

It should be noted that fuel price is particularly critical for the financial performance of the vegetable oil system. A variance of just 5c/litre results in a change of up to €850,000 in NPV over the lifetime of the system.

Table 4: Maximum Fuel Prices Required to Return Positive NPV

3.8 Electricity and Heat Revenue

In community energy supply scenarios, an ESCO will often strive to provide heat and electricity to residents at a competitive price compared to a mainstream energy supplier. Minimising wholesale energy import prices (along with energy purchased to meet any on-site generation shortfall) whilst maximising electricity export prices via a PPA (to increase the value of any excess electrical generation) can be seen to improve economic viability. An NPV analysis showing the impact of net revenues is shown in Fig. 7, assuming a capital grant of 50%. This shows on-site energy selling prices expressed as a percentage of the import prices of electricity and gas needed to meet any daily and seasonal shortfall. The analysis indicates that all solid fuel systems become economically viable as the price obtained for on-site electricity and heat sales exceeds 50-60% of the import price. However, for an optimal continuous operation scenario, whilst electrical and thermal net revenues are maximised., there is a drawback in that a significant proportion of generated thermal energy may need to be rejected (especially during the summer months). The larger systems are more sensitive to this parameter as they are selling a larger quantity of heat and electricity to on-site customers. The vegetable oil system becomes rapidly unprofitable as the sale price falls below 80% of the import price, though this is again highly dependent on the feedstock fuel price.

Fig 7. Effect of relative electricity and heat sales price on BCHP economics.

At the time of writing, two key renewable energy generation-based incentives are in place or under consideration in the UK, namely the electrical Feed in Tariff (FIT) scheme (for which BCHP is not eligible) and the forthcoming Renewable Heat Incentive scheme, which currently does include BCHP within its current list of eligible technologies [30]. In the current study, the effects of the prospective RHI tariffs have not been included in the analysis; however their potential impact can be assessed by assuming an additional heat sale price of between 3.0C/kWh and 8.7C/kWh, the effects of which can be seen by referring to the sensitivity analysis in figure 7. A similar approach can be employed to assess the impact of comparable energy generation incentives in other countries. Clearly, it is important to consider the impact of technical factors (such as electrical and heat generation efficiencies) when assessing the impact of specific electrical and thermal generation incentive schemes. In particular, the eligibility of BCHP in countries which currently have in place electrical generation-based incentives needs to be carefully assessed.

3.9 Impact of Financial Parameters

The underlying financial assumptions during the lifetime of the project such as discount rate and inflation rate have a significant effect on the BCHP project economics. Given that such parameters are highly circumstantial, the base case assumes fairly pessimistic figures due to uncertainties associated with technology risk and the market, so as not to present a misleading or overly optimistic picture. The results of a sensitivity study to model the effects of varying the discount rate is shown in Fig. 8, assuming no capital grants apply. It can be seen that the larger systems are more sensitive to variations in discount rates; the downdraft gasifier ICE and direct combustion ORC systems perform particularly well when discount rates are below 8%.

Figure 8. Effect of discount rate on economic viability of candidate BCHP systems

3.10 Effect of thermal storage

The optimum operating conditions for the systems as described in section 2 give the best performance from an economic perspective assuming that generated heat cannot be stored. However, for this scenario, a significant proportion of the heat generated has to be disposed of. If this waste heat, which occurs at times of low thermal demand, could be stored it can then be used to meet peaks in daily demand, thus increasing heat sale revenue and increasing the overall efficiency of the system. Also, from a sustainability point of view, less fossil fuel needs to be imported thus reducing CO_2 emissions and more efficient use of biomass resources.

Fig 9. Proportion of heat rejected for candidate BCHP platforms operating under optimal economic conditions.

Fig. 9 shows the proportion of heat that must be rejected for each system in its economically optimum operational mode with and without short-term daily thermal storage, assuming negligible heat dissipation over this time scale. It should be noted that the year-round impact of thermal storage is limited as it cannot be utilised effectively in the summer months since heat supply significantly exceeds demand for a high proportion of the time. The effect of storage on the NPV of each system is shown in Fig. 10, assuming base case assumptions, a 50% capital grant and zero cost for the storage system. For this scenario, the difference in NPV values for systems with and without storage represent the maximum viable cost of thermal storage when operating optimally from an economic viewpoint. Table 5 shows these data for each technology platform operating under optimum operational (including the optimal number of dwellings for each platform). It can be seen that systems with higher power to heat ratios generally benefit from higher levels of storage, and that specific maximum thermal storage costs (in terms of Euros/kWh) vary widely across platforms. This comparison is useful in enabling the economic feasibility of storage options for various scenarios to be assessed, especially where system efficiency and flexibility are important factors. Overall efficiency could be further improved by utilising the waste heat for summer-time absorption chilling or distributing to nearby non-domestic clients with complementary heat demand profiles if this is possible [31].

Fig 10. NPV analysis for candidate BCHP platforms operating in optimal economic mode and assuming a 50% capital grant.

Table 5: Maximum thermal storage investment costs for candidate BCHP platforms under optimal operating conditions.

4. CONCLUSIONS

The economic viability of small-scale biomass CHP is dependent on a number of parameters, but the results of this study indicate that appropriate sizing of BCHP systems for specific developments and electrical and thermal load profiles is a crucial factor. The availability of up to capital grants, low interest loans or renewable energy generation tariffs can result in a positive NPV for all the solid fuel systems in specific scenarios. However, these scenarios are very sensitive to a number of financial parameters such as energy sale and import prices, fuel feedstock costs and discount rates. Where cost effective fuel supplies are available, all the considered systems can be viable without capital grant incentives, especially if beneficial net revenue streams arising from energy sales and generation-based incentives apply. It has been shown that the optimum operational mode for all the solid fuel systems is continuous operation, with the exception of the vegetable oil ICE system which is more economically viable in electrically led mode.. In terms of the optimum development size for a given generating platform, this occurs when the maximum quantity of electricity and heat is sold onsite, as excess heat is wasted and exported electricity is generally of lower value than that sold onsite. In general, smaller systems are less profitable than larger platforms. In summary, this study demonstrates that small-scale biomass CHP can be economically feasible at the current time provided appropriate deployment circumstances pertain, and presents a potentially environmentally attractive method of generating electricity and heat using biomass feedstock.

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Table 1

Description	Electric Power (kW)	Thermal Output (kW)	Electrical Efficiency	Overall Efficiency	Power: Heat Ratio	Approx Installed Cost (Euro)	Specific Cost (Euro/kWe)
Direct Combustion, ORC	200	980	14%	85%	0.20	1,250,000	5,950
Direct Combustion, IFGT	100	200	20%	80%	0.50	635,000	6,248
Downdraft Gasifier, ICE	250	500	23%	70%	0.50	1,350,000	5,355
Direct Combustion, Stirling Engine	35	215	12%	86%	0.16	250,000	7,140
Updraft Gasifier, Stirling Engine	35	145	18%	90%	0.24	250,000	7,140
Modified ICE	400	630	33%	85%	0.63	900,000	2,231

Table 1: Biomass CHP System Information. Key: ORC = Organic Rankine Cycle; IFGT = Indirectly Fired Gas Turbine; ICE = Internal Combustion Engine

Table 2

Parameter	Base Case Value
Fuel Heating Value (Solid)	19 MJ/kg
Fuel Heating Value (Oil)	37 MJ/kg
Fuel Cost (Solid)	€62/ODT
Fuel Cost (Oil)	40c/litre
Availability	100%
Operation & Maintenance Cost	1c/kWh
On-site Electricity Sale Price	10c/kWh
On-site Heat Sale Price	2.5c/kWh
Electricity Import Price	12ckWh
Gas Import Price	2.8c/kWh
Renewable generation tariff	3.4c/kWh
Utility power purchase price	8c/kWh
Project Period	15 years
Inflation rate (RPI)	4%
Discount rate	10%

Table 1: Baseline Input Financial Parameters

Table 3

System	Number of Dwellings	Operation Mode
Direct combustion, IFGT	200	Continuous
Downdraft Gasifier, ICE	500	Continuous
Direct combustion ORC	500	Continuous
Direct Combustion, SE	100	Continuous
Updraft Gasifier, SE	100	Continuous
UCO Genset	1,000	Electrically Led

Table 3. Optimal community development size and operational modes for candidate BCHP systems.

Table 4

System	**Maximum Fuel Price for Positive NPV (€/ODT)**	
	No Support	**50% Grant**
Direct Combustion, IFGT	43	118
Downdraft Gasifier, ICE	56	112
Direct Combustion, ORC	56	93
Direct Combustion, Stirling	42	81
Updraft Gasifier, Stirling	45	100
Vegetable Oil Genset	26c/litre	34c/litre

Table 4: Maximum Fuel Prices Required to Return Positive NPV

Table 5

System	Power to heat ratio	Maximum Storage Expenditure (Euro)	Storage Capacity (kWh)	Storage Capacity (kWh/ dwelling)	Maximum specific storage cost (Euro/kWh)
Direct Combustion, IFGT	0.20	32,000	1150	5.8	23.17
Downdraft Gasifier, ICE	0.50	79,000	2875	5.8	23.15
Direct Combustion, ORC	0.50	109,000	5910	11.8	15.47
Direct Combustion, SE	0.16	18,000	1240	12.4	12.30
Updraft Gasifier, SE	0.24	20,000	767	7.7	22.27
UCO Genset	0.63	95,000	3542	3.5	22.51

Table 5: Maximum thermal storage investment costs for candidate BCHP platforms under optimal operating conditions.

Figure 1

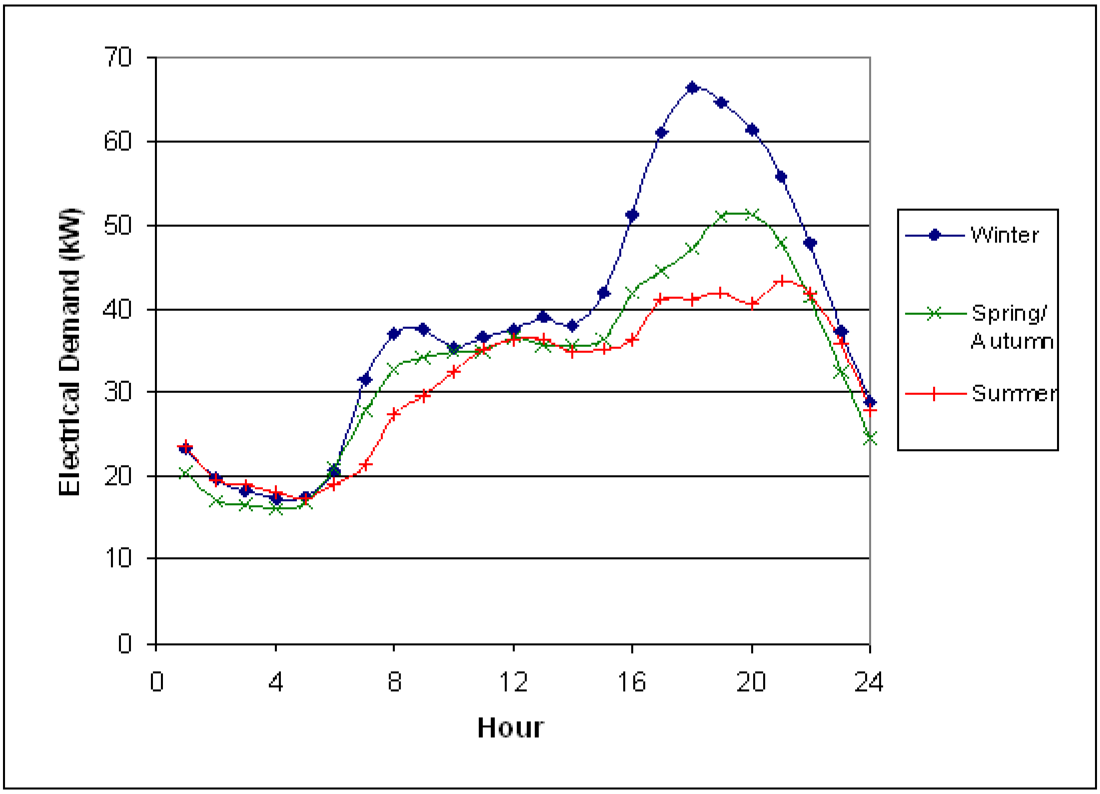

Figure 1. Daily electrical demand profiles used in the analysis.

Figure 2

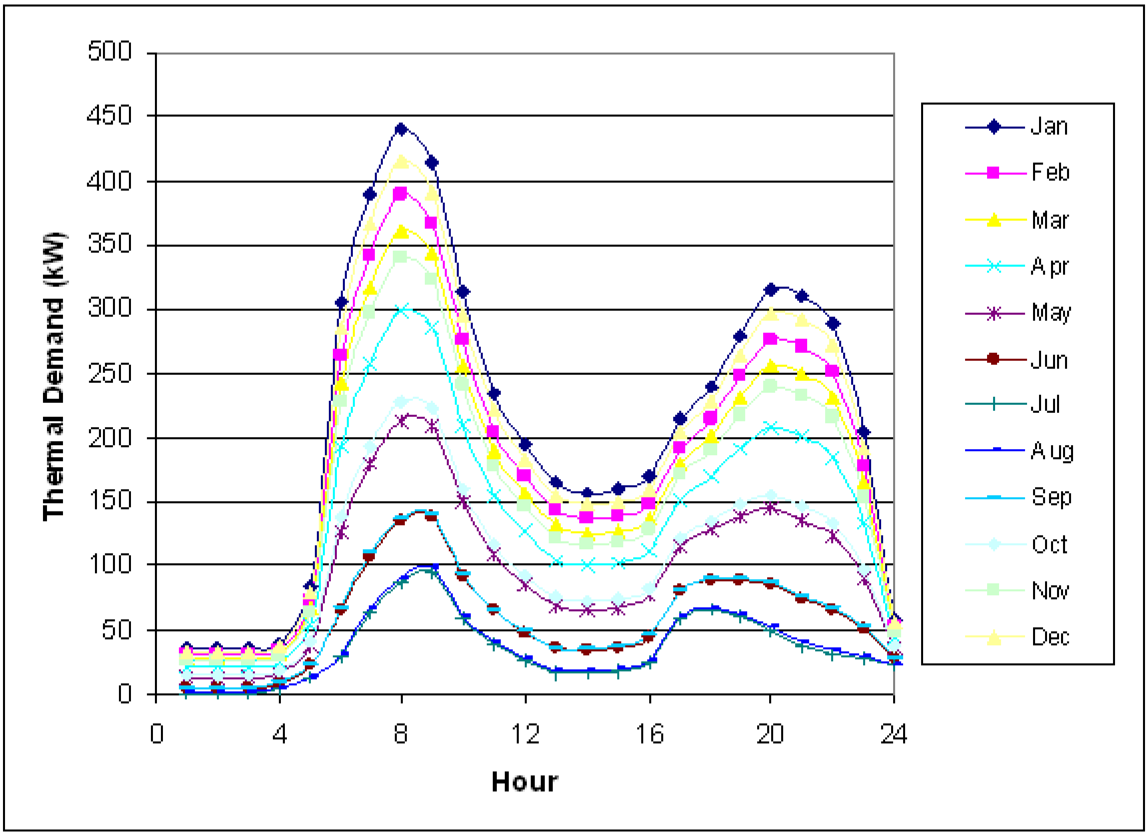

Figure 2. Daily thermal demand profiles used in the analysis.

Figure 3

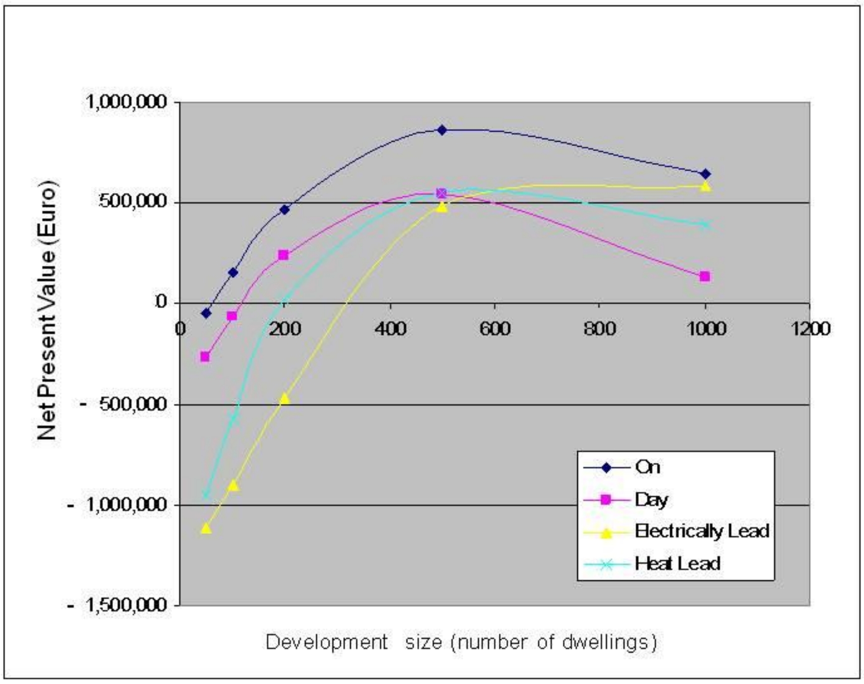

Figure 3. Effect of operational mode for a downdraft gasifier based system.

Figure 4

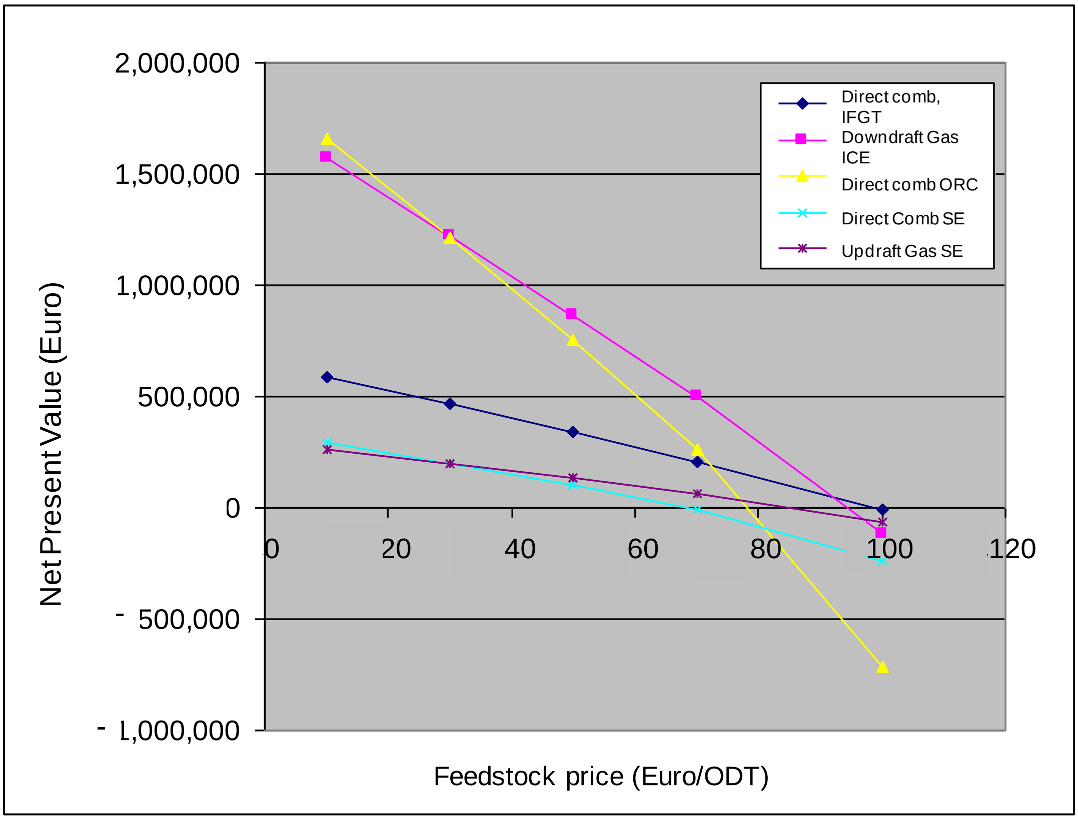

Figure 4. Effect of feedstock price on BCHP economics.

Figure 5

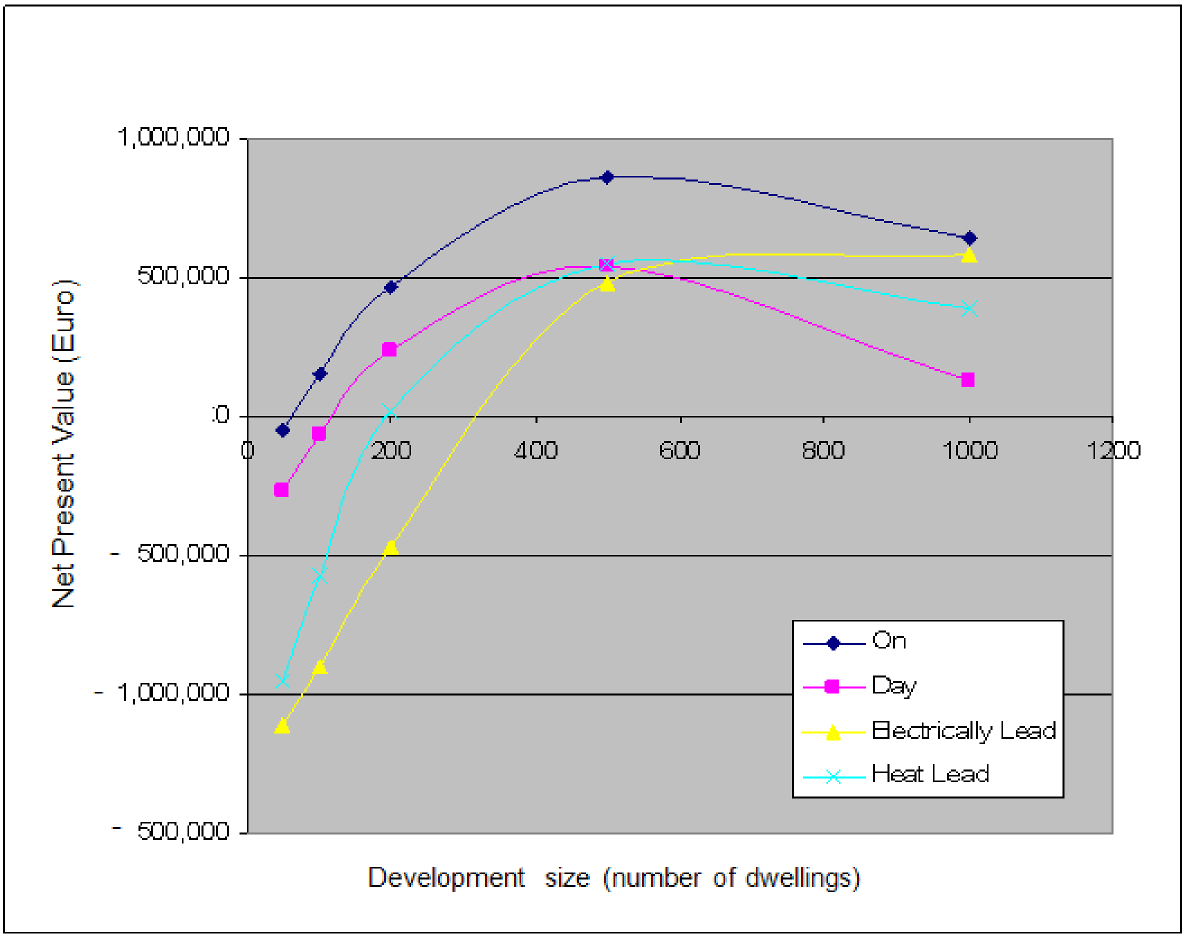

Figure 5. Effect of operation mode on downdraft biomass gasifier ICE system economics

Figure 6

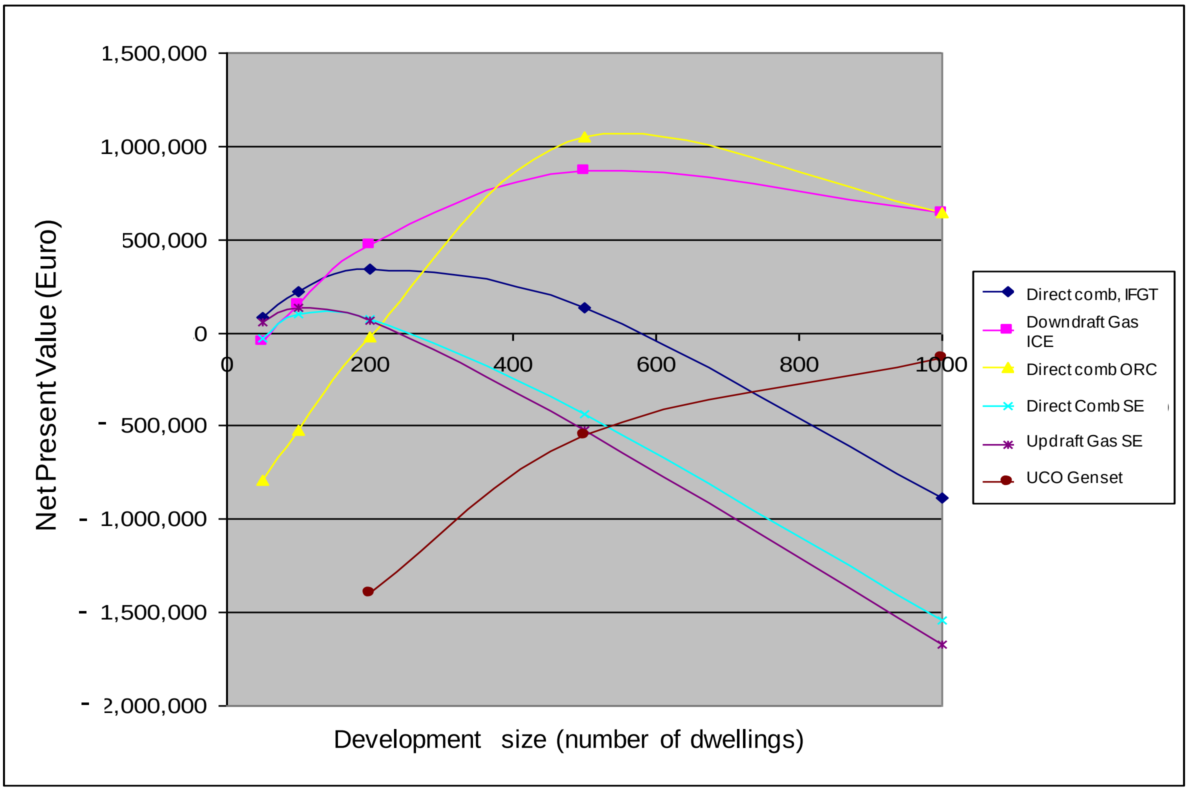

Figure 6. Effect of a 50% capital grant on BCHP economics.

Figure 7

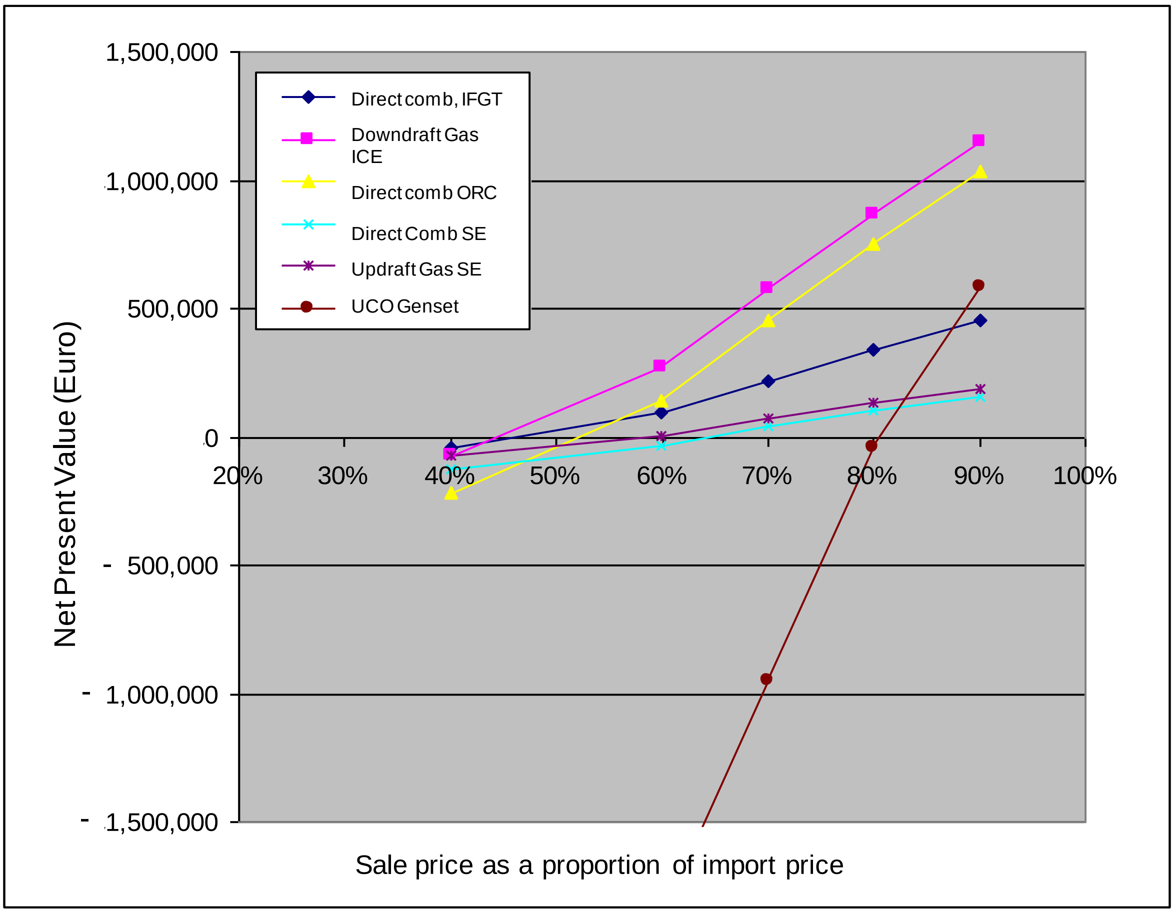

Fig 7. Effect of relative electricityand heat sales price on BCHP economics.

Figure 8

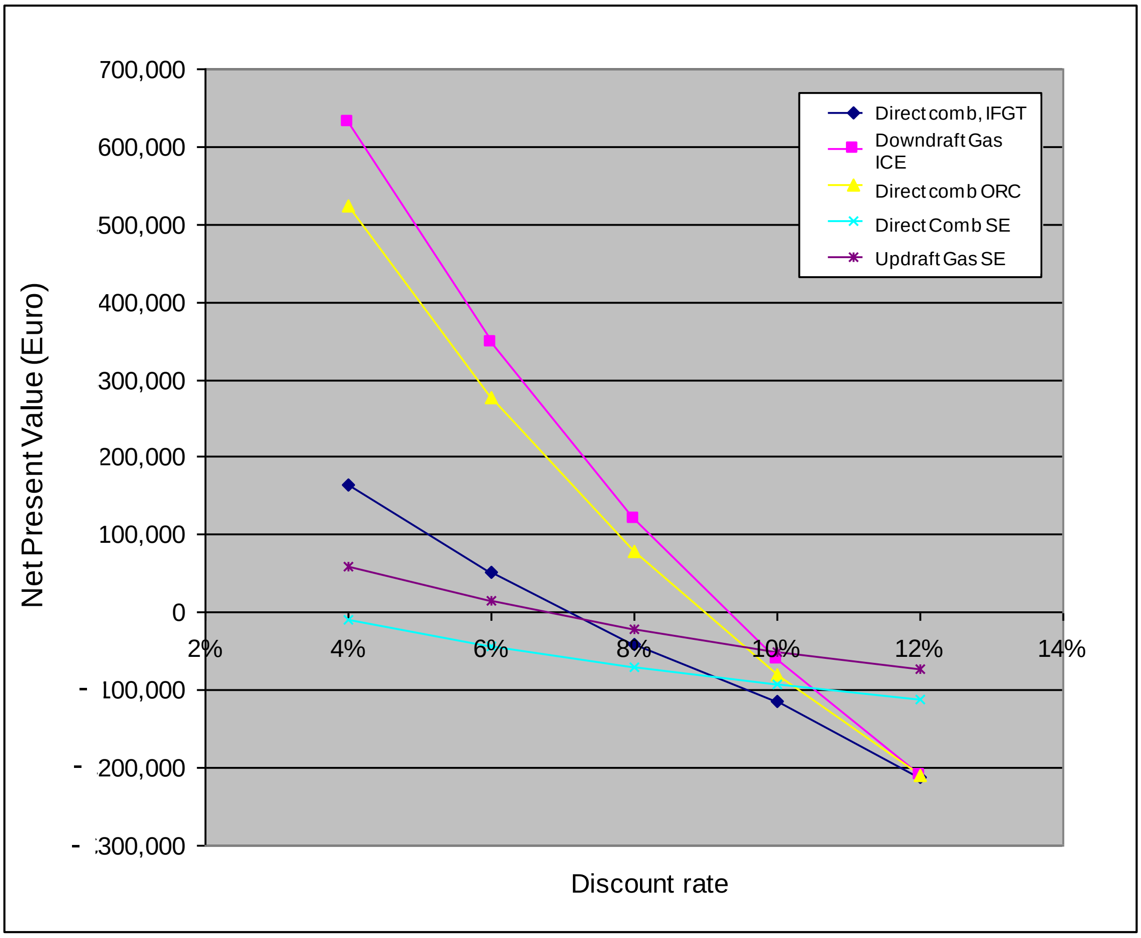

Figure 8. Effect of discount rate on economic viability of candidate BCHP systems

Figure 9

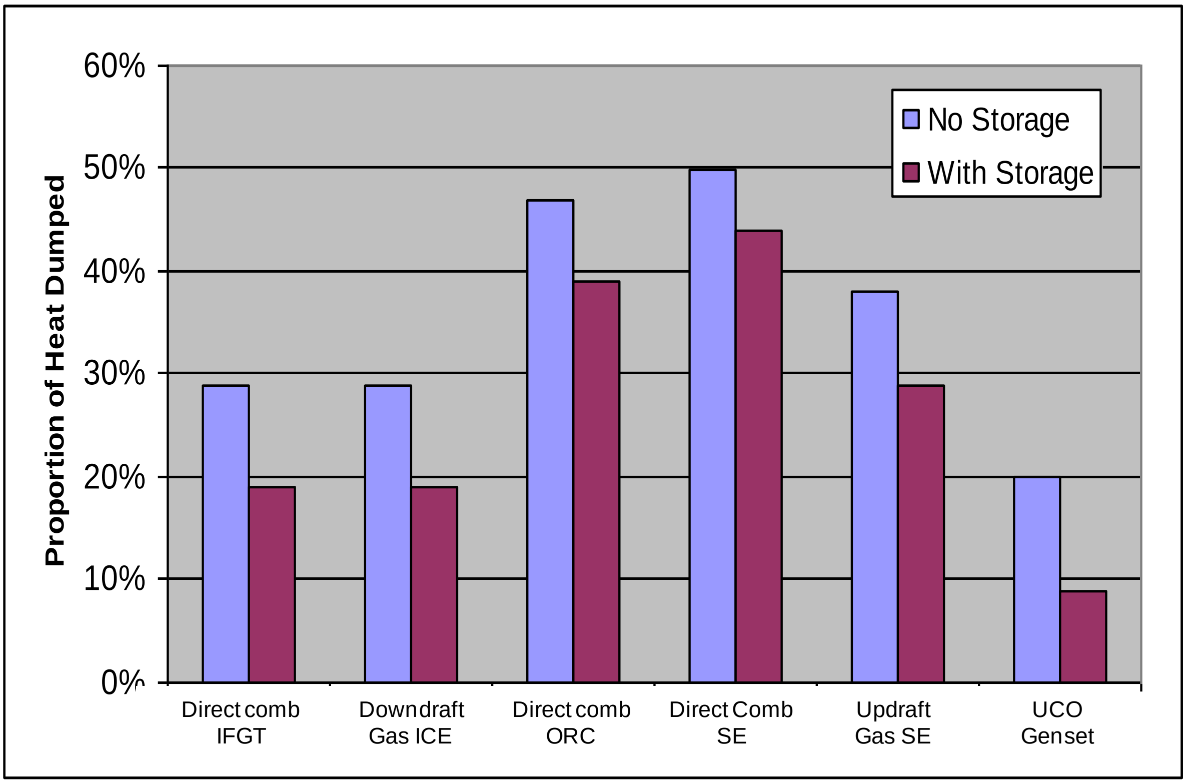

Fig 9. Proportion of heat rejected for candidate BCHP platforms operating under optimal economic conditions.

Figure 10

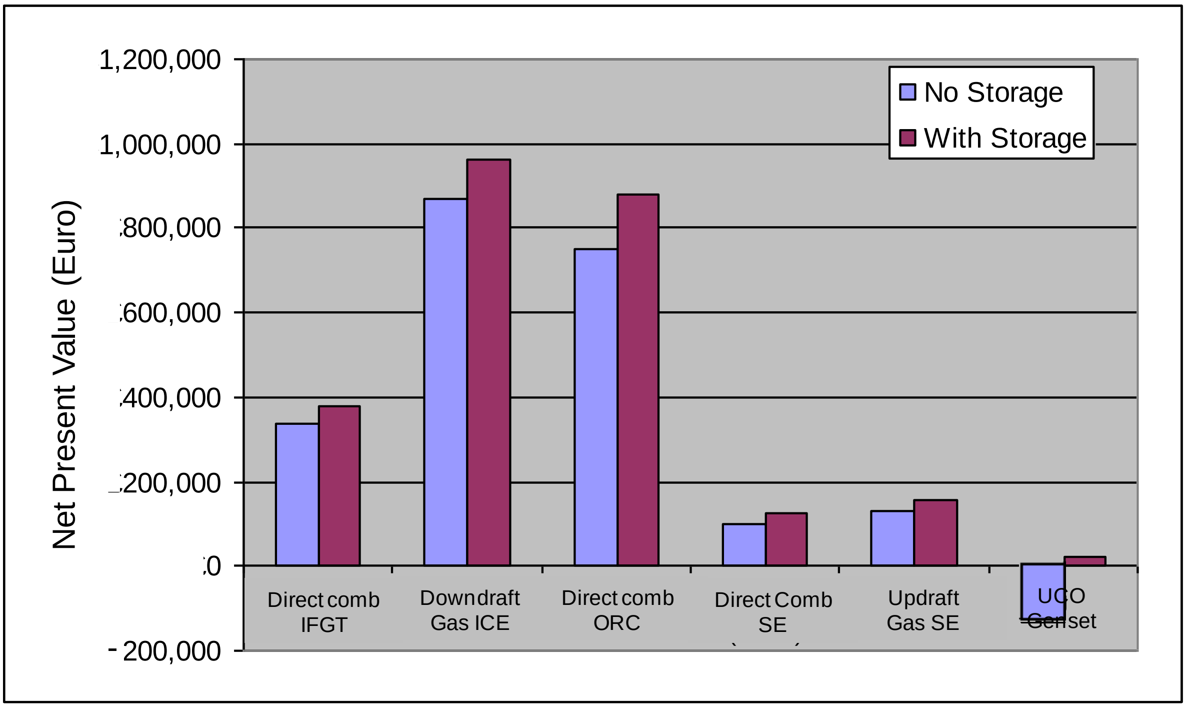

Fig 10. NPV analysis for candidate BCHP platforms operating in optimal economic mode and assuming a 50% capital grant.