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Optimal Design of Combined Heat and Power Plants Using Thermal Stores in the UK:

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Abstract

There has been discussion about the extent to which combined heat and power (CHP) plants with thermal stores are suitable for sustainable energy production and, under certain conditions, for integration of wind energy. At the moment, in the UK the development of this type of plants is limited. This paper analyses the economics and optimum size of (CHP) operating with gas engines and thermal stores in British market conditions assuming that all electricity is exported to the public electricity supply. This is achieved using energyPRO software. It is shown that the use of thermal stores could make the practice of exporting electricity from CHP plant much more profiatble in the UK. Hence this system can improve the overall economics of CHP in the UK. The optimal size of CHP plant (exporting its electricity to the grid) for a heat load of 20000 MWh per year is found to be a 3MWe gas engine with a 7.8 MWh thermal store. In this case the analysis reveals that the use of thermal store more than doubles the return on investments (as measured in net present value). It is concluded that thermal stores will make CHP plants more economic in present British circumstances; therefore, in the future CHP with thermal stores could potentially offer a flexible strategy to integrate fluctuating wind power production as is currently practiced in Denmark.

Keywords: CHP, Sustainable Energy, Thermal store, wind

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1. Introduction

Combined heat and power is the simultaneous production of electricity and heat. Combined heat and power plants (CHP) produce energy in an efficient way by decreasing the fuel consumption while producing the same amount of electricity and heat with the conventional generation, where electricity and heat are produced in separate plants[1,2]. For this reason, CHP and renewable energy sources are the focus of recent research on innovative concepts for sustainable energy production[3,4,5]. Furthermore, CHP technology can be combined with thermal stores which allow the CHP to generate electricity when power prices are high, and go offline when prices are low. They allow CHP plant to store heat when it is not needed, and they allow CHP plant to go offline because heat load can still be met from the stores. CHP plants with big thermal stores offer the possibility for integrating wind energy into the electricity network. This is an established practice for dealing with wind energy fluctuations in Denmark[6,7,8].

In the longer term, it is likely to be the premises, the so called district heating[2]. While the efficiency of the electricity production is thus reduced the overall thermal efficiency of the plant is significantly increased.

It has been observed, in Scandinavian studies, that the installation of a device for storing heat in CHP plant can be desirable on economic grounds. This heatstore is typically called thermal store or heat accumulator[17]. The thermal store is used for short term energy storage. It is a tank with a zone of hot water at the top and a zone of cold water at the bottom[18]. The two zones are separated due to the stratification effect with an approximately 1 metre high non-usable separation layer. The water content in the tank is constant in terms of weight and is independent of the energy content. When charging the thermal store hot water is supplied in the top of the tank simultaneously with extraction of the same amount of cold return water at the bottom. The process is reversed when discharging. The thermal store is connected to the district heating system between the CHP plant and the district heating network. When the heat production is higher that the heat consumption the thermal store is charged and it is discharged in the opposite case.

Thermal storage is a way of dealing with the mismatch between the electricity and heat demand. Typically, the electricity demand is high during morning and afternoon, lower during the rest hours of the daytime and even lower during nigh-time, weekends and holidays. This variation is reflected on the electricity prices, especially prices for exporting electricity to the public supply system.

Typically much electricity generated by CHP plant is consumed ‘in-house’. A major problem in the UK is that electricity export prices have often not been high enough to justify generation by CHP plant for the purpose of exporting electricity to the grid. However, use of thermal stores may make this a more profitable exercise. This is a key focus of our investigations, and in order to simplify our model, we make our calculations assuming that all electricity is exported.

Consequently the prices of the produced or consumed electricity may vary significantly with the time of the day. The heat demand is usually low during the summer and higher during winter. The CHP is worth running when the electricity price is high. If the heat demand is low (e.g. summer daytime), the excess heat is stored in the thermal store. The stored heat can then be used when the electricity demand and therefore the electricity price are low and it is not economical to run the CHP (e.g. night-time). In other cases, the heat stored when the production exceeds the demand the heat can be used when the heat produced by the CHP is not enough to meet the heat load (e.g. winter). If there was no thermal store we would have to size the gas engine to meet the minimum heat demand or to stop or modulate the engine in order to avoid dumping the extra heat. Part load operation of the engine is undesirable because it reduces the engine efficiency. Large numbers of engine starts and stops has a significant negative effect on the performance and the lifetime of the engine[19]. Nevertheless the belief that gas engines are are able to start and stop with lower negative costs, in addition to their relatively low capital costs for small units, accounts for their widespread use in Denmark as the basis of CHP plant with thermal stores.

A further, interesting use of CHP plants with big thermal stores regarding sustainable energy production is for balancing the electricity production from renewable energy sources. This kind of operation presupposes that the CHP plants are decentralised CHP plants and therefore do not deliver frequency or voltage stabilization. This is the case in Denmark, where the wind penetration is high and the electricity production from wind turbines is sometimes as high as the electricity demand in the whole Denmark [6,7,8]: Decentralised CHP plants with thermal stores are at present being used, (indirectly, via the electricity spot market), to balance fluctuating wind energy output. The CHP plants might in the nearby future be widely used for offering system balancing for fluctuating wind energy outputs. The process is described briefly here.

In cases of a sudden increase in electricity production from the wind turbines, it is possible for the decentralised CHP plants to shut down some engines to reduce the amount of electricity produced. Due to the big thermal storage capacity the Danish CHP plants can still deliver heat. In other occasions, the wind turbines may fail to produce the expected amount of electricity. For example, they may have to shut down because of an approaching hurricane. As much as 1500MW[20] can then be obtained from CHP plants since their big thermal stores will be able to accommodate the excess heat produced simultaneously. Consequently large CHP and thermal storage capacities are required for this type of operation . This method of integrating fluctuating productions can be achieved if there is the possibility for CHP plants with thermal stores to aggregate and to act as a ‘virtual big power plant’[1].

Clearly this concept presupposes that there exists an electricity market in the country which allows this type of aggregation. In addition there has to be a sufficient number of CHP plats with thermal stores, of the required size, to aggregate. The investigation of the market conditions in the UK that allow for the aggregation of the CHP units is beyond the scope of this study.

In the UK, at present, most of the CHP capacity is industrial CHP. Such plant does not normally have thermal store. In addition, industrial CHP plants deliver steam and therefore have to follow the steam demand which makes them inflexible and unsuitable for wind turbine integration in the utility network. Therefore, in the UK CHP plants suitable for the integration of wind energy have yet to be developed and as mentioned earlier, there are calls for the amount of non-industrial ‘community’ CHP to be built up. We define community CHP broadly as being CHP deployed in the non-industrial sector. The key difference with industrial CHP is that the bulk of the heat load is likely to be concerned with delivering heated water for heating, and other hot water requirements. This concern with delivering hot water means that thermal stores could be an important part of community CHP developments. Hence it is important to analyse the extent to which thermal stores could make such strategies of decentralised CHP more economic.

In order to assess the optimum sizes of engines and thermal stores and the improvement in plant economics, it is useful to conduct an analysis using variable electricity tariffs that are available in British electricity markets for exported electricity from CHP plant. This is what we do in this paper.

3. energyPRO

energyPRO[15,16] is an input/output software tool which is used for modelling energy systems. It can consider an unlimited amount of demands and energy units. energyPRO allows for changes in the modelled energy systems and the operation strategy in order to determine the optimal productions. In this work the energyPRO has been used for one year calculations. The input data that have to be specified for a study are the types of demands, like electricity, heat and cooling demands, the fuels, the specifications of energy units (production units and the thermal store) and the operation strategy. There is a decision table which is used to describe the priority amongst energy production units in all different specified periods of plant operation. In addition, the economy calculations should also be specified. There are several sorts of input data for the economy calculations depending on the nature of the study. In this work the input has been restricted to the revenues and the operating costs. The output includes the results of the calculations regarding the income from operation and the energy conversion. The latter refers to annually and monthly results of the energy productions, hours of operation, number of starts and fuel consumption of the production units.

The calculations in energyPRO are carried out, typically on hourly steps. However, instead of calculating the energy productions in a chronological order, the software calculates, productions of the most favourable periods for the whole year, as those are defined by the user. As a consequence, before being accepted, each new planned production is carefully checked sothat it will not disturb already planned productions with higher priorities.

The non-chronological operation is based on the concept of the division of the year in periods of priority. The prioritization is done according to the electricity prices most of the times. Then the operation strategy of the production units can be determined. As a result, in energyPRO the production is prioritised by the user according to the following argument: First production by the unit of the highest priority, one of the gas engines for example for the most favourable period, say the period with the highest electricity prices. This production is set by the user to have priority number 1. The second priority, priority number 2, corresponds again to a production unit and a period characterized by certain electricity tariffs. The rest of the priorities are established in a similar manner.

The software goes through the whole year six times for each priority number, performing the following loops[10,16]. In the first loop it tries to fill the production gaps. If for example a day had two periods characterised by high electricity prices, then an attempt is made by the software to keep the unit running during the intervening period . If not successful, all productions for these calculation periods in between will be inserted. In the third loop the production unit is forced to the most general case. The data have been obtained from the energyPRO files (Test Reference Year).

Heat demand

The total heat demand was assumed to be 20,000MWh a year.

A typical heat demand profile has been assumed here[9] which is more representative of University campuses in the UK[9].

In the colder months, there are on a typical University campus a number of experiments that have to be kept warm at night, while the majority of units like teaching rooms, lecture theatres, offices, sports facilities, restaurants, would all have no requirement for heat during the night. Therefore a ratio of 2:1 daytime to night-time demand has been assumed.

Given that University campuses are usually compact, network losses are expected to be between 20% and 10%. The same percentages are expected for the summer heat demand for hot water, as there is only a small demand for hot water if there are no residential blocks on the site. Therefore, in overall, 25% of the heat demand is assumed here to be independent of the outdoor temperature, while the rest 75% of the total heat demand is assumed to be dependent linearly on ambient temperature between September and May inclusive. The reference temperature for the dependent demand is also required as input by software in order for the demand to be distributed after a simple degree-day method[16]. The reference temperature is the temperature below which room heating is initiated. For the UK the reference or the so called base temperature, is typically considered to be 15.5^{o}C[21]. At this value of ambient temperature most UK buildings can heat themselves without the need for supplementary heating, due to the internal gains from occupants and equipment and the solar gains through the building fabric – walls and windows.

Gas engines

Gas engines of 2MW and 3MW have been considered to get total CHP capacities between 2 and 4 MW. The largest natural gas engines currently available in the UK market[22,23] are 3MW capacity. As indicative values of efficiency[22,23] for the gas engines, 38% electrical efficiency and 40% heat efficiency have been assumed, when the energy input is measured in gross calorific value (GCV). The engines in this study are assumed to have the same efficiency which is a good approximation given that they differ little in size.

It has also been assumed that the gas engine(s) is not available for 4 days twice a year either for maintenance purposes or due to grid failure. Due to the negative effects of starting and stopping the engine frequently, it is desirable to consider solutions with a reduced number of starts of the engines. To this end a restriction has been introduced, according to which the minimum operational time of the engine is set to two hours.

Boilers

In UK boiler plants typically run standard boilers[9,27] and the existing systems are not designed for the low temperatures required for the condensing boilers[24,25]. For this reason in the general case that is examined in this work a plant with standard boilers has been considered. However, it should be mentioned that recent regulations are pushing for higher efficiency in boilers[26].

Typical efficiency value of a standard natural gas boiler used in UK plants is 80% to 85% in gross calorific value for 2.5-3 MW boiler size[27,28]. It is common practice in applications to use more than one boiler of smaller capacities than one big boiler. In this way, firstly, there are always boilers available for operation in case one is out of order for maintenance purposes and secondly more control can be achieved on the resulting temperature since the change in the output by starting up a new boiler is small. The disadvantage is that increasing number of boilers will increase the operational and maintenance costs and therefore there is always a compromise to be made. According to the above arguments, it has been assumed that the plant consists of 3 boilers of 82% efficiency.

Fuel

The fuel used for the boilers and the gas engine is natural gas. The heat value of the natural gas[22] is 10.73 kWh/Nm^3 in gross calorific value.

The thermal store

The temperature difference in the thermal store is the difference between the hot zone of the thermal store and the cold zone at the bottom of the thermal store. This difference in the UK is 30^{o}C[9]. Part of the thermal storage is not used in daily operation. Therefore there is an effective used volume or net volume. The percentage of the net volume has been set to be 90% of the total volume of the thermal store. These settings allow the software to associate the volume of the thermal store with the heat capacity. For example, a 100m^3 thermal store has thermal storage capacity of 3.1 MWh.

Periods of priority

The year is divided in periods of priority which are set according to the electricity prices. Therefore, each period is characterized by a fixed electricity price.

Operation strategy

The production of the gas engine during the hours of the highest electricity prices is set to be the production of the highest priority (priority number 1). In the case of a plant with more than one gas engines both gas engines are set to have the same priority for production during a particular group of hours characterized by a certain electricity price. The gas boilers are prioritised after the gas engines.

The gas engine(s) is only allowed to operate at full load and it is allowed to produce heat in the thermal store. The boilers can operate either at full load or part load and they are not allowed to produce in the thermal store.

Revenues-expenditures

The revenues are from the heat and electricity sales. The expenditures are for the fuel used and the operational and maintenance costs of the gas engines and the boilers. The gas cost and electricity sale prices that are used in this study are approximate values indicative of costs observed in various UK applications for the years 2005-2006 and they do not refer to all particular applications. It is not possible to produce benchmarks to cover all applications although some data, such as operating costs, have been generated by some studies in a generic fashion which we cite elsewhere in this study.

For a boiler plant the cost of the gas includes the climate change levy (CCL). The CCL[29] is a tax which came into effect on the 1st of April 2001, and applies to energy used in the non-domestic sector, that is industry, commerce and the public administration sector. There are several exemptions from the levy in order to support energy efficiency schemes and renewable sources of energy. A boiler plant is not exempted from the CCL and has therefore to pay £1.5/MWh for the gas consumed.

In contrast to boiler plants, CHP schemes are exempted from the CCL on the energy use if they are assessed as being 'good quality'[29,30] CHP. There are two key parameters for assessing a CHP scheme; the power efficiency and the Quality Index (QI). A scheme that qualifies as Good Quality CHP for its entire annual energy input is one where the power efficiency equals or exceeds 20%. The power efficiency is defined as the ratio of the total annual electricity output of the scheme to the total annual fuel energy input and it is based on the gross calorific value of input fuel. A scheme that qualifies as good quality CHP for its entire annual power output is one where the QI equals or exceeds 100. The Quality index of the plant is an indicator of the energy efficiency and the environmental performance of the scheme. It takes account of the fact that power supplied is more valuable than heat supplied[30].

energyPRO allows for the calculation of the QI of the plants.

In the cases of the CHP plants examined here the plant is always qualified for CLL exemption.

The price at which the plant sells the heat is assumed to be equal to the cost of producing 1kWh heat with the boilers. This cost includes the cost of the gas and the operational and maintenance costs of the boilers.

The electricity is sold at variable tariffs[9]. There is price variation during the day and during the year with high prices during the daytime and in winter and low prices during the night and during summer. The tariff profile considered in this work is applies to an example of plants with capacities 2.5 to 3.5 MW. We use this as the best data to hand, in the absence of representative data. The fact is that tariff profiles are, in any case, not publicly avialable. For reasons of commercial confidentiality we cannot publish our example in full, but we can give an idea of the range. Figure 1 shows a comparison between the highest peak and the lowest off peak electricity tariffs in February. 3.4 £/MWh has been added to the prices to account for incomes in respect of the CCL exemption that applies to electricity exported by CHP plant. This amount is 80% of 4.3 £/MWh, and is typical of the contract offer from electricity suppliers[29].

It should be noted that there is a minimum acceptable electricity price for a given gas price. This is the price at which the boiler and the gas engine are producing heat at the same price. At lower electricity prices the boilers are producing heat cheaper than the gas engine and in this case we should not run the gas engine. This minimum accepted electricity price has been calculated in our model to be £29.4/MWh_{el}. Similarly, there is a maximum electricity price for a given gas price, above which it is better to dump heat using a device like a cooling tower (if the thermal store is full). This maximum electricity price is equal to the cost of producing 1MWh electricity with the gas engine and it includes the cost of the consumed gas and the operational and maintenance cost of the engine. This price has been calculated to be £55.7/MWhel.

The operation and maintenance costs of the engines are assumed to be dependent on the size of the engine[22]. The operational and maintenance costs of the range of the engines considered here engines considered here are estimated to be within the range of £5.5 to £6.5 /MWh_{el} and these values can be considered representative of an average UK situation. The starting and stopping of the engine during the operation of the unit is done automatically and there is not additional cost involved.

Typical operational and maintenance costs[27] of 2.5-3 MW boilers are £250 per year for cleaning. In the case of larger boilers that require more time for cleaning the cost will be doubled. It will cost £500 per year to maintain the burners. In this study, there are three boilers in the plant, so the operation and maintenance cost of the boilers will be £2,500 per year.

Investments

As in the case of the operation and maintenance cost and the electricity prices the investment cost assumed in this application are typical UK costs.

The capital cost of one MW engine including installation and the additional equipment needed (heat exchangers, chimney etc) is 500,000 £/MW for 1MW engine and it is reduced for bigger engines[22].

The investment cost in the thermal store[9] is 714 £/m^3.

The lifetime of the investments is taken to be 15 years and the discount rate 5%.

These are used because they are common parameters for assessment of large scale energy projects in the UK financed through project finance[31]. Small companies may require more rapid rates of return, but there is some benefit in using parameters also used for large power projects since we can use the analysis to compare the economics of CHP with other power projects.

5. Methodology

The reference plant is assumed to be a natural gas boiler plant which covers the total annual heat demand. The various plant designs examined in this study are compared with this reference plant. The expenditures of the reference plant equal the revenues since it has been assumed that the heat is sold at a price equal to the production cost. It is assumed, in the first simulation with energyPRO, that this plant invests in a 2MW gas engine and a small, 1.6 MWh (50 m^3) thermal store. In the new plant, the production of gas engine will meet part of the heat demand, either directly, or indirectly, through the thermal store. The latter refers to the heat stored during the time of production to be used later on when the heat demand exceeds the production of the engine or when the engine is off.

The heat is sold at the same price as before and the electricity is sold at variable tariffs presented in section 4 of this paper under the heading 'Revenues-Expenditures'.

The software calculates the annual income of the plant and this value is used as input in an Excel file to calculate the present value (PV) and the net present value (NPV) of the investments in the gas engine and thermal store. The net present value (NPV) is the present value minus the capital cost of the investments. So, as has been mentioned earlier, the net present value represents the net financial benefits derived from the project after taking into account the cost of the plant and after discounting the net income from the revenue stream.

The next step is to consider investment in the 2MW engine and larger sizes of thermal stores. The operation income is calculated each time in the energyPRO and the NPV of each alternative configuration in Excel. The optimum solution is the one that corresponds to the maximum NPV. The process is repeated for CHP sizes of 3 and 4MW. Hence we consider 1x2MW engine, 1x3MW engine and 2x2MW engines plant taking into account the availability of the gas engines in the UK as mentioned earlier.

A sensitivity analysis is carried out regarding the heat demand by comparing with a case study heat demand variation. The calculations, therefore, for the plant which runs only boilers in order to cover 20,000MW heat demand annually are repeated in the energyPRO for heat demand assumed to follow the same monthly variation with the heat demand[32] in the Kings Buildings CHP scheme in Edinburgh University. The daytime to night-time ratio is assumed to be the same with the heat demand of the general case[28].

The reference temperature was calculated from the monthly average values of the heat demand at the site and the monthly average temperatures of East Scotland obtained from the met office website[33]. The reference temperature was found 12.9^{o}C as opposed to 15.5^{o}C, which was the reference temperature assumed in the general case. Assuming 1.16MW constant hot water and network loss the fraction of the dependent demand was calculated to be 61%, which is smaller than the fraction assumed in the general case. Different alternatives of gas engine-and thermal store were investigated and the net present values of each investment were again calculated in Excel.

Further sensitivity analysis was carried out regarding the investment cost of the gas engines and thermal stores and the operational and maintenance costs of the gas engines. Danish figures[34] have been used for this analysis for comparison, since Denmark is leading in terms of integrating distributed production into the national electricity production system[8]. This correspond to 20% reduction in the investment cost of the gas engine, 72% reduction in the investment cost of the thermal store and in 18% reduction in the operational and maintenance costs of the engines. Prices like these might occur in a future UK market with a high dissemination of these systems.

6. Results and discussion

Figure 2 shows three curves representing CHP sizes between 2 and 4 MW. Each curve shows the NPV as a function of increased storage capacity. It can be seen that the NPV increases in the beginning by adding storage capacity and then falls as the cost of expanding the heat storage becomes higher than the benefit. The optimal design is the point of the curve that results in the highest NPV. The optimum investment in gas engine and thermal store for a plant which uses only boilers to meet 20000 MWh annual heat load is the investment in 1x3MW engine and 7.8 MWh (250m^3) thermal store. In this case the net present value was found to be £804,231 for the 15 years lifetime of investments and 5% discount rate. In addition, it has been found that the engine covers 85% of the annual heat demand in a year and runs 61% of the time. The optimum size of thermal store for the 2MW engine is 4.7MWh (150m^3) and the engine covers smaller percentage of annual heat demand, 67.7%, and runs fewer hours a year, 73.2%. The optimum size of thermal store for a 2x2 MW engine is 6.3 MWh (200m^3) and the engines cover larger amount of heat demand, 94.6%.

Clearly there are various combinations of engine sizes that give a total capacity of 2MW, 3MW or 4MW. The effect of the different combinations on the Net Present Value of the investment will depend on the efficiency and size relationship of the engines and the pricing mechanisms regarding the investment and operation and maintenance costs in relation to the engine size. The pricing policy assumed here favours the use of one large engine instead of more engines of smaller capacity. On the other hand the assumption that the efficiency is independent of the size of the engine favours the use of smaller engines instead of one big since smaller engines have lower efficiencies. Furthermore it can be seen that the bigger the engine the bigger becomes the optimum size of thermal store (e.g. the 3MW engine needs 7.8MWh thermal store for optimum operation while the 2MW needs 3.1). However, the use of several small engines instead of one bigger leads to smaller optimum storage size since, one of the small engines can operate during low heat demand with out the need of big thermal store. This is why the 3MW plant needs smaller thermal store for optimum operation than the 2X2MW plant.

It is important to note that the addition of thermal storage makes more larger CHP units more economic; e.g. without thermal store the 2MW CHP would be better investment than the 3MW (Figure 2).

It should also be noted that the addition of a thermal store makes a considerable improvement to the economic functioning of the CHP plant. As can be seen in Figure 2 without the thermal store the NPV of the 3MWe plant is less than £350,000 whilst if it works with the optimal size of thermal store the NPV is over £800, 000. Hence the (NPV) financial benefit of having the thermal store compared to not having the thermal store approaches half a million pounds And is more than doubled in size.

It has been commented that, because of the administrative changes brought in during the latest stages of electricity market liberalisation, the effective export tariffs available for small CHP plant have been lower compared to electricity prices on the main wholesale electricity markets[20]. This is essentially because they have to sell to third parties who discount the value of the electricity compared to what is available to power stations through power exchange trading.

It has been calculated that, were a regulatory reform introduced to give the same variable tariffs to small generators that is available through power exchanges, then income from electricity export sales would increase by around 30 per cent compared to the figures used in this study[20]**.** This would improve the economics of the use of thermal stores with gas engines still further.

It is useful to present how the CHP plants operate according to the input settings in the energyPRO. Figure 3 shows a production graph from the energyPRO of one week winter operation of the optimum plant. The upper curve shows the variation in the electricity tariffs. The next curve shows the heat productions of the gas engines and the boilers as well as the heat demand (heat consumption). The bottom curve gives the expected content of thermal energy in heat storage. It can be seen that the engine runs when the electricity prices are high while at night (when the prices are low), the engine may stop for some hours. In addition, it can be seen, that, the engine turns on only when it can operate continuously for at least two hours. When the engine(s) produces more than the heat demand then the extra heat is stored in the thermal store if there615 -ps ason fon(ored in the)]TJ0054(l store1.15 TDwe)-5.5.5(f)-5.5(hours. In

On Monday at 00:00 the heat from the engine is not enough to meet the heat demand and the heat from the thermal store is used. At 6:00 the thermal store is completely empty and the boilers turn on to meet the demand that is not covered by the engine. The boilers are running until 21:00. After 21:00, the engine itself can cover the heat demand until the midnight. Then the heat demand drops and the engine produces more heat that is needed. As a result the thermal store starts to fill in. At a latter stage, on Wednesday at 00:00-02:00 that the engine is off the heat is provided only by the thermal store.

It is important to investigate the effect of the variable electricity tariffs on the optimization of the plant operation.

Without the variation in the electricity tariffs the operation of the CHP plant would be as shown in Figure 4. It should be noted that in Figure 4 the curve with the electricity tariffs has been omitted here because a fixed tariff is assumed:

The engine stops only when the thermal store is full, for example on Wednesday at 3:00. The engine starts again whenever it is possible to operate continuously for two hours-as it set in the input- without the need to dump heat. When this condition applies and the engine starts again to operate, the thermal store may be either completely empty, like, for example, on Wednesday at 7:00, or party empty, like, for example, on Sunday at 4:00. If this condition does not apply, and the thermal store is empty, it is the only case that the heat will be provided exclusively by the boilers.

Having prioritized the production according to variable electricity tariffs the above operation is modified as it can be seen in Figure 3. The engine does not stop only when the thermal store is full like on Tuesday at 00:00; it also stops when the thermal store is partly empty and further operation of the engine during the following hours is going to prevent its operation at a latter stage during hours of better electricity prices (higher priority). This is the case on Wednesday at 4:00, when the engine stops so that the operation is possible between 7:00-24:00 when the electricity prices are higher. The same principle, together with the requirement of the engine being able to run for at least two hours without the need to dump heat, determine when the engine turns on; if the engine should not turn on, and yet there is still a need for heat then the boilers start. It is possible in this case, that only the boilers are running while the gas engine is off and the thermal store empty, like for example on Friday 6:00-8:00. In this case, the operation of the boilers during the hours of low electricity tariffs allows for the operation on the engine during the consecutive hours 8:00-19:00.

Clearly the highest the difference in the electricity tariffs between day and night the most pronounced the benefit of using thermal storage.

In UK the development of CHP with gas engines is made more economic if it is done with thermal stores given that the variable rates of electricity tariffs apply. The reason is that the high difference of electricity tariffs between day and night makes it possible to take advantage of the thermal storage ability of the plant in order to exploit the high electricity rates during the day. It becomes more economic for the engine to run for a larger part of the year.

In the case of heat demand variation similar with that at Kings Blds in Edinburg, the optimum investment is a 1x3MW engine, that is the same size with the general case and 4.7 MWh (150 m^3) thermal store (Figure 5), as opposed to the larger thermal store of the general case. In addition the NPVs are higher for all engine and thermal store sizes compared to the general case. The reason for finding smaller thermal store as optimum investment, is, that the heat demand variation is smother between winter and summer than in the general case, with higher heat demand in summer and lower heat demand in winter, as shown in Figure 6. For the same reason the engine is running more hours during the year (65%) and covers higher percentage of the annual heat demand (91%) in the case of Kings Blds heat demand variation.

Now we will discuss the results from the sensitivity analysis regarding the investment costs in gas engines and thermal store as well as the operational and maintenance costs of the gas engines. Figure 7 shows the results of investment in 2x2MW gas engines and in a 3MW engine when the costs mentioned above are similar with those in Denmark. In this case, it is better to invest in larger gas engine capacity and a larger thermal store; the 2x2MW engine with 12.5MWh ($400m^3$) thermal store is shown to be a better investment.

The difference between the UK and Danish prices could be due to: the differences in the real purchasing power of the exchange; because there are many CHP plants with thermal stores in Denmark, or because costs of different installation needs are included in the pricing.

Further research is needed to show whether the optimum size of CHP plants that can be developed in the UK and has been identified in this study, is suitable for aggregated operation under the rules of the UK electricity markets, in order to be used for wind[35] integration.

7. Conclusions

It has been shown how the high variation in the electricity prices between day and night allow thermal stores to improve the economics of CHP plants in the UK. It has been shown how the thermal store can allow for the engine to operate as a priority during hours of high prices. It has been found that the optimum plant designed to cover most of an annual heat demand of 20,000MW, would consist of a 3MW engine and 7.8MWh ($250\ m^3$) thermal store. In this case the Net Present Value of the investment in the 3MW gas engine and 7.8MWh thermal store is improved by nearly half a million pounds compared to the case of not having a thermal store. A smaller thermal store is optimum if there is lower variation in the heat demand between winter and summer with higher summer and lower winder demand. In this case more fraction of the heat demand is covered by the gas engine and the NPVs are higher. Finally, it has been shown that investment and operation and maintenance costs as low as those in the Denmark would make a larger CHP plant a better investment. Further investigation should deal with the possibility of the optimum size CHP plants, which has been identified here, to aggregate in the UK electricity market in order to be used for integration of wind turbines.

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Figure captions

Temperature	• Daily temperature data of Central England
Heat demand	• Annual demand =20,000 MWh • 75% temp. dependent September to May • ref. temperature =15.5^o C • Daytime demand/Night-time demand =10/5
Gas engine (s)	• n_{el}=38% (GCV) • n_{heat}=40% (GCV)
Boilers	• n_{heat} =82% (GCV)
Fuel	• Natural gas • Heat value =10.73 kWh/Nm^3 (GCV)
Thermal store	• Temp difference=30^{o}C • Utilization=90%

Table 1 Technical input for the energyPRO calculations

Gas cost	18.9 £/MWh
Climate Change Levy (CCL)	1.5 £/MWh
Engine(s) O&M costs	~6-7 £/MWh
Boilers annual O&M costs	£2,500
Heat sale price	25 £/MWh
Electricity sale price	Variable tariffs
Investment cost of 1MW engine	£ 500,000
Investment cost of thermal store	714 £/m^3
Lifetime of the investments	15 years
Discount rate	5%

Table 2 Economical input for the energyPRO and Excel calculations

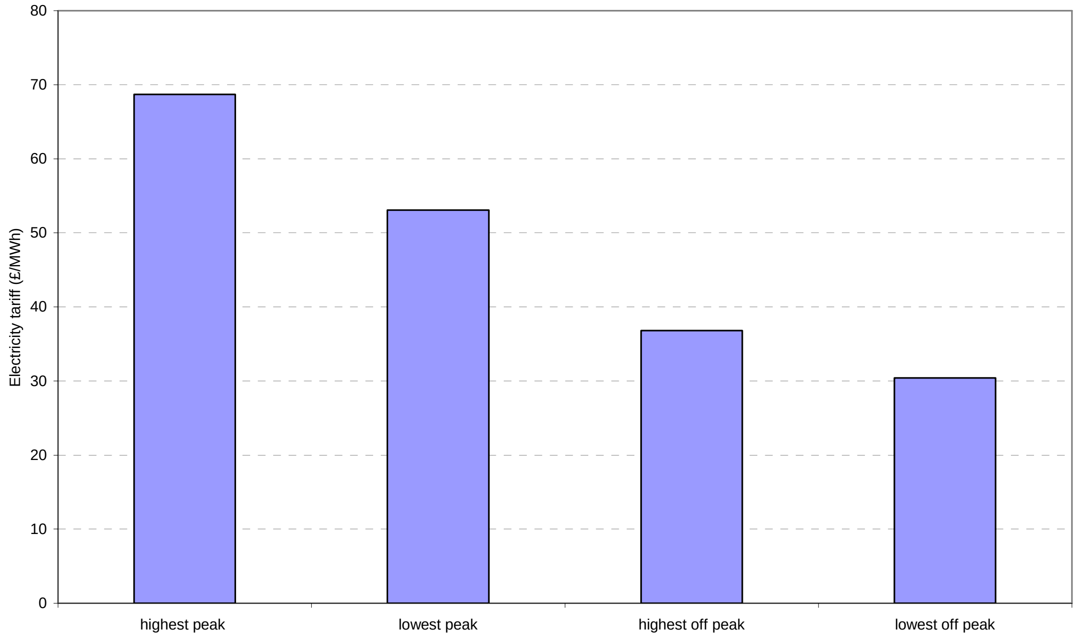
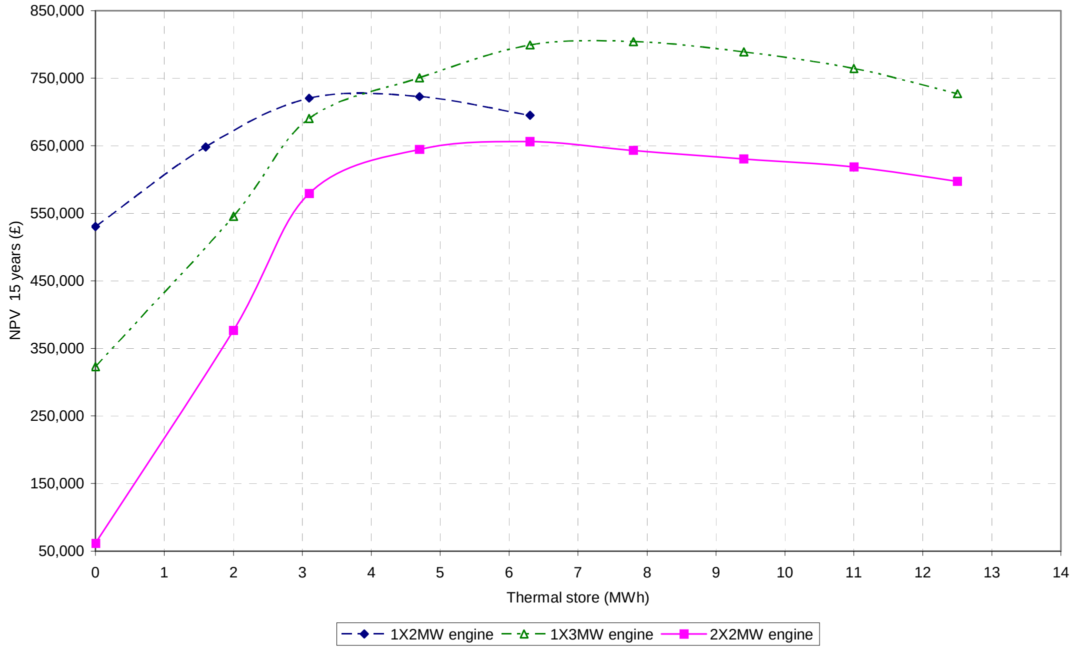

80
70
60
50
40
30
20
10
0
Electricity tariff (£/MWh)
highest peak
lowest peak
highest off peak
lowest off peak

Figure 1



850,000
750,000
650,000
550,000
450,000
350,000
250,000
150,000
50,000
NPV 15 years (£)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Thermal store (MWh)
1X2MW engine
1X3MW engine
2X2MW engine

Figure 2

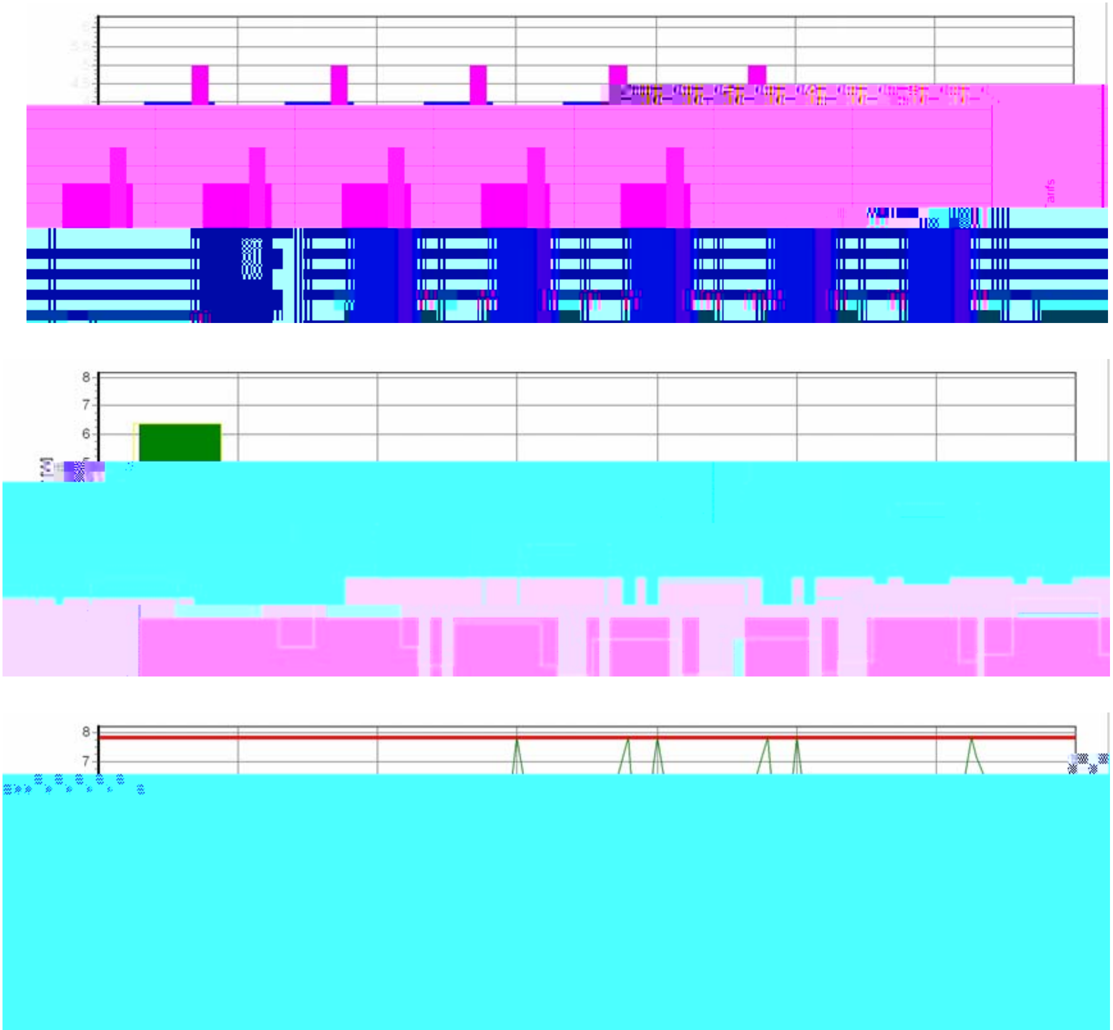


Figure 3

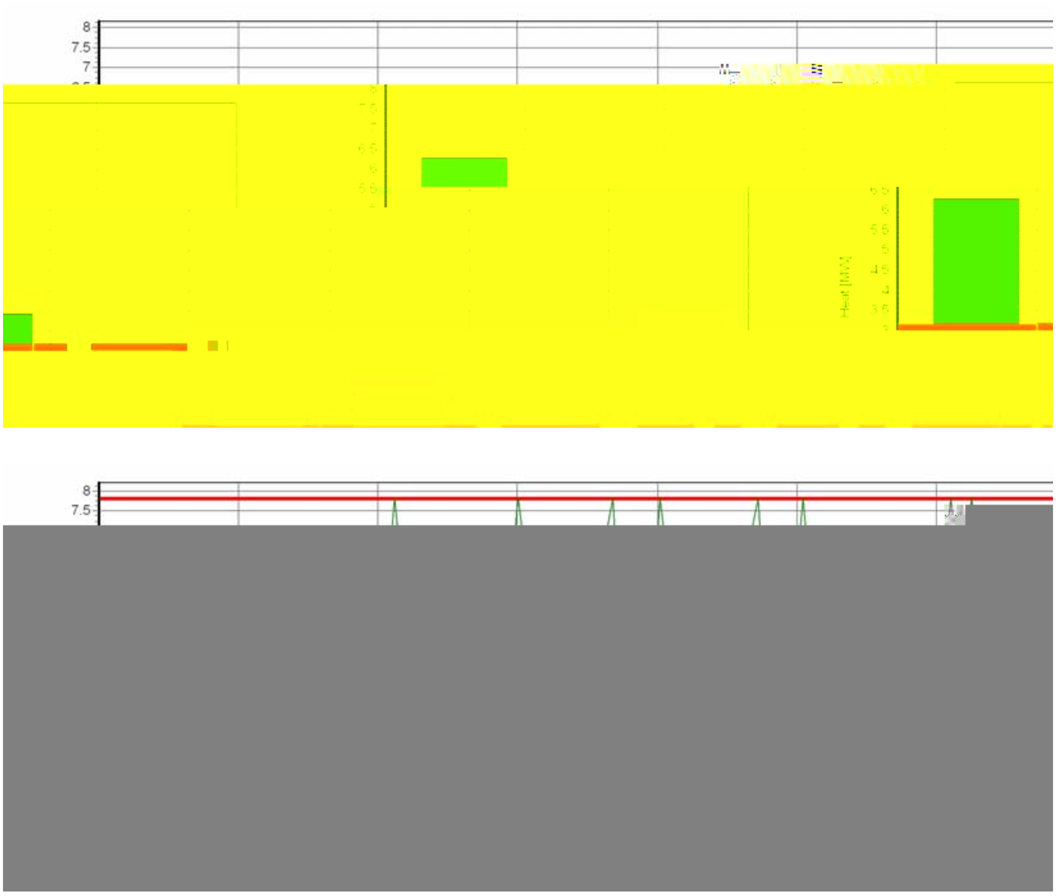
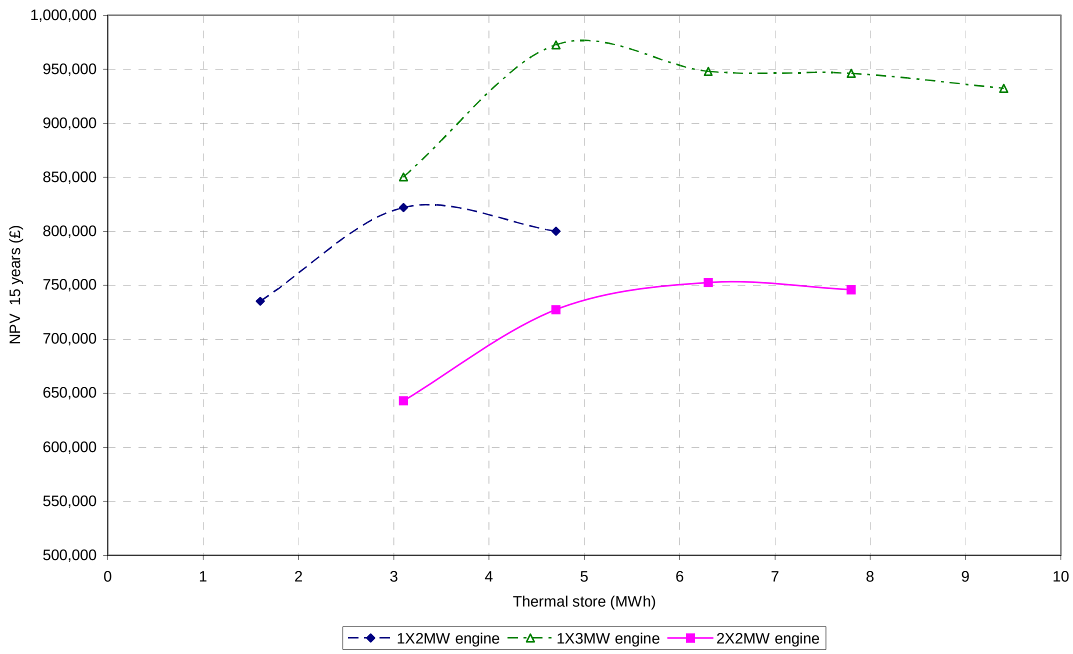
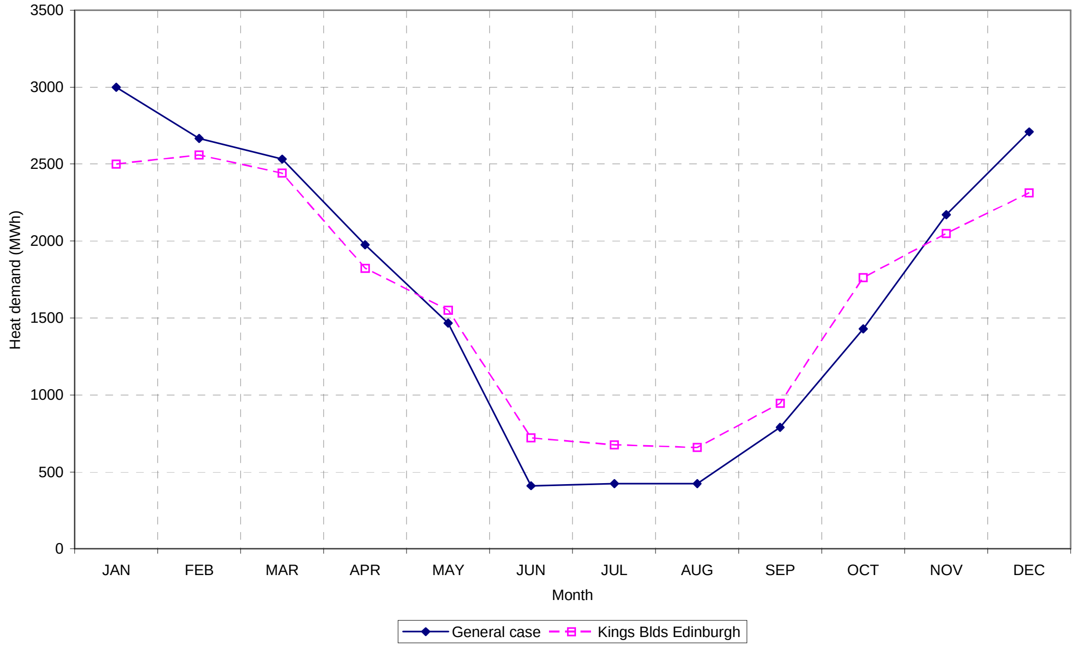


Figure 4



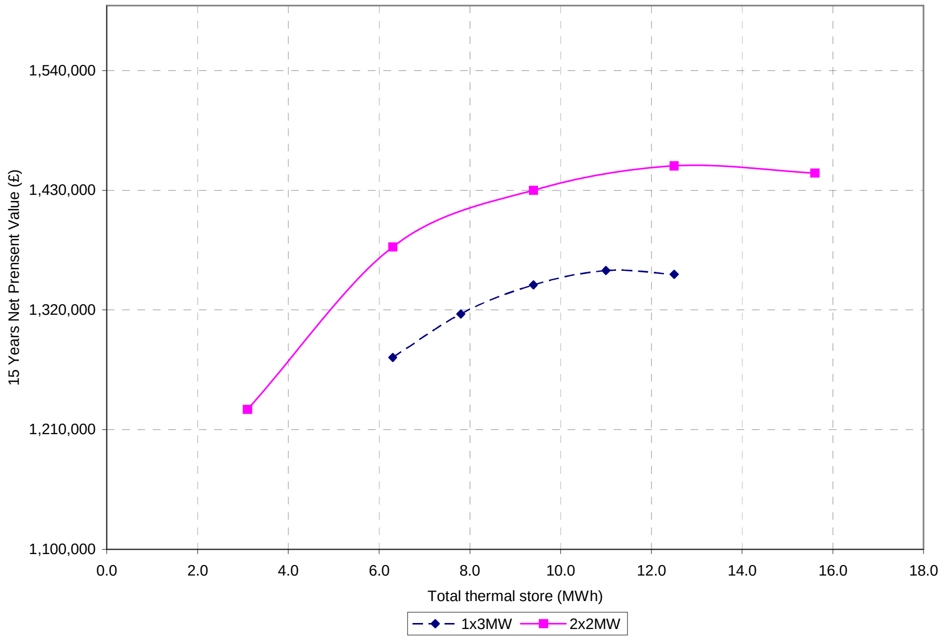
1,000,000
950,000
900,000
850,000
800,000
750,000
700,000
650,000
600,000
550,000
500,000
NPV 15 years (£)
0
1
2
3
4
5
6
7
8
9
10
Thermal store (MWh)
1X2MW engine
1X3MW engine
2X2MW engine

Figure 5



3500
3000
2500
2000
1500
1000
500
0
Heat demand (MWh)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
General case
Kings Blds Edinburgh

Figure 6



1,540,000
1,430,000
1,320,000
1,210,000
1,100,000
15 Years Net Prensent Value (£)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Total thermal store (MWh)
1x3MW
2x2MW

Figure 7