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TECHNO-ECONOMIC ANALYSIS OF SMALL SCALE CCHP SYSTEMS FOCUSED ON EMISSIONS PERFORMANCE

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ABSTRACT

The Combined Cooling, Heat and Power (CCHP) market appears to be in a favourable condition for investors; the ever-growing energy demand and the increasingly strict air quality targets foster, even more, CCHP applications.

The objective of this study is to firstly assess the economic convenience of CCHP systems through a spark spread and carbon valuation analysis up to 2050. Secondly, to compare the economic and emissions performance of different prime movers for densely populated urban areas, focusing on the case of central London. Different scenarios were considered to evaluate the impact of including externality costs for carbon and NOx emissions.

The case study is based on the electricity, cooling and heating demand correspondent to three buildings from City, University of London. The results of these models have been integrated and compared against consuming directly from the National Grid and gas boilers.

The systems comprising micro-gas turbines resulted in the most economical and environmentally optimal amongst the evaluated systems. In particular, the combination of two 400 kW_e micro-gas turbine modules proved the most adequate for the university's application due to high electrical efficiency, modularity and optimum sizing.

INTRODUCTION

Combined heat and power (CHP) is the process in which electricity and heat are simultaneously generated from one single energy source. If an absorption chiller is used to produce cooled water for refrigeration, this process is then called combined heat, cooling and power (CCHP). In order to generate both heat and power, fuel is burnt to drive the prime mover and generator to transform mechanical energy into electrical energy. To date, the following prime movers are used: reciprocating internal combustion and Stirling engines, gas and steam turbines and fuel cells.

CCHP for Urban Application

Distributed generation (DG) has diverse benefits. However, having the energy production process closer to the end consumer, inevitably incurs the direct emission of noxious gases closer to the consumer and the surrounding population. The pollutants concentration in the air, which is higher closer to the source of emissions, negatively impacts the urban air quality. This is particularly significant with nitrogen oxides (NOx) and fine particulate matter (PM), which have been proven to have more imminent health risks than other pollutants.

The government's environmental strategy for London estimates that by 2025 gas-fired generation will become the main source of NOx, surpassing transportation (GLA, 2018). Furthermore, urban population is expected to increase to 70% by 2050 (United Nations, 2018), where a 1% increase in population corresponds to a 2.2% increase in energy demand (Spataru, 2017).

For this reason, despite the numerous advantages that CHP urban applications can provide, the environmental and health implications should be carefully studied before selecting the system's prime mover. The reciprocating engine is the most widespread prime mover due to its low capital costs, fuel flexibility, modularity and the fact that it can be sized to any power output. However, it might not be the best option from an emissions standpoint.

In this study, the application of micro-gas turbines is proposed. Gas turbines are widely used in larger systems, but their low electrical efficiencies at smaller scales made them economically unfeasible for most CHP applications. However, recent technological advances have achieved electrical efficiencies of 40.2% at design load (Jaatinen-Värri et al., 2016). It is believed that the market will continue expanding in this field now that it has been proven to be a viable option.

NOMENCLATURE

CCHP	Combined Heat, Cooling and Power
CHP	Combined Heating and Power
CO_2	Carbon Dioxide
DG	Decentralized Generation
GE	Gas Engine
GHG	Greenhouse Gases
MGT	Micro-Gas Turbine
NOx	Nitrogen Oxides
PM	Particulate Matter
SG	Spark Gap
SS	Spark Spread
NPV	Net Present Value

COMBINED COOLING, HEAT AND POWER

The implementation of CCHP systems in urban applications has increased in recent years, this can be attributed to the many benefits they provide:

Improved Fuel Efficiency: A great advantage of CCHP systems is the increased fuel efficiency. In traditional power plants, only about 30% of the energy input is converted into useful electrical energy, the other 70% is lost to the atmosphere as waste heat. Cogeneration and trigeneration systems, however, use this rejected heat for space heating or to feed an absorption chiller for the purpose of cooling, bringing up the overall system efficiency to 80% in most cases. A more efficient combustion of fuel not only results in an economic benefit but also in emissions reduction.

Distributed Generation: Ofgem defines DG as ‘an electricity generating plant that is connected to the distribution network rather than the transmission network’ (Ofgem, 2019). As the generation takes place closer to the end consumer, distribution and transmission losses from transporting the electricity along the power lines are reduced, in most cases remaining only the losses from the own site. Additionally, the possibility of more than one energy source increases the security of supply.

Reduced Emissions: The fact that less fuel is needed for the same power output and that distribution and transmission losses are significantly reduced directly implies lower greenhouse gases and other pollutants. Furthermore, as society becomes more conscious about air pollution, new prime mover technologies are being developed with improved emission performance, with notable advances in the field of nitrogen oxide emissions.

Economic Savings: All the above-mentioned benefits can be translated into economic savings: more efficient fuel combustion and reduced losses imply lower fuel costs, reduced emissions mean fewer tax charges and social damage, a reliable supply is vital, especially for health care applications where lives directly depend on proper machinery operation.

Incentives

The CHP Quality Assurance Programme (CHPQAP) is a government voluntary initiative that promotes a better application of combined heat and power in the UK by monitoring and evaluating the different schemes and supporting the most efficient throughout different incentives. The eligible CHPs are classified as ‘Good Quality’ and can benefit from:

Climate Change Levy

The Climate Change Levy (CCL) is a tax that affects businesses and public sectors and is charged on ‘taxable commodities’ such as electricity and fossil fuels used for heating, lighting and other energy purposes. A qualifying CCHP system is exempt from paying CCL on electricity and fuel used on-site. (HMRC, 2016).

Carbon Price Floor

This is a UK government policy aimed to reinforce the EU Emissions Trading System, under this scheme, the Carbon Price Support (CPS) is a tax on carbon emissions that aims to decarbonise the UK’s electricity production by targeting fossil fuel driven plants. Good Quality CHP are exempt from paying CPS on fuel used for electricity generation with self-supply purposes. (BEIS, 2019)

Business Rating Exemption

Businesses containing a CHP scheme that is fully or partially qualified as Good Quality are exempt from paying the rate associated with such generation plant. (BEIS, 2019)

Capital Allowances

First year allowances and the Annual Investment Allowances scheme entitle an investor to fully claim the first-year tax relief on qualifying energy-efficient technologies, allowing the deduction of the product’s expenditure to be discounted from the annual taxable profits in the tax year of purchase. (HMRC, 2019)

Micro-Gas Turbines

Micro-gas turbines (MGTs) are promising to provide an excellent solution to the urban energy demand. Their few moving parts make them apt competitors for noise and vibrations constraints, this translates into lower maintenance requirements and therefore longer lifespan. They also provide high flexibility in terms of fuel and modularity to achieve the desired power output (Wang et al., 2004). The very low NOx emissions avoid the need of buying catalytic converters and in doing so, reduce the capital investment and consequently the payback period.

Another great advantage is the possibility of avoiding liquid lubricants, the previously mentioned few moving parts in the gas turbine design allowed the implementation of new technologies such as air and magnetic bearings to protect the rotary shaft. Erasing the need for oil drainage and filter changes contributes to even lower maintenance costs as well as fewer maintenance hours, therefore achieving a better availability when compared to reciprocating engines. However, the most important benefit would be the elimination of the hazardous oil itself.

ENVIRONMENTAL AND HEALTH IMPLICATIONS

Air pollution is the largest environmental risk to human health in the UK, and the fourth greatest threat to public health after cancer, heart disease and obesity according to the 2011 Department of Health Public Health Outcomes Framework. It accounts for more deaths than smoking, while costing the UK economy over £20 billion a year. Only in the UK, it is estimated that 40,000 early deaths are caused due to air pollution, particularly because of particulate matter and nitrogen oxides; worldwide, this number rises to 3 million (Royal College of Physicians, 2016).

Particulate Matter

Particulate Matter (PM), is defined as any non-gas (liquid, solid or combination of both) particles existing in the air, which can be from natural or anthropogenic sources. PM are classified according to their size either as PM10 or PM2.5 (fine particulate matter), referencing the diameter in nanometres respectively. Fine particulate matter is of special concern, because of its smaller size, it has a devastating impact on health; it can easily penetrate lung tissue and enter the bloodstream, travelling to the heart, brain and other organs.

Nitrogen Oxides

Nitrogen oxides (NOx) refer to the gases formed by the combination of oxygen and nitrogen during the combustion of fossil fuels, the most notorious being nitric oxide (NO) and nitrogen dioxide (NO_2). These noxious gases have been proven to cause inflammation of the respiratory airways and a decrease in pulmonary function, as well as the formation of smog and acid rain. The government has publicly announced intent in reducing NOx emissions with respect to 2005 baseline by 55% by 2020, upgrading to a 73% reduction by 2030 (DEFRA, 2019) therefore, legislations reinforcing this target are expected in the future years.

Greenhouse Emissions

Greenhouse gases (GHG) cause the greenhouse effect by absorbing radiant energy within the thermal infrared range and holding heat in the atmosphere, consequently leading to global warming. The primary greenhouse gases are water vapour, carbon dioxide, methane, nitrous oxide and ozone.

On June 2019, the UK government became the first major economy to sign legislation for a net-zero greenhouse gas emission target. This is an improvement to their previous commitment in the 2008 Climate Change Act, which aimed for an 80% reduction in GHG emissions by 2050 with respect to 1990 levels.

The Impact of Used Engine Oil

Used engine oil has devastating effects on the environment; a single litre can contaminate up to 1 million litres of water (DG ENV, 2021). Lube oil is contaminated with by-products produced during combustion, acquiring numerous hazardous substances such as aromatic hydrocarbons, which are a recognised human carcinogen. In order to avoid oil contamination and ensure safety for the workers and the environment, used engine oil disposal must follow the appropriate procedures. However, some other repercussions are not so easily avoided; fine particles of metals such as zinc, calcium, arsenic and lead from engine wear and corrosion often end up in used oil and are discharged into the environment through exhaust gases as a result of oil consumption. Despite the existence of new studies considering lubricating oil impact on PM emissions that have shown alarming trends, this is a field that needs to be further explored in order to get conclusive results, but the presence of fine metal particles in the exhaust gases certainly implies its contribution in emissions.

SPARK SPREAD AND CARBON VALUTION MODEL

The spark spread is a common method of reviewing the feasibility of a CHP system for investors; it is a very useful technique since it allows the simultaneous assessment of different parameters, in this case: gas, electricity and carbon valuation. Including carbon prices in this analysis allows the savings in CO_2 emissions from using a cogeneration system to be given a monetary value, providing a better indicator of the benefits when compared against the base case of using gas boilers and imported electricity from the National Grid.

The model features carbon prices based on UK non-traded CO_2 forecast (DBEIS, 2021) and electricity and gas prices based on National Grid projections. From these data, two different analyses are conducted, the Spark Gap (SG) and the Spark Spread (SS). The former represents the simple difference between the gas and electricity prices and gives a rough indication of the economic feasibility of the plant. The latter is a more complex way of assessing the CHP economic performance that considers other factors such as the efficiencies of the prime mover, the boiler, and the overall CHP system. The greater the difference between electricity and gas prices, the more economical a CHP system is. Contrarily, if this difference is not enough, the installation of the system would not be profitable since the annual benefits, if any, would never be able to compensate the initial investment.

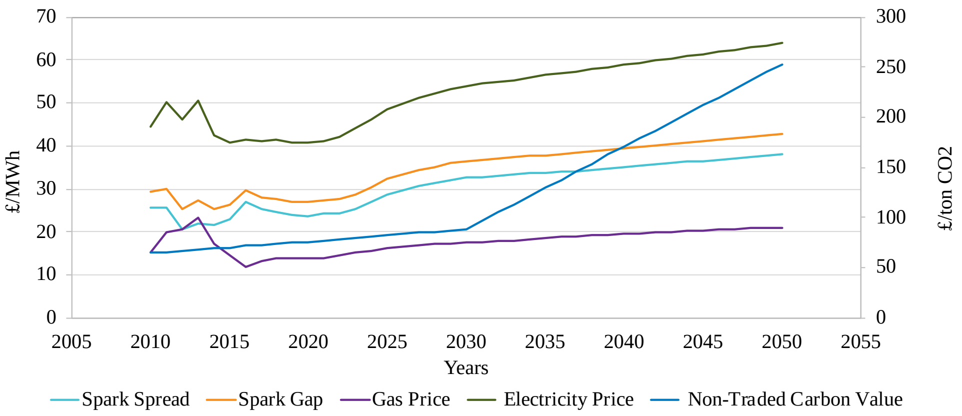

Figure 1: Spark Spread and Carbon Valuation Model

According to the National Grid's projections, both the whole sale prices for electricity and natural gas are expected to rise in the future. The difference in the rate of increase is crucial to the economic convenience of CHP systems.

The electricity price is expected to rapidly rise in 2020, reaching a more stable rate in 2030. The gas price shows a decelerating rate of increase over the years. The fact that the electricity price is expected to always increase at a higher rate than the gas price reflects that the difference in their prices will continually grow in the future, increasing the convenience of CHP applications with time. The carbon price trend shows a steep increase from 2030 onwards, fostering the adoption of CHP units. This analysis was based on wholesale prices, and due to the increasing green energy generation, the values might vary according to the production of renewables.

ECONOMIC ANALYSIS

The economic aspects considered in this study are:

- Price of natural gas
- Price of imported electricity
- Price of exported electricity
- Capital investment
- Maintenance costs
- Discount rate
- Carbon footprint
- NOx emissions externality cost

The prices for natural gas and electricity were based on the 2021 Prices of Fuels Purchased by Non-Domestic Consumers in the UK, published by the Department for Business, Energy & Industrial Strategy. The prices were considered excluding the Climate Change Levy and corresponded to 14.16p/kWh for electricity and 2.11p/kWh for natural gas. The exported electricity was also given a monetary value of 5.38p/kWh based on the Ofgem export rate for non-solar generation.

The capital investment considered in this study does not include installation costs, as this parameter widely varies with the site's location and the complexity of the piping system. Electric chillers and gas boiler costs are not considered either as these are assumed to be already in the university's possession since they constitute the base case. The capital expenses comprise the costs correspondent to the prime mover unit, the absorption chiller and gas compressor of each system. The discount rate was set to 6% to account for the depreciation of money and materials.

Maintenance costs can be fixed and variable, the latter one being more arduous to predict. For this reason, the average cost per kWh was allocated for each of the technologies based on historical data. The maintenance hours correspondent to the prime mover's availability (*Table 1*) were allocated randomly throughout the year by the program.

The emissions impact was based on the following externalities:

<u>Carbon valuation</u>

The carbon valuation gives a monetary value to the cost of emitting one ton of carbon dioxide into the atmosphere. The government sets the carbon values for purposes of evaluation and policy appraisals, although these are not currently monetized.

The carbon footprint of the electricity and heat generated onsite was easily calculated since the natural gas consumption for the prime mover and gas boiler was known from the analysis performed. However, the UK grid has diversified in the past years, incorporating different electricity generation sources. For this reason, an emissions factor provided by the Department of Business, Energy and Industrial Strategy was considered to estimate the CO_2 emissions of each kilowatt-hour of imported electricity, giving that the grid produces 0.30675 kg of CO_2 per kWh_e generated.

The carbon value considered for this study is based on the official non-traded sector from the UK government (DBEIS, 2021), which as of 2021 is £77/ton of CO_2; this corresponds to outside of the EU Emissions trading scheme. This value is expected to rise as regulations get tighter approaching the 2050 net-zero target. However, in this analysis, the value will remain fixed since the projections of carbon valuation are already assessed along with the spark spread.

NOx emissions valuation

For NOx externality cost, the scenario of inner London was considered as this is the location of City University. The externality cost was obtained from the 2019 DEFRA's Air Quality Damage Cost Guide and it accounts for the effects of NOx pollution on human health, materials and crops. The value for the inner London case was £100,000/ton, considering that the exhaust gases from CHP applications are not at risk of direct inhalation as it occurs with vehicles' fumes and therefore the impact is lower.

Case Study

The university is located in central London and is currently using a CCHP system operated by a reciprocating gas engine. This system is connected to three buildings and its operational strategy is driven by the heating and cooling demand load.

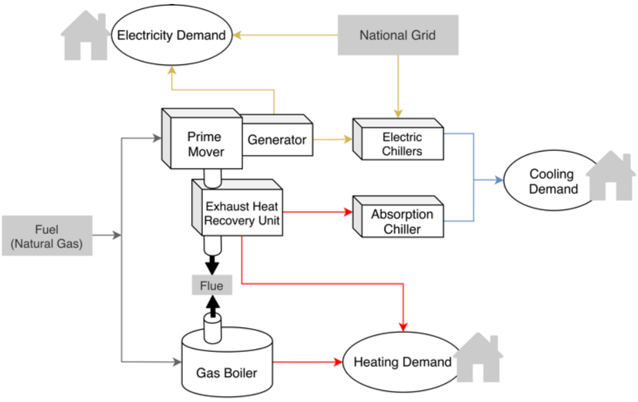

Figure 2: CCHP system

Along with the current gas engine system (GE system) and the base case (importing electricity from the National Grid and employing a gas boiler for space heating), three other prime movers are going to be considered and compared for the university's case. These alternatives are all micro-gas turbines, and for the purpose of this study, have been hypothetically designed following a current existing model and a model that is not yet commercialised.

They have been denoted as system 1 (1 module), system 2 (2 modules) and system 3 (3 modules). The prime mover of system 1 is a single 400kW$_e$ micro-gas turbine, system 2 comprises two modules of the latter, and system 3 has three modules of the market-available micro-gas turbine making a total of 570 kW$_e$. The characteristics of the GE system and the 3 micro-gas turbine systems are summarized in the *Table 1*.

Operational Strategy

The heating, cooling and electricity demand profiles *(Appendix 1)* were obtained from an unpublished study by Watts' Group for City University where the specific demand load is detailed for a sample day of each month in 30-minute intervals. These sample days were then extended over the corresponding span of each month and the estimated heat losses were evenly distributed and added to formulate the yearly demand.

System	1	2	3	GE
Electrical Output kW$_e$	400	800	570	772
Heat Output kW$_{th}$	600	1200	860	834
Absorption Chiller Power kW$_{th}$	400	800	540	540
Prime Mover's Availability	97%	98%	98%	92%
Electrical Efficiency at Design Load	40.2%	40.2%	33%	41%
Absorption Chiller Efficiency	70%	70%	70%	70%
Electrical Chiller COP	4.0	4.0	4.0	4.0
Gas Boiler Efficiency	70%	70%	70%	70%
NOx Emission Factor g/kWh$_e$	0.3	0.3	0.223	0.8
Oil Consumption g/kWh$_e$	-	-	-	0.3

Table 1: Technical specifications of the evaluated systems

Each system features a different availability based on the maintenance requirements; this is the first constraint considered when determining the CCHP's working profile. If the system is available to operate, the heat demand and the heat input required for the absorption chiller to meet the cooling requirement are compared against the prime mover's operating threshold, defined by its part-load efficiency. Below this threshold it would not be feasible to use the CCHP and consequently the demand would be entirely met by the National Grid and gas boilers.

In the case of using the CCHP, the next step is determining if the system would run at design load or at part load to fulfil the heat and cooling demand combination considering the electrical part-load efficiency and corresponding fuel consumption. Additionally, the micro-gast turbine modules run independently, therefore one of the modules could run at design load while the other at part-load or could even be shut down entirely.

The final step is to check if the system's output is enough to fulfil the customer demands or if it would still be necessary to import electricity (for running the electric chillers or for meeting the electricity demand) or the use of gas boilers (for space heating). Alternatively, excess electricity generated by the system is sold back to the National Grid at the export rate for non-solar generation.

In the event of liquid lubricants, the annual specific lube consumption would be calculated with the annual electrical generation and the prime mover's performance specification.

RESULTS

The results section is divided in emissions performance, operational costs and discounted payback period and net present value. This is to firstly understand the potential environmental and health impact of each system, secondly the annual economic performance, and thirdly to integrate the emissions performance in the economic analysis by giving a price valuation to the systems' emissions.

Emissions Performance

Carbon Dioxide

The carbon footprint of each system was calculated considering emissions from the prime mover, the gas boiler, and the electricity imported from the grid making use of the carbon emissions factor.

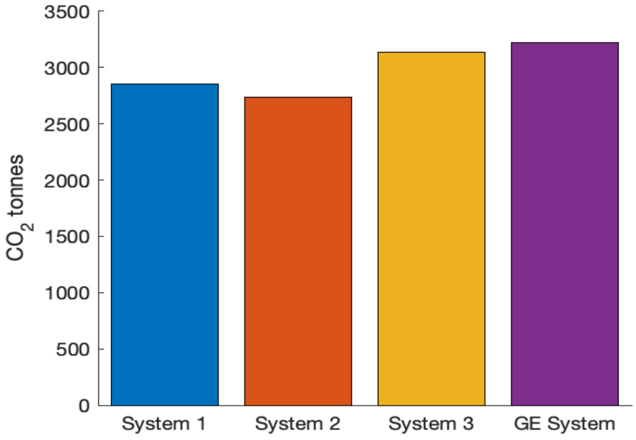

Figure 3: Carbon footprint comparison

Carbon dioxide is directly related to fuel consumption. System 2 shows the most distinguished annual carbon savings; its high electrical efficiency leads to more efficient combustion where less fuel is required for the same thermal output. The GE system also has high electrical efficiency, but due to its limited operating range, it resorts more to the grid and boiler, therefore increasing its carbon footprint.

Nitrogen Oxides

NOx emissions were estimated with the emissions factor for each prime mover and for the gas boiler. Emissions from the electricity imported from the grid were not considered.

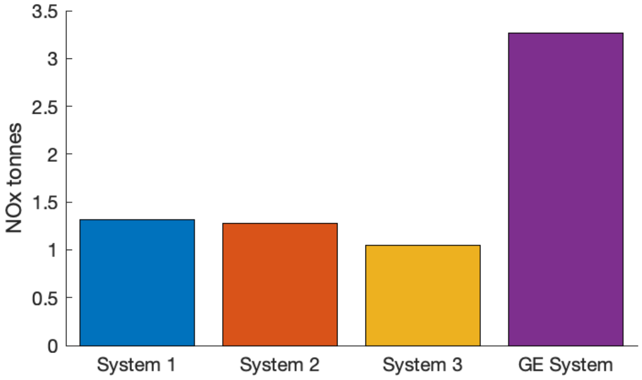

Figure 4: NOx emissions comparison

The production of nitrogen oxides depends on the prime mover technology. System 3 has the lowest emission factor, resulting in the best performance.

Oil Consumption

Oil consumption is only applicable to the GE system since the MGT's can benefit from cleaner alternatives as previously mentioned. This characteristic makes a difference between the two technologies, the results show that the GE system consumes nearly one tonne of lube oil every year.

Operational Costs

The following figure represents the annual electricity and natural gas costs correspondent to the use of the different systems. It considers the prime mover's natural gas consumption cost as well as the boiler's and imported electricity. The base case corresponds to meeting the customer's demand without a CCHP unit.

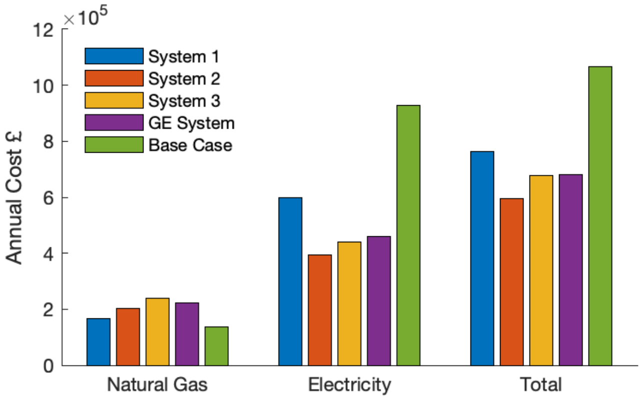

Figure 5: Annual operational costs comparison

Despite having the lowest natural gas cost, the base case is the most expensive overall due to its high electricity costs. The CCHP units have higher natural gas costs since through this source they can generate both heat and power, lowering the need for importing electricity which is much more expensive than gas.

For this combined generation to be optimum, the CHP should be sized correctly. Despite having high electrical efficiency, system 1 exhibits high electricity costs since the unit does not generate enough to meet the customers' needs and it relies on importing most of the electricity needed. For this reason, it is the least profitable among the CCHP systems regarding annual gas and electricity costs.

The cost performance of these systems is mainly determined by the unit's efficiency and working profile. This is reflected in system 3 cost performance, despite having a better operating range its lower electrical efficiency increases the fuel demand and therefore the cost. Contrarily, the GE System has high electrical efficiency but limited operating range, most of the customer demand being met by the boiler and grid.

System 2, besides great electrical efficiency, is sized accordingly to the demand. The imported electricity annual cost is reduced by more than half concerning the base case against a little increase in the natural gas cost.

Discounted Payback Period and Net Present Value

For a better understanding of these analyses, the different capital expenses considered should be contemplated first, where the costs included correspond to the prime mover unit, absorption chiller and gas compressor of each CHP system as previously discussed. It is notable the difference between gas engine and micro gas turbine technologies, considering that system 1 is the smallest sized and therefore the associated costs are lower.

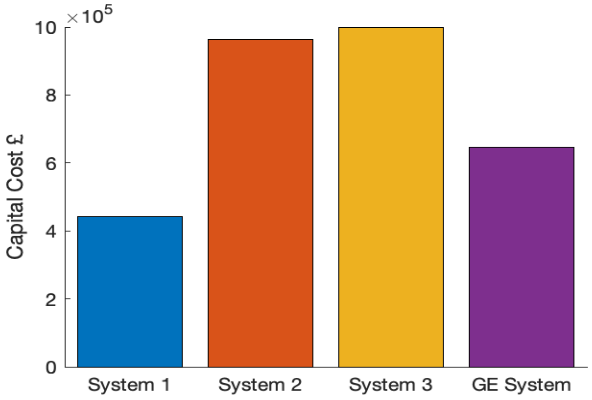

Figure 6: CAPEX of the evaluated systems

Scenario 1: No emissions valuation

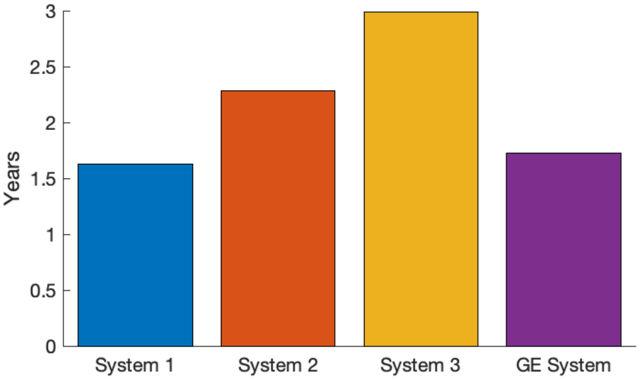

Figure 7: Discounted payback period with no emissions valuation

The capital cost contribution to the payback period is clear, systems GE and 1 having the shortest payback periods, as it would be expected from their low capital expenses. This can explain the abundance of gas engines in CHP applications. Nonetheless, all technologies would be paid-back within a competitive time range.

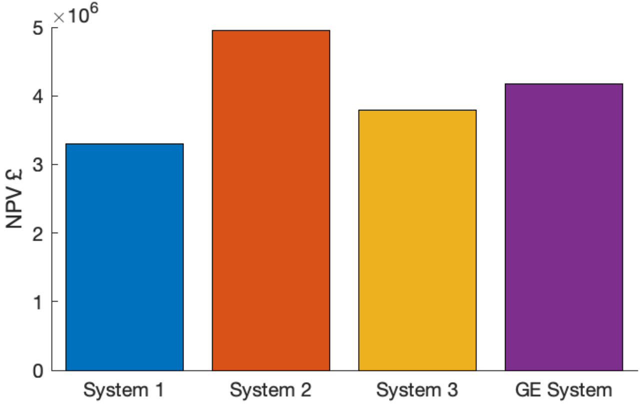

Figure 8: NPV with no emissions valuation

The NPV results show that, although having short payback periods, systems GE and 1 do not prove to be the most profitable over time. As previously discussed, the NPV is calculated throughout the unit's lifespan. Despite having higher capital costs, system 2 provides the greatest annual savings, and therefore it is the best option long-term.

Scenario 2: Including carbon valuation at £77/ton

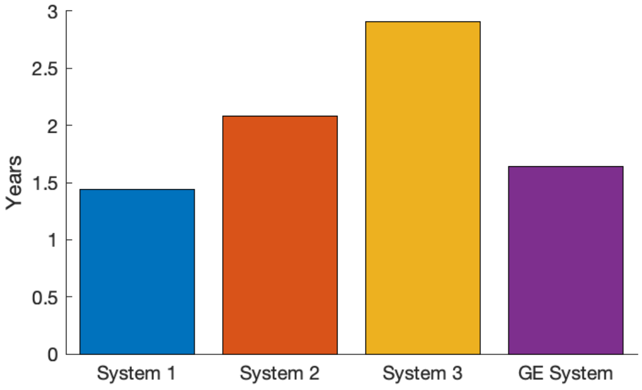

Figure 9: Discounted payback period including carbon valuation

The discounted payback periods of the systems when carbon valuation is included follow the same trend as the previous ones, although the values have decreased. This is explained as all CHP units benefit from annual carbon savings with respect to the base case. However, since carbon production depends directly on fuel consumption, the most efficient plants are those who have reduced their payback period the most; these are systems 1 and 2.

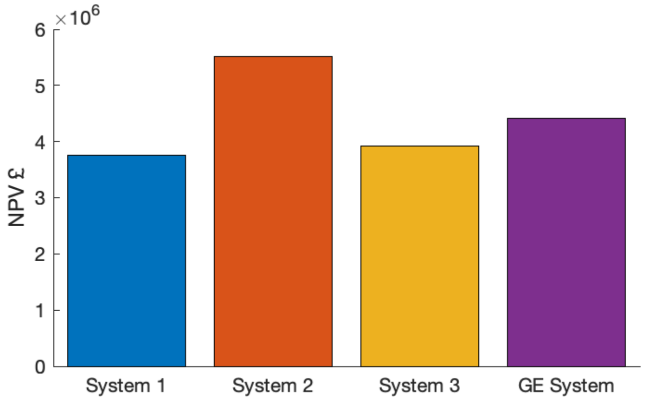

Figure 10: NPV including carbon valuation

The carbon savings are also reflected in the NPV. In this case, the values increase, giving place to more profitable projects. The same trend that for the payback period can be observed, where systems 1 and 2 profit the most.

Scenario 3: Including carbon valuation at £77/ton and NOx externality at £100,000/ton

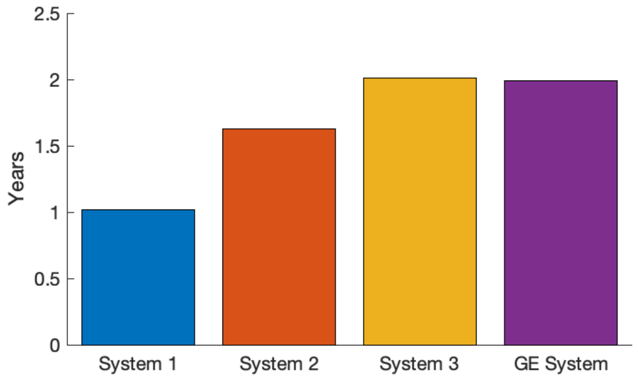

Figure 11: Discounted payback period including carbon and NOx valuations

From the discounted payback period results in *Figure 10*, it can be seen that not all systems benefit from the addition of NOx social impact. This can be explained through the different emission factors the prime movers present; the micro-gas turbines offer better emission factors than the gas engine. System 3 shows the most significant decrease in the payback period, following the fact that it is the unit producing the least NOx emissions. Contrarily, the GE system increased its payback period due to poor NOx emissions performance.

The Net Present Value has yet increased for the micro-gas turbines, the highest increment being for System 3, although system 2 remains the best option. The GE system's NPV has decreased by nearly £1m with the addition of NOx social cost.

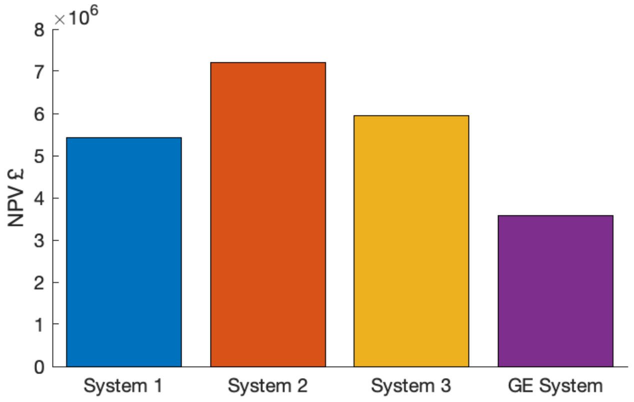

Figure 12: NPV including carbon and NOx valuations

CONCLUSIONS

Both the reciprocating engine and the micro-gas turbines have demonstrated a good economic performance and have offered a reduction in the carbon footprint with respect to the base case of grid electricity and gas boiler. However, the consideration of NOx social damage cost only appeared beneficial for the micro-gas turbine CCHP systems, as the application of a reciprocating gas engine resulted in higher NOx emissions than the base case. Moreover, the gas engine also presented the added drawback of nearly one ton of lube oil consumed per year, where the micro gas turbines comprised air or magnetic bearings instead of liquid lubricants.

The different analyses have demonstrated that, for the City university case, the application of two micro-gas turbines (system 2) has outperformed the other systems considered in this study, both when taking and when not taking into account emissions impact. This can be attributed to two factors:

- Its sizing, modularity and great operating range allows the prime mover to meet great part of the customer demands, thereby making it the system with the lowest electricity import and boiler working hours.
- Its high electrical efficiency achieves lower fuel costs and reduced carbon footprint.

In all the scenarios studied, system 2 had a relatively short payback period and the highest net present value among the options considered. It also presented the highest carbon savings and the second lowest NOx emissions.

The CCHP market continues to expand and the existence of new micro gas turbines with improved electrical efficiency should be of interest for investors, especially as new and more stringent emission regulations are being set as the energy demand continues to increase each year.

APPENDIX A

This appendix presents the average annual electricity, cooling and heating demand profiles for the case study.

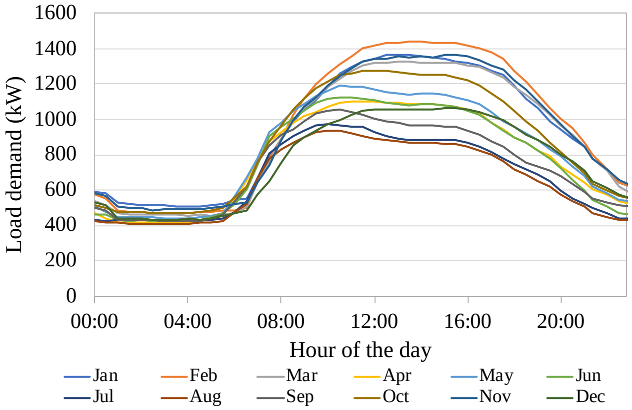

Figure 13: Electricity demand

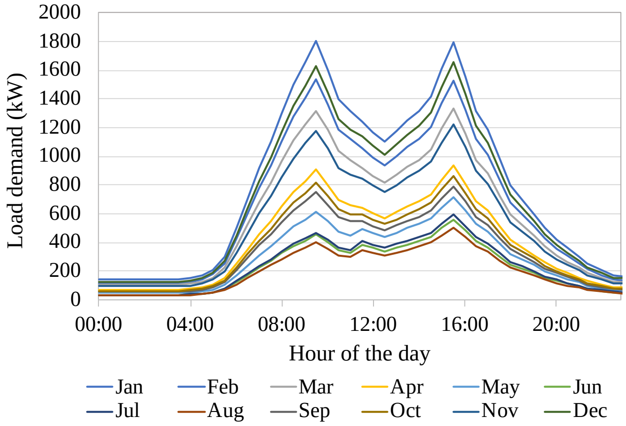

Figure 14: Heating demand

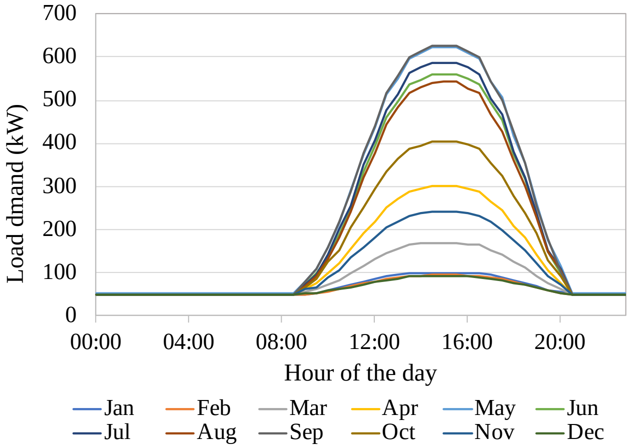

Figure 15: Cooling demand

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