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Hybrid heating and cooling system optimisation with TRNSYS

Submitted in partial fulfilment with the requirements of the degree

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Copyright Declaration

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"Earth provides enough to satisfy every man's need, but not every man's greed."

Mahatma Gandhi

Abstract

The aim of this project is to optimise the design of a heating and cooling system for a new building development, based on a real case study.

The different system configurations were simulated using TRNSYS, a transient energy systems simulation program developed at the University of Wisconsin-Madison. Detailed simulations were used to assess the advantages and inconvenient of hybrid system configurations including combined heat and power (CHP) engines and water-source heat pumps (WSHP). The comparison looked at CO_2 emissions, renewable energy share, and economic performance.

The results show that hybrid systems with adapted control strategies allow to maximise the benefits from the different technologies involved. This was particularly important when a target for on-site renewable energy production is introduced, as it often the case in sustainable building codes and planning requirements throughout the UK. In some cases, increasing the renewable energy share of single-technology systems would have required significant extra investment costs, while they could be obtained simply by modifying the control strategy of a hybrid system.

The thesis also points out the need to establish a clear definition of some of the targets often required by local authorities. Some rules currently used to assess CO_2 savings of microgeneration in residential buildings are unclear and can easily be misinterpreted. On the other hand, the definition of the renewable energy share of heat pumps used for cooling simply could not be found.

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1. Introduction and objectives

With the introduction of energy policies that target ever increasing CO_2 emission savings and a significant share of on-site renewable energy generation, a new series of challenges and concerns are presented to energy suppliers and end-users.

System designs that provide the best answer to these economical and technical challenges often require a combination of technologies, e.g. Ground-Source Heat Pump (GSHP) and Combined Heat and Power (CHP), or solar thermal / photovoltaic in combination with CHP or a conventional system. These hybrid systems are more complex to design and optimise than single-technology systems, because of the need to integrate detailed control strategies in the design problem. And since they integrate renewable energy sources and often a significant amount of storage, the design must also take into account the annual or multi-annual performance (up to 25 years for GSHP systems).

The objective of this dissertation is to present the design and optimisation of a hybrid system designed to supply the heating and cooling loads of a large-scale building development based on a real case study. The thesis presents and discusses the results obtained in designing the system and comparing it to “single-technology”, or non-hybrid, system configurations.

Chapter 2 presents the broad context of this study, including the historical events that led to the actual concern over the impact of energy generation at the environment, including an example of the kind of action being taken to control those impacts. The next sub-sections go through the basic information related with the two main technologies utilized in the case study: Water source heat pumps and combined heat and power. The concept of hybrid systems is then presented and its potential advantages are discussed.

Chapter 3 explains the methodology utilized to simulate the energy systems performance evaluate the outputs of the simulations and provides some details on the models used in the simulations. . First, the definition of CO_2 emission savings and renewable energy fraction is discussed, and the need for clarification of both definitions in building codes and local planning documents is pointed out. The case study and the base case configuration are then described and some key simulation assumptions are presented. The base case configuration is the system that will serve as a basis to assess the performance of all other configurations. Economic calculations are then presented and applied to the base case system. Capital, operational and maintenance cost used in this study are provided. The last part of chapter 3 is dedicated to the heating and cooling systems, and the different configurations including heat pumps and combined heat and power are described.

In chapter 4 the results from a series of simulations are presented and analysed. The simulations were divided into two main groups: first without limitation on the design capacity of the different system components, then using component sizes obtained from the design team involved in the real case study. The second group of simulations is also used to perform a sensitivity analysis to assess the impact of the methodology employed to assess the simulation outputs.

The most relevant findings and results are then summed up in the last chapter, “Conclusions”.

2. Background

2.1. Historical motivation

Through history, different sources of energy have been explored in order to supply human needs. Since the beginning, this energy extraction, even though in a smaller scale, has followed some kind of environmental depredation. Initially the burning coal, utilized in large scale to feed steam machines, in the early 19th century, gave place to the oil that, with the energy crisis of 1973 and technological development, opened space to a broader variety of sources, including here a higher penetration of electricity generated by renewable sources into the market. (1)

Although new technologies have been created to allow and optimize the extraction of energy from a large amount of natural sources, its availability is not evenly spread around the globe, making many nations still dependent on the traditional fossil fuels, which can be transported and stored conveniently. Added to this, is the actual growth of energy consumption. Being able to generate or extract energy from new sources is not enough. It is necessary to follow the continuous expansion of consumption. The picture below (1) compares the electrical demand at 1995 and the predicted one at 2010, discriminating the origin of that energy.

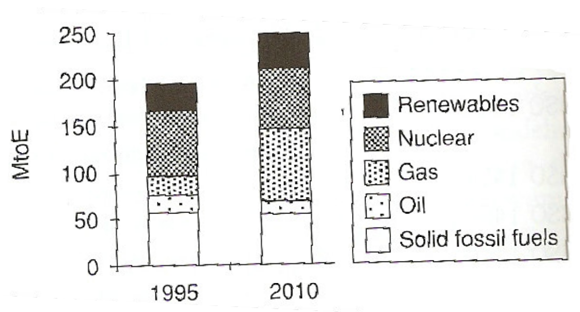

Figure 1 - Electrical consumption and energy source

If classical economic theory was applied to energy generation, it would indicate that society would be following the lower cost generation method. And it did happen for a period of time, but is not the case anymore. One of the reasons is the reduction of the availability of some sources, such as oil and gas, not just naturally raising the prices but also making consumers of this kind of energy possible hostages of the provider. Another point is the resultant amount of pollutants thrown into the atmosphere as consequence of this kind of generation. Some cities have reached pollution levels that make living in these areas as dangerous and unhealthy as being exposed to a nuclear leakage like Chernobyl (2) .

The governments of different countries, at this point, felt the need to step in and create stricter rules and targets regarding the energy generation, aiming the reduction of pollutants and the dependence of fossil fuels.

One example is the Edinburgh code for sustainable buildings which states that “a minimum of 10% (20% in Areas of Major Change developments of 2000 sqm or 20 residential units or more) of its remaining energy requirements to be supplied by on site renewable energy generation. This on-site renewable energy generation must provide at least a further 10% (20% in AMC’s) reduction in the development’s CO_2 emissions” (3).

Two technologies that have been gaining importance with this new reality are explained in the next sub-sections: Heat pumps and combined heat and power systems.

2.2. *Heat pumps*

Heat pumps are equipment that do exactly what their name suggests. They pump heat from one source where it is abundant or not necessary, and deliver to a second point, the heat sink. No energy is generated, just replaced, making the heat pumps different from most of the heating technologies, which utilize a combustion process to convert a primary source of energy into heat and is very often related with sensitive amount of losses.

With a moisture content of 20%, one kilo of hardwood woodchip may produce in a complete combustion process, 15.1MJ[*] of energy. Just 80% of this is usually converted into heat at a biomass boiler, given its usual efficiency. With heat pumps, one unit of energy is used to extract around 3 units from the source and deliver at the sink. There is no energy conversion and correctly selecting the sources and technologies may further improve this relationship. In the case of utilizing a renewable source to drive the heat pump, the heating or cooling process may happen almost free of CO_2 emissions.

The high efficiency of the heat pumps, including environments of extremely cold or warm weather (4), the capacity to add renewable energy to a heating load and the possibility to work combined with electricity generated through renewable sources make the heatpumps attractive options when dealing with

[*] Based on a calorific value of 4.2 kWh/kg for hardwood (21)

a sustainable development. More details about the heat pump technology are shown bellow.

2.2.1. Heat pump principle

Changing thermal energy at low temperature to thermal energy at a higher temperature is the main principle of a heat pump. To achieve it, the working fluid is submitted through different pressure levels and change of states. The picture below is a simplified illustration of what happens with the working fluid during the heating process.

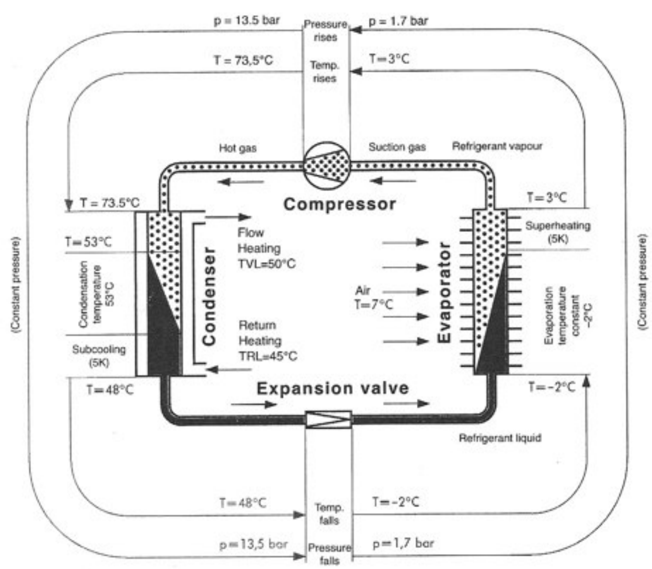

Figure 2: Heat pump cycle (5)

At low pressure and temperature, the refrigerant liquid is driven to the evaporator, where heat exchange happens with the heat source. Being at a lower temperature than the source, heat flows to the working liquid, which results into a change of phase from liquid to vapor state. The refrigerant is then driven through a compressor, where a pressure rise takes place, followed by a rise of the liquid temperature. The now heated refrigerant passes through a second heat exchanger, the evaporator, where energy flows from the working fluid to the heat sink. With the energy reduction, the refrigerant changes state once more, becoming liquid and being pumped back towards the evaporator, passing first through an expansion valve, where the pressure is reduced. As a consequence, the temperature of the working fluid also reduces. The cycle, then, starts again.

2.2.2. Coefficient of performance

The performance parameter for a heat pump is known as coefficient of performance, COP, which compares the quantity of heat transferred between source and sink with the network input to the cycle, usually in the form of electricity, supplied to the compressor. The definition is:

$$COP = \frac{Delivered\ heat\ energy}{Network\ input\ to\ the\ cycle}$$

It is desirable to deliver or extract a certain amount of energy from a given ambient with the minimum expenditure of work. In order to understand which conditions may improve the COP of a system, one must understand that, following the second law of thermodynamics, the COP of a cyclic device operating between two given reservoirs, with different thermal energy stored, can't be greater than a device operating on the reverse Carnot cycle. This cycle consists into two reversible isothermal processes, and two reversible adiabatic processes.

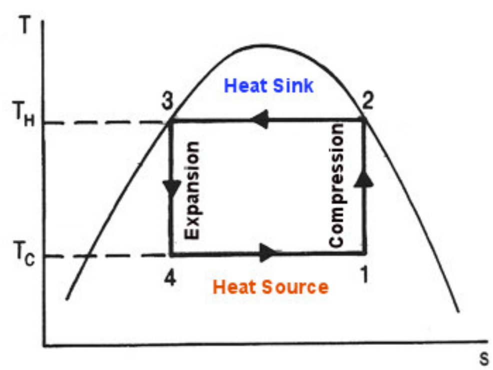

Figure 3 - Carnot cycle

Imagining a heat pump working in such conditions, with the isothermal process happening at the heat source and sink, and the expansion and compression happening in an adiabatic process, the COP may be defined by:

$$COP = \frac{|Q_{heat\ source}|}{|W_{compressor}| - |W_{expander}|}$$

After some simplifications, leads to:

$$COP = \frac{T_{Source}}{T_{Source} - T_{Sink}}$$

From there is easy to observe that, the smaller the difference in temperature between the reservoirs, the greater will be the COP.

Given to practical difficulties associated with the reversed Carnot cycle, modifications are made in practice at the heat pumps. For example, the evaporation process is allowed to continue to the saturated vapor line. Another modification is the fact that the expansion process is replaced by a throttling valve where the refrigerant undergoes an irreversible isenthalpic process.

2.2.3. ***The ground source heat pump***

Heat pumps can be classified according to its function (heating, cooling, domestic hot water, etc), heat source (ground, ground-water, air, etc) and working fluids (brine/water, water/water, air/air, etc) [2]. The ground source heat pumps use the soil or the water present in it as the heat source or sink, depending of the desired application. The advantage of having the ground as a sink or source is its stability and elevated temperature through the year, when compared with, for example, the air. This attribute allows a higher COP during severe climatic situations (summer or winter) where the difference between internal and external temperature is more sensitive.

If water is available at a reasonable depth and temperature, its utilization as source allows the achievement of the highest COP. Water heat pumps can also work with certain surface water, like from rivers or lakes, and water in heat rejection systems.

One of the possible configurations is knows as open system (also open source or loop). Water is pumped from the source (water bed, lake, river, etc), circulates through a heat exchanger and then returns to the origin.

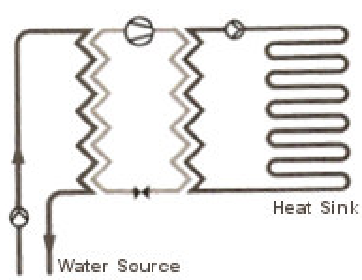

Figure 4 - Open loop configuration (5)

If water is not available, the ground can work as an effective heat source or sink. Horizontal or vertical collectors, depending of the available area, are buried into the ground and a working fluid, circulating into them, extracts the energy that will be used into the heating process (or delivers the heat in the case of cooling). This configuration may also be utilized at water source heat pumps, in places where the open system is not desirable. In this case, the heat collector will be placed inside the water bed.

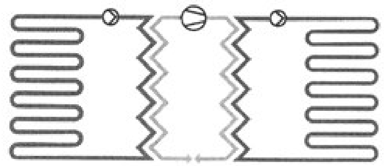

Figure 5 - Closed loop configuration (5)

2.3. Combined heat and power

The most conventional forms of electricity generation works through the conversion of heat into mechanical power, which is then converted to electricity. The process usually presents overall efficiency around 40%, not counting losses related with the transmission of the generated electricity until its final point of consumption.

The low efficiency comes from the fact that part of the available initial energy is lost in the form of heat. Creating schemes that may use this unused heat will raise the system efficiency. Also, having the generation and consumption points located close from each other will reduce the transmission losses.

Combined heat and power plants works exactly over those points. Electricity and heat are generated together, with the system usually supplying part of the heat requirements and importing any extra energy needed. Also, at moments of low electrical consumption, electricity may be sold to the grid. Since the CHP plants need to be close to the heating load, in order to avoid thermal losses, electrical losses are also reduced. Using the heat that at other schemes of electrical generation would be lost makes possible the achievement of a 90% overall efficiency.

The picture bellow shows two options for a given location that needs heating and electricity supply. First one, electricity and heat are generated independently, the second, through CHP (still connected to the grid).

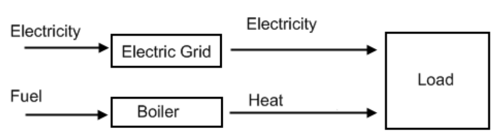

Figure 6 - Gas boiler energy flow

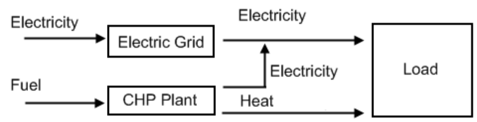

Figure 7 - CHP energy flow

Two efficiency figures are used for CHP. The first one, already commented before, is the overall energy efficiency. It compares the amount of the energy supplied to the load with the total of energy in the fuel consumed.

$$\eta = \frac{Q+E}{Q_{Fuel}};$$

Q = Heat supplied to the load
E = Electricity supplied to the load
Q_{Fuel} = Total energy supplied by the fuel

Other way to quantify the efficiency of the CHP plant is through the incremental electrical efficiency. It compares the electricity generated with the total of heat that was actually used for that generation (6).

$$\eta_E = \frac{E}{Q_{Fuel} - \frac{Q}{\eta_S}}$$

Q = *Heat supplied to the load*
E = Electricity supplied to the load
Q_{Fuel} = Total energy supplied by the fuel
η_S= Thermal efficiency of steam production with a conventional boiler

It is also important to say that CHP generation may be divided into two different groups of systems. The first one utilizes the heat generated by the fuel to first produce electricity and then the thermal energy at lower temperature is utilized to produce steam. These are called Topping Systems. They are more common where the heating requirements do not need high temperatures.

The Bottoming Systems utilize the heat from burning the fuel first to satisfy the heating needs and then the residual heat is used to produce electricity.

Several different schemes may be used to achieve a combined heat and power generation. They differ from the kind of primary energy source utilized (biomass, coal, liquid fuel, gas), the driving engine (steam turbines, gas turbines, reciprocating engine, etc)or even of how the thermal energy is used.

The table bellow compares typical configurations and its energy consumption.

TABLE 1
COMPARATIVE PRIMARY ENERGY SAVINGS

SYSTEM		ENERGY PRODUCED kWh	COGENERATION		CONVENTIONAL		SAVINGS % OF PRIM. ENERGY
			OVERALL EFFICIENCY	PRIMARY ENERGY CONSUMPTION kWh	EFFICIENCY	PRIMARY ENERGY CONSUMPTION kWh	
Gas turbine	Electricity	26.5	–	–	0.33	80.3	–
	Heat	54.4	–	–	0.93	58.5	
	TOTAL	80.9	81%	100	–	138.8	28
Gas turbine with post-combust.	Electricity	17	–	–	0.33	51.5	–
	Heat	69.7	–	–	0.93	74.9	–
	TOTAL	86.7	87 %	100	–	126.4	21
Steam turbine	Electricity	15	–	–	0.33	45.5	–
	Heat	75	–	–	0.93	80.6	–
	TOTAL	90	90%	100	–	126.1	21
Reciprocating engine	Electricity	36	–	–	0.33	109	–
	Heat	34	–	–	0.93	36.6	–
	TOTAL	70	70%	100	–	145.6	31

Table 1 - Primary energy savings (6)

An important point at this moment is to highlight what has been said before about the electrical generation. It was supposed that the electricity generated and not used would be sold to the grid. Some times and locations such option may not be available, or even may not be economically interesting (with the price of the electricity being sold bellow the price for the imported electricity). The combination of the CHP system with heat pumps may be an interesting option to ensure that electricity and heat will be generated when there is a requirement for it. In other words, may be interesting to create a system where part of the thermal load will be supplied by a CHP plant and the other part will be supplied by a heat pump system, using the electricity generated by the combined heat and power process.

The thermal losses related with these processes may be a problem.

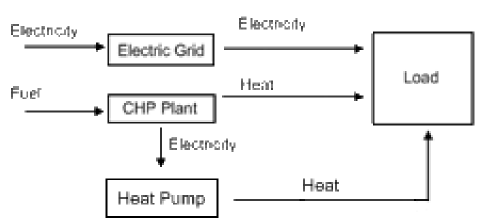

Figure 8 - Hybrid system energy flow

2.4. *Hybrid systems*

At a big transmission system, the power drawn by the customers oscillates expressively during a day. Taking a city as example, while at late hours of night, or early mornings, as most people are sleeping, the energy consumption is mostly from street lights, domestic equipment on idle mode, etc. At early evening, this consumption rises noticeably when people return to their homes, and commercial and industrial facilities are still operating. It is important to have this information to mind when, for example, it is planned to raise the participation of renewable energy sources into the energy production, as matching demand and generation may be a problem. Sun energy is only available a few hours a day and the wind levels may drop exactly when the demand for energy is high. Biomass boiler can rapidly burn more fuel to follow the demand variation, but its relatively low turn down ratio* makes it hard to match the peak demands or the hot water demand during summer months.

Combining different renewable technologies, or even traditional energy generation methods, may raise expressively the reliability of a system, still reducing its final CO_2 footprint. These arrangements, where the energy from different sources is combined in order to achieve the same end, are called hybrid systems. In the preceding example, the biomass boiler could have a traditional gas boiler running as backup, supplying the peak load during the winter or the hot water demand during the summer, with the base load being supplied by the biomass. This is a small example of a hybrid system.

For heat pumps, the expression hybrid system is often related with the presence of different heat sinks (or sources), aiming the reduction of the imbalance between heat extraction and rejection during the year, at locations with a predominant weather (7). A number of studies were made in this areas including utilizing simulation tools in order to optimize these systems (8) (9). In these cases, the optimization process compared heat exchanger options and sizes, also observing the best control methodologies for a specific application. What we plan to do at this dissertation is observe the optimization process where the heat pump will be dealing not with an extra heat sink/source, but an entirely different technology.

The optimization of such systems will depend on not just knowing the particularities of each technology involved, but also the creation of a specific

* Turn down ratio is the relationship between the maximum and minimum power output of the boiler. The minimum output is defined by the minimum value at which the boiler will work with high efficiency.

control system to coordinate how they will relate between themselves and the objectives to be achieved.

The problem of dealing with renewable technology is that the site environment, responsible by the consumption behavior, has also great influence over the generation capacity. This makes it more difficult for a designer to work with pre prepared templates. The solution found at location A may not be applicable at location B, even though both utilize similar systems. The capacity to simulate how all the variants will behave is a powerful tool during the design of these systems, giving enough flexibility to the designer to play with the variants, comparing the obtained results and through that, optimizing the system.

During the optimization process, the control system must be very well defined, since it will influence the required size of equipment, storage tanks, etc. Circuit connections and fluid temperatures may change expressively depending on how the control will coordinate the different technologies. The start-up period of a biomass boiler may be reduced using the backup gas boiler to pre heat its internal lining. This may have impact over the necessary storage tank. One can’t define if the storage tank is over or undersized without knowing the details about the heating circuit. Just looking for the system load and boilers won’t give an accurate answer.

Another aspect that will define the efficiency of a system is its financial data. Given the complexity of the energy changes that may happen in a hybrid system, it may be complex to get a precise feedback about the financial savings that can be achieved without the presence of a simulation tool.

3. Methodology

This chapter will be dealing with the assumptions made and methods utilized during the analysis of the results, at chapter 4.

It starts discussing the CO_2 emission and renewable energy fraction calculations. Being introduced for the first time to the emission factors table in the government's Standard Assessment Procedure for the energy performance of dwellings (SAP) **(10)** some people may feel unsure how those values must be used. Section 3.1 utilizes simple examples and formulas explain how SAP was utilized at the present dissertation and the reasons for it.

In section 3.2, the importance of how to define a system renewable energy fraction is discussed. The main point of this sub-topic is to highlight the importance to have a better definition of the capacity of a heat pump to supply renewable energy and how it must be counted.

The remaining sections introduce the studied system, its loads, heating circuits' configuration and how the data received was manipulated in order to be utilized at TRNSYS. The base case, from where the results will be used as reference for comparing the outputs at the simulation stage, is also presented.

In addition, in this chapter can also be found the method utilized to define the financial gains delivered by each studied system, including here the equipment, operational and maintenance costs.

3.1. CO_2 emission, conversion factor and savings

During the result analysis, an important output is the CO_2 emission related with the energy production.

Tables relating the amount of CO_2 emission with the used energy source can be found at different literature, such as *Defra's green house gas conversion factor guideline* (11) or *the government Standard Assessment Procedure for the energy performance of dwellings, SAP 2005-2008* (10), both used as reference in this study. For heating, the process is quite simple, once it does not involve a complex and large network, such as with electricity. The total amount of CO_2 emitted will be the total of fuel consumed multiplied by related conversion factor.

The CO_2 emitted, although important information, does not give a precise idea of how effective the generation process really is. A good idea is to divide the total CO_2 emission by the total energy delivered, resulting into the amount of CO_2 per kWh of energy made available (what is basically the local conversion factor).

In the case of electricity, the discussion becomes a more complex. Once the electricity is generated, there are two possibilities: it will be locally utilized or sold to the grid.

The first option will reduce the load seen by the grid as if energy savings methods were applied, like higher building insulation or efficient lighting installed.

To calculate the local emissions, SAP suggests the following method:

- *The total emission of the generated electricity must be calculated;*
- *In case of electricity exported to the grid, the total energy must be multiplied by a base conversion value and then subtracted from the previous result;*
- *Energy consumed must be multiplied by the grid emission coefficient.*

An interesting point is that SAP applies a different conversion value to the electricity displaced from grid (0.568 kg CO_2 per kWh) and imported from the grid (0.422 kg CO_2 per kWh). This may cause some discomfort to who is first introduced to the formula since consumption and production are completely related activities and one might expect that both have the same conversion value.

To avoid instability problems in the grid, production and generation must match. When a new source of energy is added to the grid, maintaining the load, somewhere one or more plants must reduce their production. The amount of CO_2 being produced changes, and its magnitude will depend of how much CO_2 the new source is producing to generate the displaced power. An example is given below.

First let's imagine the CO_2 emitted by **the energy producer**:

Power is being generated by the main producers connected to the grid, each one with its related emission coefficient, which multiplied by the energy production gives the total CO_2 emission. It can be said that the total emission will be the total production times a conversion factor.

$$E_1 * c_1 + E_2 * c_2 + E_3 * c_3 + \cdots + E_n * c_n = c_{av} * \sum_{x=1}^{n} E_x$$

Where E_n represents the energy generated by the producer n and C_n the related emission coefficient. For example, if 10 MWh was generated by a gas turbine with efficiency of 40%, the emissions would be: 10 000 x (0.194/0.4) kg of CO_2. The value inside the bracket can be interpreted as producer emission coefficient. Once the left side of the equation above in known, c_{av} can be defined.

Now let's observe the CO_2 emitted from the perspective of the **energy consumption:**

Since the energy generated will be consumed somewhere, can be said that the CO_2 emissions related with the generation must match the emissions related with the consumption. Being the left side defined by the energy production, the right might represent the CO_2 emission from the demand side where $\sum_{x=1}^{n} E_x$ can be seen as the total energy from the grid consumed and c_{av} the grid emission coefficient.

A base case can be then built, imagining a system with a heating demand of 50 kWh and the electrical one of 20 kWh. This energy will be supplied by the grid and a gas boiler with 80% efficiency:

	Load (kWh)	Efficiency	Used energy	Emission coef. (kg per kWh)	Kg of CO_2 emitted
Heating	50	80%	63	0.194	12.1
Electricity	20	100%	20	0.422 (c_{av})	8.5
				Total	**20.6**

Table 2 - Example CO_2 emission

It is assumed now that this same consumer has a gas turbine, with efficiency of 40% connected to the grid, not supplying any energy directly to his building. The load on site does not depend of the generation. Somewhere, less energy will be produced to balance this surplus added to the grid. This reduction can be concentrated at a specific plant or spread at several ones. For simplification reasons, it will be assumed that just one plant will have to reduce its production. E3, for example. The new CO_2 emission will defined be as shown below:

$$E_1 * c_1 + E_2 * c_2 + (E_3 - E_{new}) * c_3 + \cdots + E_n * c_n + E_{new} * c_{new} = c_{av2} * \sum_{x=1}^{n} E_x$$

Which can also be written as:

$$E_1 * c_1 + E_2 * c_2 + E_3 * c_3 + \cdots + E_{n*} c_n + E_{new} * (c_{new} - c_3) = c_{av2} * \sum_{x=1}^{n} E_x$$

E_{new} and c_{new} represents the amount of energy and the emission coefficient of the new source (gas turbine in the example).

Is interesting to observe that "$E_{new} * (c_{new} - c_3)$" does not represent the CO_2 emission of the new source, but its contribution over the changes at the total CO_2 level, giving credit to the "clean" producer over the new emission. Its importance becomes more evident when the calculation done at table 2 is repeated.

It is understood that the new energy source changed the emission factor value, but wouldn't be practical to keep the table constantly updated. What happens is that most of the time this value is changed at yearly bases. This means that if a consumer calculates its CO_2 emission, the table 2 wouldn't change. What happens is that, now, the credit from the cleaner producer must be applied. The right side of the previous formula can be rewritten as:

$$c_{av} * \sum_{x=1}^{n} E_x + E_{new} * (c_{new} - c_3) = Total\ Co2\ emission$$

Or, showing the entire system

$$E_1 * c_1 + E_2 * c_2 + (E_{3-}E_{new}) * c_3 + \cdots + E_{n*}c_n + E_{new} * (c_{new}) = c_{av} * \sum_{x=1}^{n} E_x + E_{new} * (c_{new} - c_3)$$

SAP defines c_3 (the emission coefficient of the electricity displaced from the grid) as 0.568. Looking for the new consumer that now is also a producer, the following table is built:

	Load (kWh)	Efficiency	Used energy	Emission coef. (kg per kWh)	Kg of CO_2 emitted
Heating	50	80%	63	0.194	12.1
Electricity	20	100%	20	0.422 (c_{av})	8.5
Gas turbine	-2	60%	3.3	(0.194-0.568)	-1.2
				Total	**19.4**

Table 3 - CO_2 emission including gas turbine

The site is receiving credits for the generation of a cleaner energy. But how would be the same table if the energy produced was utilized on site, not sold to the grid?

	Load (kWh)	Efficiency	Used energy	Emission coef. (kg per kWh)	Kg of CO_2 emitted
Heating	50	80%	63	0.194	12.1
Electricity	18	100%	20	0.422 (c_{av})	7.6
Gas turbine	-2	60%	3.3	0.194-0.568	-1.2
				Total	**18.5**

Table 4 - CO_2 emission including local generation

Observe that the emissions related with the gas turbine did not change. The question that comes in mind is: Why the same case is giving different results?

The answer is because the calculation of the gas turbine emission, at table 3, defines its contribution to make the electricity present over the grid cleaner or not, rather than its real emission. The rest of the CO_2 will be spread all over the grid, between all the other consumers (that will be using the 0.422 as emission factor).

When the turbine was connected to the load, the destination of the electricity became known, so now what should be defined is the real emission, and not the contribution over making the grid cleaner or not. There is no electricity going into the grid. And there is the mistake: The displacement factor was used wrong. Utilizing SAP table correctly would give me:

	Load (kWh)	Efficiency	Used energy	Emission coef. (kg per kWh)	Kg of CO_2 emitted
Heating	50	80%	63	0.194	12.1
Electricity	18	100%	20	0.422 (c_{av})	7.6
Gas turbine	-2	60%	3.3	0.194~~-0.568~~	0.6
				Total	**20.3**

Table 5 - CO_2 emission no surplus

The displacement coefficient just can be applied if the total **grid load** does not depend of the amount of energy being sold. If electricity that could be internally used starts to be sent to the grid, the total grid load will change, making the previous formula inaccurate. This observation is important since misunderstanding what SAP table means or using it with malice may show lower emissions than the real ones. Someone producing 1 MWh from an emission free source and consuming 1MWh would calculate negative emission, instead of the real zero, if all the production was sold to the grid.

The important point to be aware here is that no energy production from other sources will be reduced when electricity is being sold to the grid while there is still internal load to be supplied. It is being reduced $(E_{surplus} + E_{load)}$ and then required E_{load}. Observe that this energy consumed from the grid will have the same emission coefficient of the source that ended up not being replaced (here represented by C_3 or 0.568 from SAP data), and not the grid average.

The picture below represents 3 possible situations and illustrates how the calculations should proceed. The grid emission coefficient is 0.422, the displacement coefficient is 0.568 and the generation coefficient is 0.

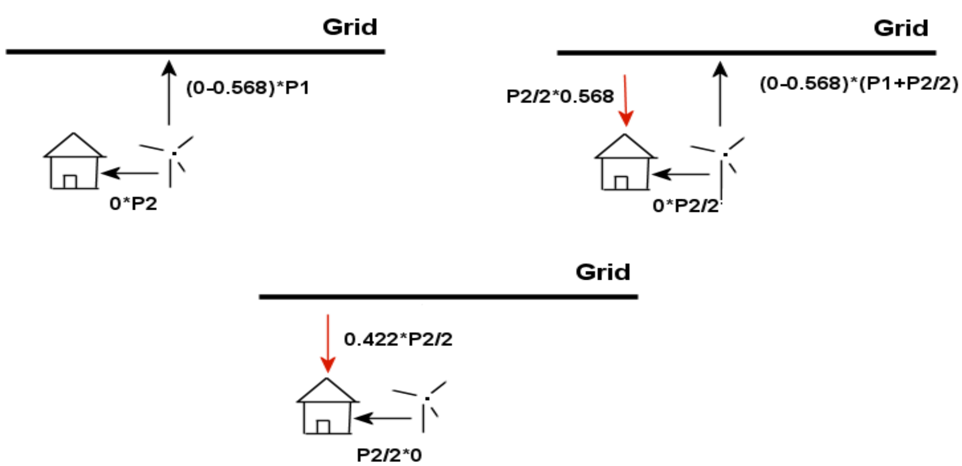

Figure 9 - CO_2 calculation

These examples may also show the importance of defining how much of the produced energy was actually used on site or not, which, somehow, will depend of the instantaneous values of production and generation. At part 4.2 this relevance is explored using the case study.

3.2. Renewable energy fraction

In part caused by the rise over the price of fossil fuels and the exhaustion of its local sources, governments all around the globe are realizing the importance of updating their energy infrastructure. UK government, for example, adopted a policy to achieve a 10% of renewable participation over the electricity generated (12). In March 2007, the European Council committed the EU to a binding target of a 20% share of renewable energies in overall EU consumption by 2020 (13).

These policies all have in common the focus not just on CO_2 emission, but the share of renewable energy over the total energy generated (or consumed). Energy producers now need to lead with renewable production targets and, of course, be able to deal with them.

The "London design and construction planning guidance" (14), for example, states that "*Major developments are required to show how they will generate a proportion of a scheme's energy demand from renewable energy sources, where technologies are feasible. The Mayor's Energy Strategy states that this proportion should be a minimum of 10percent".*

The first point is to make clear what is this proportion is calculated. Basically, the renewable energy faction can be seen as the share of e (14)nergy supplied by a renewable source over the total of energy consumed. This calculation can be quite straight forward when looking for electrical generation but when the energy is in the form of heat, some problems may occur, specifically when dealing with heat pumps.

A public consultation held in 2006 by the EU Initiative on heating and cooling from renewable energy sources pointed one of the main obstacles to a wide-spread of such technology the following problem:

- *Heat pump status (renewable energy technology or not) not harmonised in all Member States*

At U.K, heat pumps are accepted as renewable heat sources and its importance over the EU target of renewable share is highlighted (13) (15). But some points are not yet clear.

Is easy to define the renewable heat share during the heating cycle. The total heat supplied by the ground will be the total load minus the total electrical consumption. But what happens when the load is not heat but cooling?

The heat pump will still work in the same way, just changing its heat source and sink positions. This time it will see the ground or river as the load to the heat being displace from a building. The problem is that the building load (cooling) is the system heat source.

Some may affirm that under this configuration there is no renewable participation over the load (cooling), unless it comes from the electricity consumed by the compressor. The difficulty to fight this argument is to define what would be “renewable cool”. Any cooling load can be seen as a heat source, and it includes traditional chillers.

Cooling systems, in analogy to heating ones, may be classified as active or passive, according to whether energy is specifically added in order to bring the collector heat gain from the load areas or not (16). A passive cooling system output does not depend of energy input provided by man. An example would be a thick wall designed to, during day, absorb heat from the interior of a building and during night, transmit it to its surroundings. The heat transfer is driven by the temperature difference between the wall and the interior of the building, during day, and the external temperature during the night. Observing the cooling load (the amount of heat that needs to be displaced in order to keep acceptable temperature levels), what was the renewable participation over it? It may be accepted that, given the fact that there was no energy input by the man, the entire load was supplied by renewable sources.

Imagining now that the specifically designed wall is not present and the heat from the building is absorbed by a heat exchanger, through which circulates cool water. The heat absorbed is still thrown away from the building but now the temperature difference is achieved by, between other processes, an electrically driven compressor. The principle is the same: Using temperature difference to create the desired heat flow. If previously the renewable participation over the load was 100%, what can be defined in this new case? Imagining that the electricity supplied by the grid is equivalent to ¼ of the total cooling load, one may, by analogy with what was done with the wall case, say that the renewable participation is ¾.

This approach does seem consistent with what was done with the heat pump at the heating process. So during the cooling demand it could be said that the renewable energy is the total load (cooling) minus the non renewable one utilized to drive the process.

This is, although, one assumption and does present flaws. There is no clear position about how to count the renewable share for cooling. One of the reasons may be the fact that, if this analogy, or any other similar, is accepted, the traditional air-conditioning systems may also be able to find a renewable share over their load. Heat pumps are being sold as renewable sources of energy but no attention is being clearly giving to this issue. Although green cool is mentioned (5) no explanation about how to calculate it is done.

Because of this discussion, the calculation of renewable participation over the load will count the entire energy from cooling processes as not renewable. Not because it is the correct one, but because would be the easiest to be accepted at building allowances.

3.3. Simulation description

3.3.1. Case study

The simulations will be based on a real project in Scotland. The project involves different kind of buildings, from commercial, residential and offices to hotels. In the system configuration currently being considered by the real project design team, their heating and cooling loads are mainly supplied by three different technologies: An open loop water source heat pump, a closed loop water source heat pump and a CHP engine. The three technologies are completely independent, each one supplying energy to a different group of buildings, with the two heat pumps and the CHP engine having a capacity of 1.8 MW(th)each.

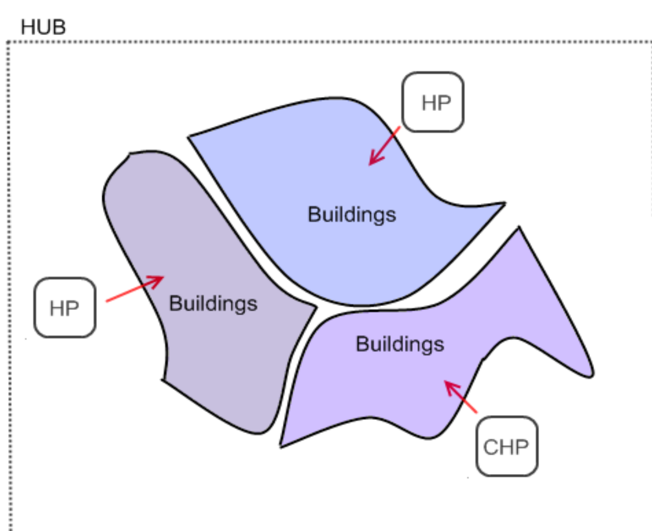

Figure 10 – Case study

The first series of simulation will be looking the entire project as one unique huge load and will observe how different heat sources can supply its demand.

3.3.2. Loads

The data received assumed that the load behavior will repeat daily, meaning that the peak demands and moments of lower consumption will happen always at the same time, as show below.

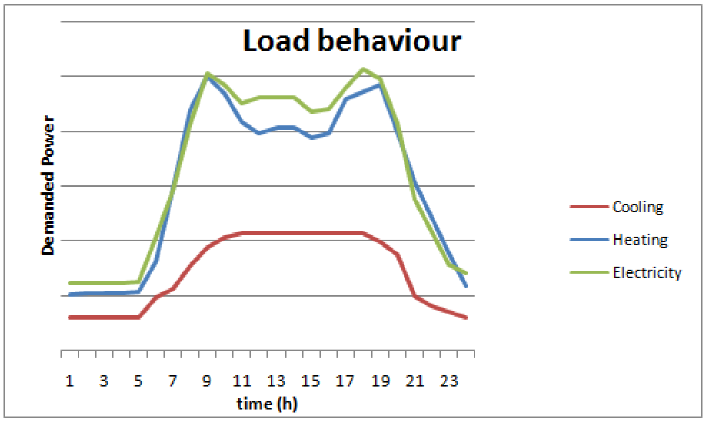

Figure 11 - Daily load behaviour

It was also supplied some data regarding the annual consumption for each kind of energy. Although an important information, it, alone, is not enough to be used by TRNSYS.

TRNSYS allows the user to define the time steps at which the calculations will be done. This value depends of the nature of the project but, does not matter the magnitude selected, the data must match the time step selection. In other words, is not sensitive to run a simulation with a time step of 30 minutes when the load or weather data just informs weakly values. It was necessary to convert the submitted information into something applicable to TRNSYS.

This process will be explained using the heating load as example.

3.3.2.1. Heating Loads

The total heating demand at the district is of **26 000 MWh** per year. This value includes space heating and domestic hot water.

As said before, it was necessary to create an, at least, hourly based load profile. The peak demand during the coldest day was defined at 14 MW, based at the load duration curve generated by this value and the size of the original heat sources. It was also defined that at days with average temperature above 16 °C there will be no heating requirement.

With those assumptions and the heating load behaviour, it was possible to generate a load profile related with the daily ambient temperature, through the year, as shown below:

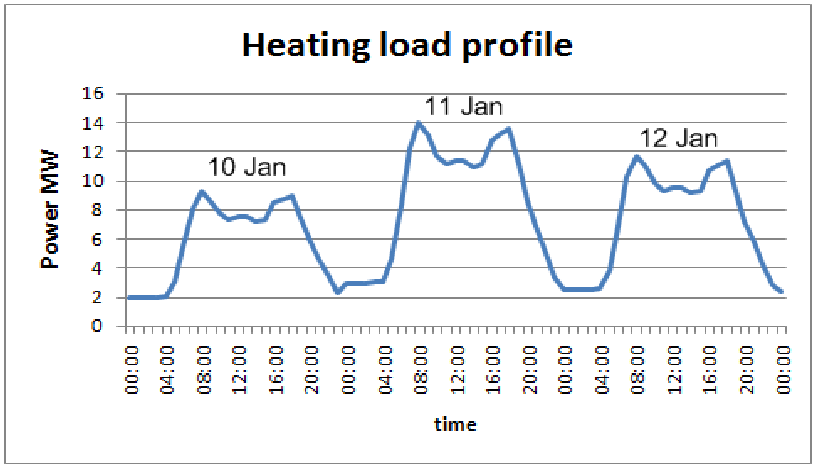

Figure 12 - Heating load profile

Since *all the controls and sizing will be focussing into the heat demand*, is relevant to observe the load duration curve, which may explain some of the results obtained. The graphic describes the amount of time that a heating demand is above a given value.

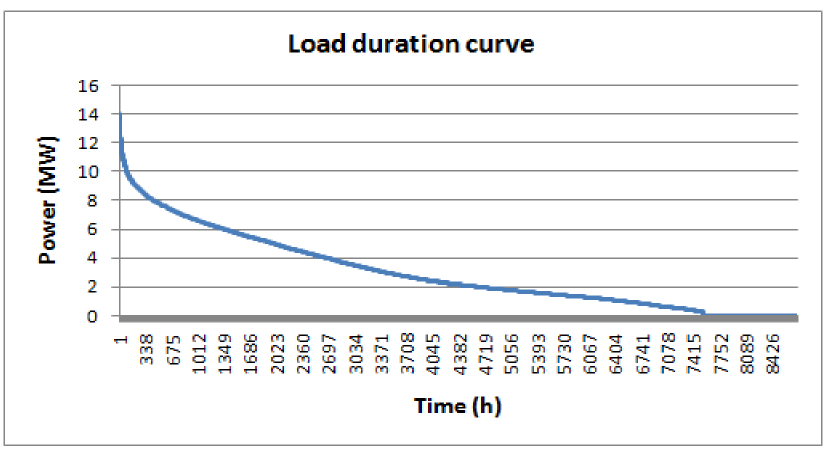

Figure 13 - Heat load duration curve

3.3.2.2. Cooling Loads

Given the level of insulation of the modern buildings, the load requirement is more related with the internal casual gains and insolation levels then to the instantaneous outside temperature itself. At the present district, the cooling load profile remains basically the same during the three months where it is above zero. There is no cooling system at the residential buildings.

The total cooling requirement is of **9600** MWh per year.

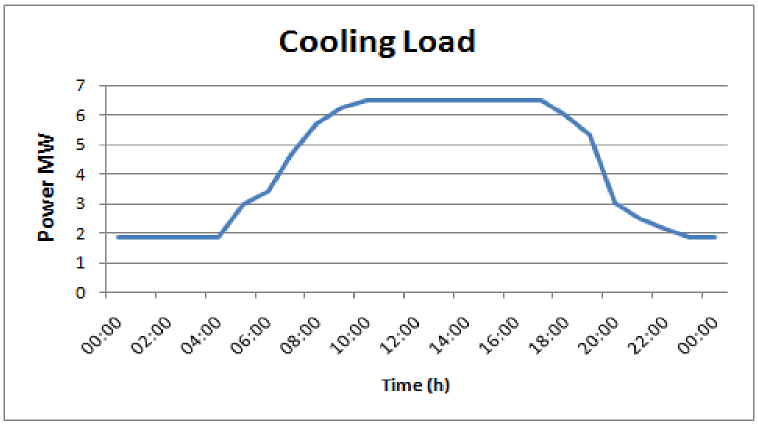

Figure 14 - Cooling load profile

3.3.2.3. Electrical Load

The electrical load does not include any energy that will be utilized by the heating system. Its behavior does not change during the year, repeating itself every day, with two peaks of 4.5 MW, one around 8 am and the second at 5 pm.

This load will be supplied mostly by the grid, with some participation from the CHP and photovoltaic panels.

The total electrical demand during the year is of **26 600** MWh.

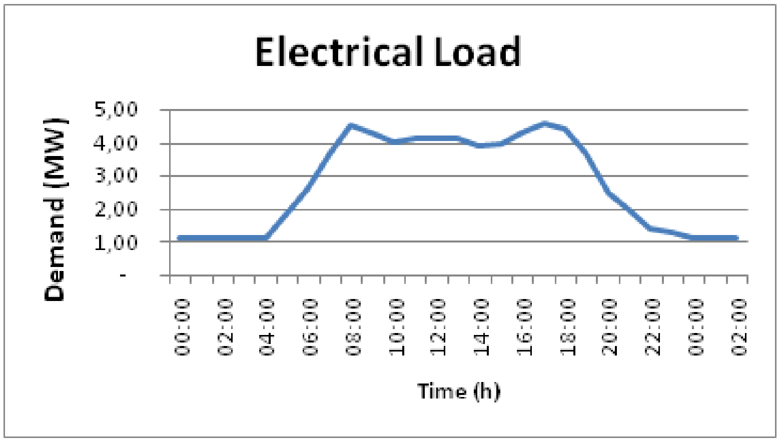

Figure 15 - Electrical load profile

3.3.2.4. Yearly profile

The next figure represents the yearly demand profile of the three different loads present into the simulation.

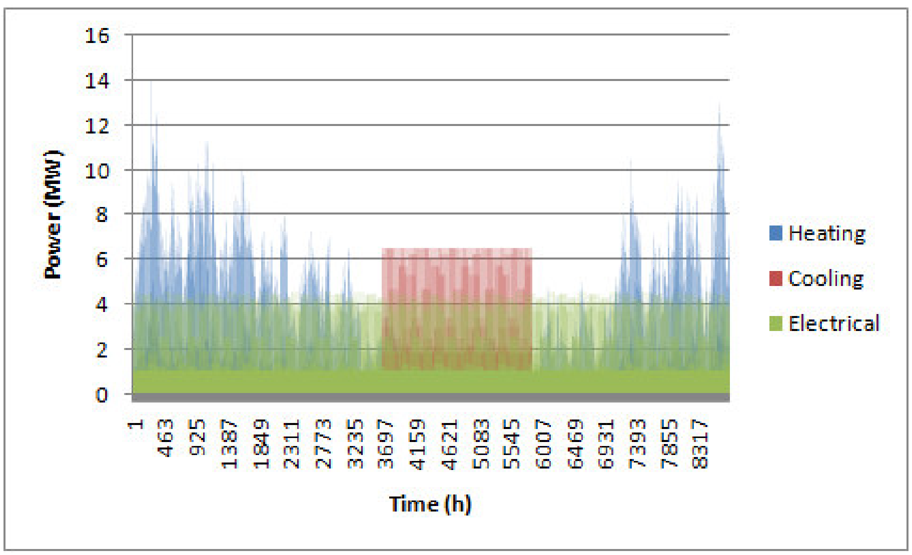

Figure 16 - Annual load profile

3.4. The base case

The following configuration will be utilized as base to compare all the other simulations results including:

- CO_2 savings
- Energy savings

- Financial cost

The heating load will be entirely supplied by a gas boiler with efficiency of 80% over the higher heating value (HHV).

The cooling load will be supplied by a conventional chiller system with COP of 2.5.

Electricity will be completely supplied by the grid.

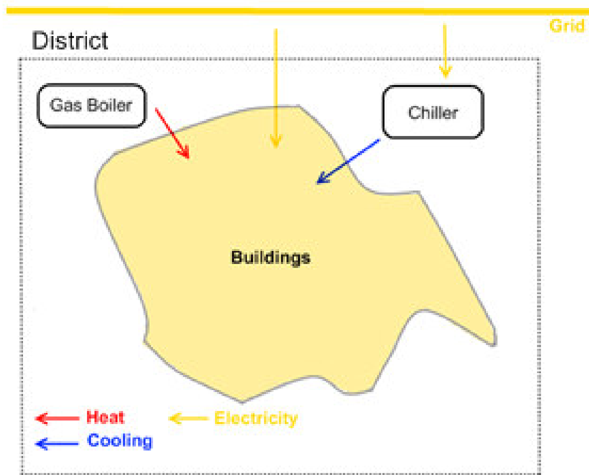

Figure 17 - Base case

In all the other configurations, the heating water will be leaving the storage tanks at around 40 °C, returning at 20 °C. It should be noted that in the configurations that include a heat pump, the energy required to top-up domestic hot water to 65 °C is taken into account separately (and assigned to auxiliary gas boilers or CHP)

Regarding to the cooling circuit, the water will leave the cooling storage tank at 10 °C, returning at 20 °C.

3.5. Financial Analysis

The financial analysis was done observing the investment required for each system, the cost for supplying the energy, operating and maintaining the equipment and comparing with the values for the base case. More details are given below.

3.5.1. Energy Cost

For all the calculations, the following prices will be used (10) (17):

Energy Source	Price (pence per kWh)
Gas	2.1
Electricity imported from the grid	7.2
Electricity exported to the grid	5.7

Table 6 - Energy price

These values will define the total energy cost at each studied system. When compared with the values of the base case, they will define the energy savings. It will be an important attribute since the financial study of the system will be based on the internal rate of return related with each configuration.

3.5.2. Internal rate of return

Before explaining the concept of internal rate of return is important to observe the meaning of the Net Present Value (NPV). The NPV defines how much a series of future payments would be worth today, taking into account a given discount rate through the studied time.

For example, if the interest (or discount) rate is 10% per year, a payment of £86.76 ha the same value as one payment of £50 in one year and another payment of £50 in two years: :

$$\frac{£50}{1.1}+\frac{£50}{(1.1)^2}=£86.76$$

The £86.76 is the present value of the 100 pounds resultant of the two payments done over two years, applying a discount rate of 10%.

The **Internal Rate of Return** (**IRR**) is the discount rate that results in a net present value of zero for a series of future cash flows. A net present value of zero means that would be indifferent to apply the money into the new investment or keep it and apply into a bank with an interest rate equal to the IRR. The higher the internal rate of return the better is the investment.

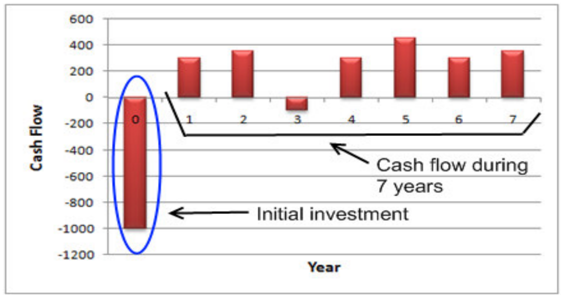

Figure 18 - Cash flow example

An advantage of the internal rate of return is that, unlike the net present value, it allows to easily compare completely different investments, since it does not result into a value dependent of the size of the investments, but a rate. It allows comparing small investments with big ones.

3.5.3. Capital, operational and maintenance costs

The capital cost was defined as the costs related with purchasing and installing *the new equipments*. To avoid energy black outs, in case of bad function of the CHP or HP system, it is considered that all the systems will have available an auxiliary system equivalent to the base case, making not necessary to define any saving related with the reduction of the gas boiler system, for example.

The values for the prices were obtained from the real project and have been slightly modified for confidentiality reasons.

CHP Engines

CHP size	Capital cost	O&M (year)
1.8 MW(th)	£ 870 000	£ 9.00 per running hour
2.7 MW(th)	£ 1 230 000	£ 14.00 per running hour
4.5 MW(th)	£ 2 000 000	£ 21.00 per running hour
6.2 MW(th)	£ 2 824 000	£ 38.50 per running hour
8.0 MW(th)	£ 3 644 000	£ 45.00 per running hour

Table 7 – CHP: capital, operational and maintenance costs

HP Engines

HP size	Capital cost	O&M (year)
1.8 MW (closed loop)	£ 603 000	1% of capital cost
1.8 MW (open loop)	£ 809 000	1% of capital cost
2.5 MW (open loop)	£ 853 000	1% of capital cost
3.5 MW (open loop)	£ 1 180 000	1% of capital cost
5.5 MW (open loop)	£ 1 785 000	1% of capital cost
8.0 MW (open loop)	£ 2 570 000	1% of capital cost

Table 8 - Heat pumps: capital, operational and maintenance costs

The operational and maintenance cost of the auxiliary boilers and chillers were defined at 2% of the consumed energy cost.

3.6. The main system components

The main system components present in the simulation are:

- Open loop water source heat pump
- Closed loop water source heat pump
- Gas boiler
- Combined heat and power system

The gas boiler was introduced in the base case description, being also utilized as an auxiliary system, connected to the storage tank of each HP or CHP circuit. Details of the remaining components are shown below.

3.6.1. The heat pumps

For the heat pumps simulation, data from commercially available 130 kW heat pump was utilized. [Appendix 1 and 2].

3.6.1.1. General operation configuration

The information below applies to each heat pump, independently, and may vary depending of the system control configuration and connections. During the simulations, any change over the values detailed bellow will be highlighted.

3.6.1.2. Heating period

Maximum temperature for the water leaving the heat pump will be 52°C, with a ΔT of 6°C between the temperature entering the heat pump and leaving it. COP values up to 5 were achieved with this configuration.

3.6.1.3. Cooling period

During the cooling cycle, the water will be leaving the heat pump, to the load, at around 7°C. The ΔT between the temperature entering and leaving the heat pump is around 5°C.

3.6.1.4. Open loop configuration

Flow rates utilized

In order to keep the temperature levels at the values described before, the flow rate through the heat pump was set always following the formula, based at the information at attachment 1:

$$\frac{(8.5*heating\ capacity[kW])}{180}$$ L/s during the heating cycle [a]

$$\frac{(8.5*heating\ capacity[kW])}{200}$$ L/s during the cooling cycle [b]

The water pump will be switched on, at heating mode, once the temperature of the water leaving the storage tank to the load is below 40 °C. It will be switched off once the temperature to the load reaches 50 °C.

For the cooling circuit, the heat pump will be turned on when the water leaving the storage tank is above 10 °C being switched off once it reaches 7°C.

This information is also valid for the closed loop configuration.

Source temperature

The project design team informed that the water temperature during the year would oscillate between 4 and 16 °C.

To create a data compatible with TRNSYS requirement, it was defined a sinusoidal wave oscillating between these values, with the peak at July and its lower value at January, and applied as the river temperature through the year.

3.6.1.5. Closed loop configuration

Heat exchanger

The heat exchanger that will be present at the heat source, a river or lake, was simulated through a cross flow unmixed heat exchanger. The hot side (during heating periods) will circulate water from the lake and the cold side (during heating periods) is filled with a solution of water and antifreeze substance, resulting into a calorific value of 3.9 kJ/kg K (5).

Flow rates utilized

The water from the lake will be entering the heat exchanger at a flow rate of 350 000 kg/h, being enough to keep the temperature above 0°C. The flow rate of the solution of water and antifreeze will circulate through the heat pump at the same rate described by the formulas [a] and [b].

Source temperatures

The water from the lake will have its temperature oscillating between 4 and 16 °C during the year, never leaving the heat exchanger under 0 °C.

The solution of water and antifreeze will leave the heat pump at -0.5 °C at the coldest days, entering at 6 °C after absorbing heat from the source.

3.6.2. The combined heat and power generation

Electrical capacity

The model is using an internal combustion engine based on Deutz TCG 2020K internal combustion engine. The control system will turn the engine on based on the heating requirements, not the electrical demand, and always working close to its maximum capacity.

Heating capacity

The internal combustion engine used is able to provide 1.8 MW of heat to the system in the form of heated water.

Efficiency

The engine was configurated to have an overall efficiency of 94%. This means that, to produce 94 kWh of utilizable energy, it consumes 100 kWh of fuel.

Temperature

The control system will start the CHP engine whenever the temperature leaving the storage tank, to the load, is below 40 °C, switching it off once it reaches 90 °C.

3.6.3. Storage system and heating circuit

The heating circuit can be divided into three similar modules, each one connected to a different heat source. This source will supply energy to a storage tank that will be connected to a load. This basic module can be seen bellow.

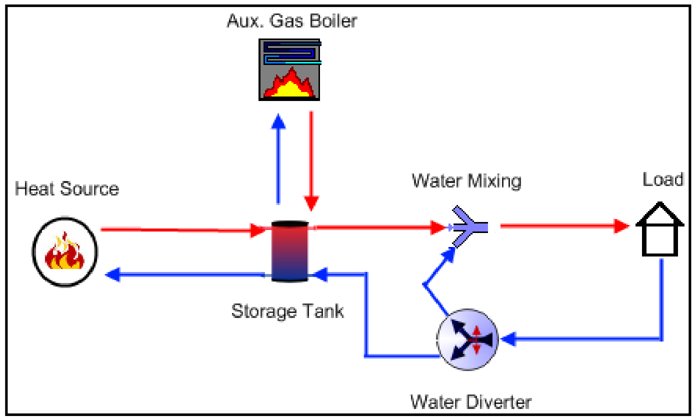

Figure 19 - Heating circuit

The temperature entering the load is expected to be at 40°C, leaving it at around 20°C. To keep this value, the water diverter will observe the temperature returning from the load and coming from the storage tank and then control how much of the water from the load will recirculate.

Storage tank

For the heat pumps, a 400 m^3 storage tank was selected. The control system will allow the temperature of the water leaving the tank, to the load, oscillate between 52 and 40°C, meaning a capacity to store up to 5.2 MWh of energy.

The combined heat and power, used a 350 m^3 tank. Since the engine is able to supply water with temperature up to 90°C, the control system will allow the oscillation of the water temperature leaving the storage to the load between 90 and 45 °C, which means a capacity of 18.5 MWh of heat.

In all cases, stratified models were used, with 10 temperature levels present at each one.

3.7. Storage system and cooling circuit

The main difference at the cooling system is the fact that there isn't a recirculation circuit. The water leaving the cooling load goes straight to the storage tank.

The volume of the storage tank is of 350 m^3, also simulated with a stratified model with 10 temperature levels.

The cooling circuit is completely independent of the heating one and is present just at the heat pumps systems. The control was modeled in a way that, in case of heating and cooling being required at the same period, the heat pumps will operate at the cooling mode and the combined heat and power system will supply the heat demand.

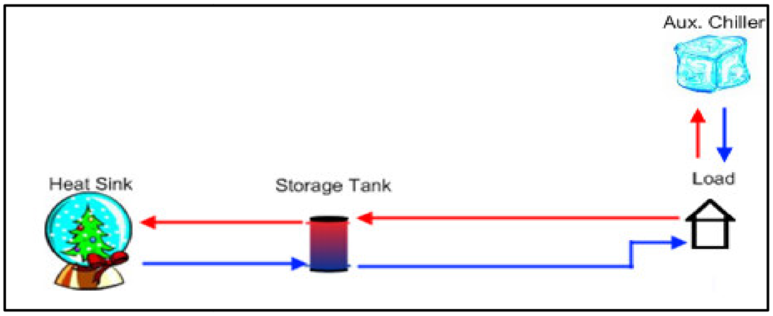

Figure 20 - Cooling circuit

4. Results

4.1. First round of simulations – Impact of sizing and control over the outputs.

The first series of simulations won't be limited by the design parameters obtained from the design team for the real project, but will play with the engines sizes and observe how the outputs behave as heat sources of different capacities are compared between themselves. It will be considered a CHP only system, a heat pump only one and then both technologies will be combined to observe the impact of sizing and controls changes at the outputs of the hybrid system.

The building site will also be considered as a whole, rather than three different subsystems (the thermal and electrical loads for the three subsystems are simply aggregated). There won't be any limitation over the capacity of the water source of supplying heat, allowing the utilization of any size of source heat pump.

4.1.1. CHP supplied system

The first series of simulation will be observing a load supplied by the following system:

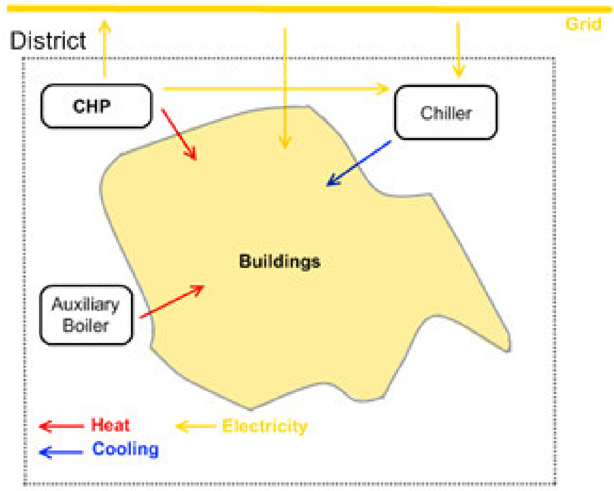

Figure 21 - CHP supplied district

Four different sizes of CHP engines will be compared:

- 2.7 $MW_{(th)}$
- 4.5 $MW_{(th)}$
- 6.2 $MW_{(th)}$
- 8.0 $MW_{(th)}$

They will be supplying the base load with the auxiliary boiler supplying the remaining, when necessary.

For the reasons described at section 5, electricity will be sold to the grid just in case of generation higher then consumption.

The graphic below represents the amount of gas consumed by the auxiliary system against the total cost of the energy consumed on site.

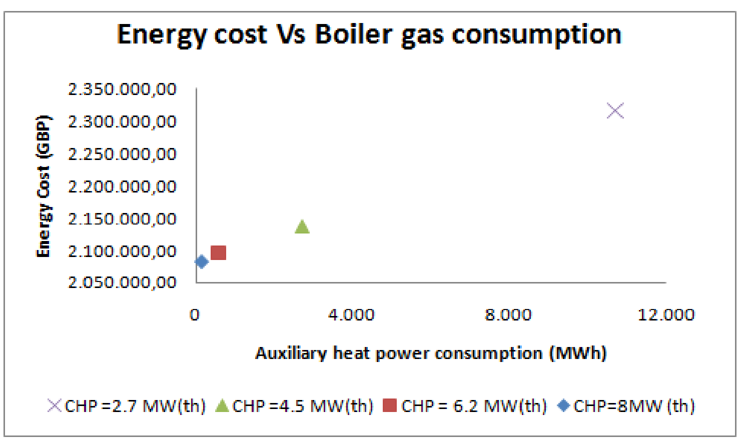

Figure 22 - Energy cost vs. Aux. boiler gas consumption

It can be observed at this graphic that the higher participation of the auxiliary system, the higher the annual energy cost. Also, improving the size of the CHP from 6.2 to 8 $MW_{(th)}$ had small impact over the final result.

Observing the load duration curve is easy to notice that the areas above the heating capacity of these two engines are very similar, meaning that close amount of energy is being supplied by both auxiliary boilers. It is not the case when compared with the area above the 4.5 $MW_{(th)}$ power demand. The bigger the difference between these areas, the higher will be the difference between the costs.

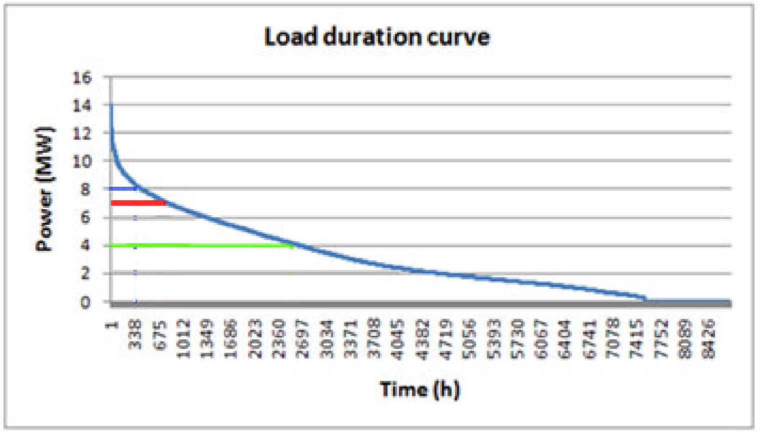

Figure 23 - Load duration curve

The simulation also permitted to observe the destination of the generated electricity. For the same reasons described above, no advantage is noticed on improving the size of the CHP above 6.2 $MW_{(th)}$

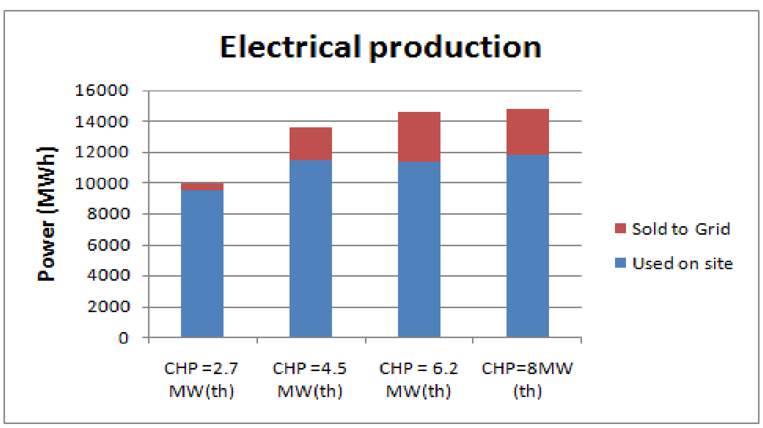

Figure 24 - CHP electrical generation

Is important to highlight here that to define where the produced electricity is being sold to, generated and consumed energy is compared at time steps of 3 minutes. This is relevant information and will be more explored at part two of the simulations.

A graphic very similar to the above is generated when the CO_2 emission reduction is plotted for each CHP size. The reduction levels are relative to the base case described previously.

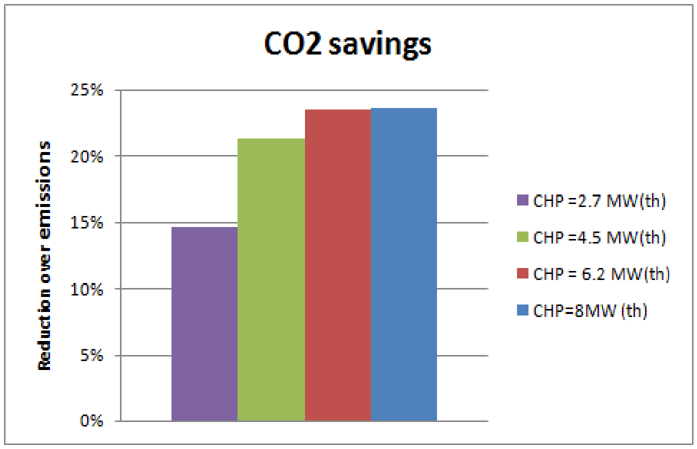

Figure 25 - CHP CO_2 savings

It can be seen how a higher saving level is achieved as the size of the engine is risen although it does seems to saturate at a given level as the amount of energy supplied by auxiliary systems (responsible by a higher emission value) stabilizes (figure 23).

To compare the internal rate of return of each engine, over the period of 20 years, the new CHP system capital cost was used as initial investment. The difference between energy, operational and maintenance cost of each CHP system and the base case will be used to define the cash flow, as shown below:

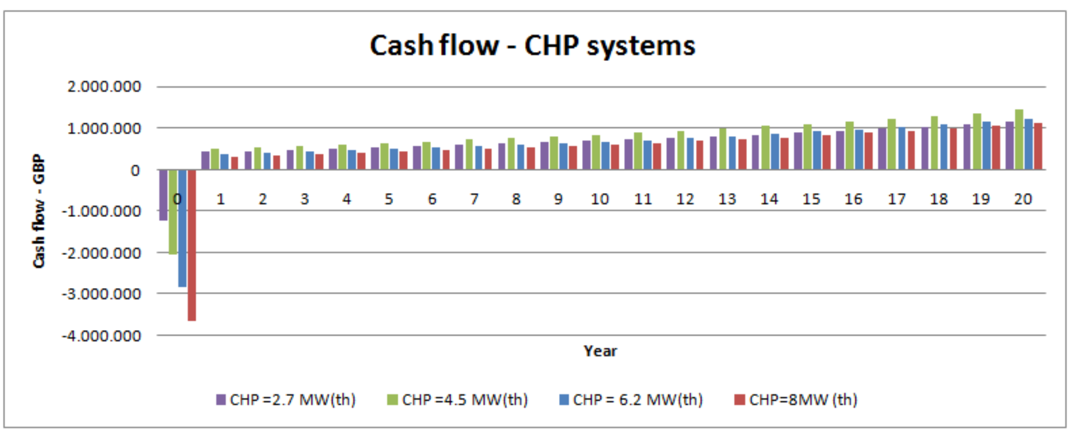

Figure 26 - Cash flow CHP

With this data the internal rate of return against the CO_2 emission could be calculated for each CHP size.

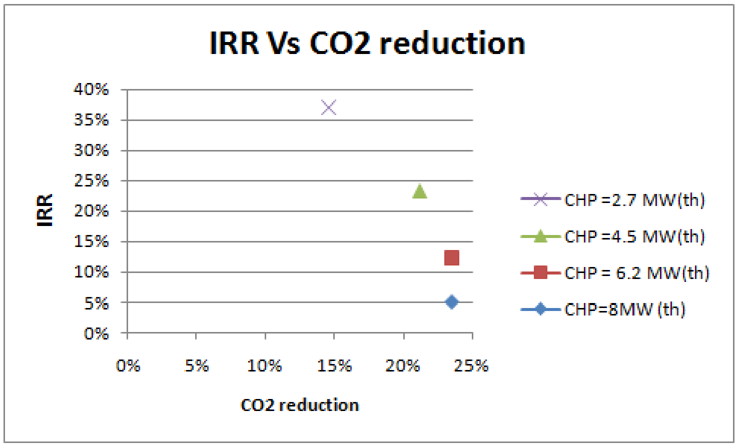

Figure 27 - CHP IRR vs. CO_2 reduction

The small difference between the cash flows from the different systems made the initial investment as main factor defining the differences between the internal rates of return. The extra energy savings of the bigger machines are not enough to overcome the fact the smaller ones require less initial investment, which results into higher IRR.

The graphic shows how improvements over the CO_2 savings requires expressive reduction over the IRR and seems to saturate close to the 25%. This suggests that for the district district heating, CO_2 savings above 20% would result into high investment for small improvements.

4.1.2. Open loop water source heat pump supplied system

The next step is to simulate the hypothetical case where the cooling and heating load of the district would be supplied by different sizes of heat pumps with gas boilers and conventional chillers working as auxiliary systems. A schematic of what is being simulated is shown below.

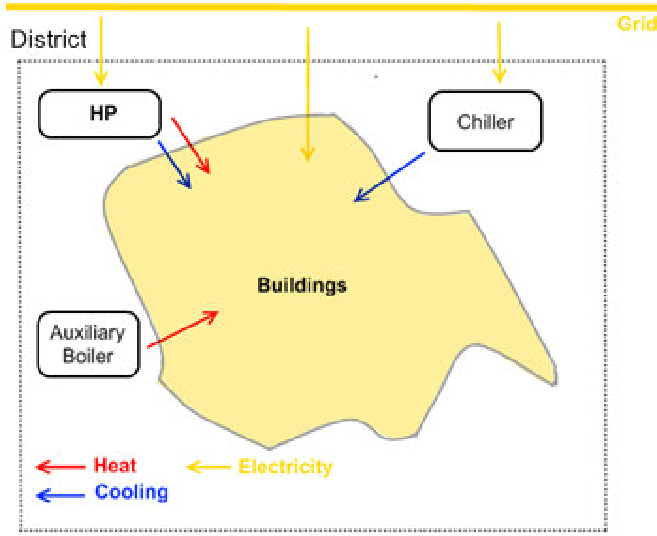

Figure 28 - HP supplied district

Similar to what was done with the CHP engines, 4 different sizes of heat pumps were utilized. It was ignored any water source heating capacity limitation at this stage. The sizes are

- 2.5 $MW_{(th)}$
- 3.5 $MW_{(th)}$
- 5.5 $MW_{(th)}$
- 8.0 $MW_{(th)}$

It was achieved an average COP of 4 during the heating periods and 6.5 during the cooling ones.

Being able to supply renewable energy to the district load, now is relevant to observe not just CO_2 reduction over the emission but also the renewable share that each configuration is able to bring on site. The next graph will compare the CO_2 emission, at the vertical axis, against the renewable share, at the horizontal one.

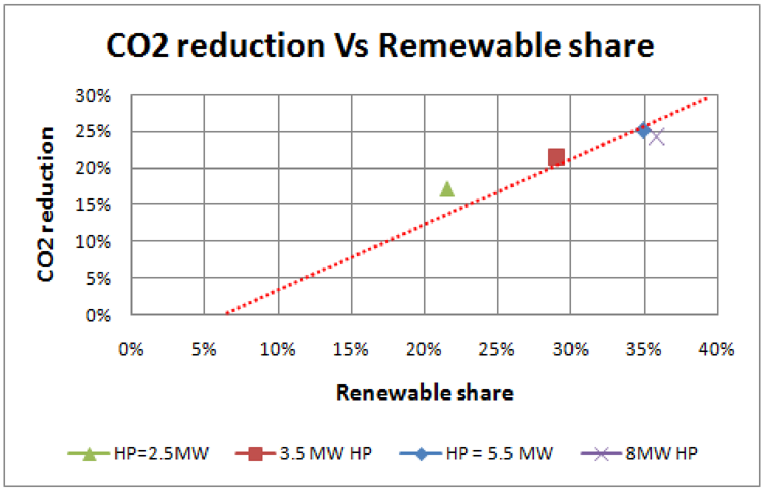

Figure 29 - HP CO_2 reduction vs. Renewable share

As expected, the renewable share and CO_2 savings improve as the heat pumps have higher participation over the total load. This relationship between both is not linear. The red line on the graph makes easier to observe that the size of the machine have higher impact over the renewable participation then at the CO_2 reduction. This is related with the fact that, to transfer the energy from the ground to the building, the heat pump needs to utilize electricity from the grid, which is associated with high emission levels (0.422 kg of CO_2 per kWh (10)). Looking just for the heating demand, ignoring the electrical consumption on site, the CO_2 reduction is around 60% with the renewable share reaching 80% with the 8MW heat pump. The high electrical demand at the buildings (26 000MWh per year) and the fact that it is entirely supplied by the grid makes the final values more modest.

The initial investment and the cash flows during 20 years are shown at the next graphic. It will help to observe how each configuration affects the total energy savings and to predict what will happen when the IRR for this period is calculated.

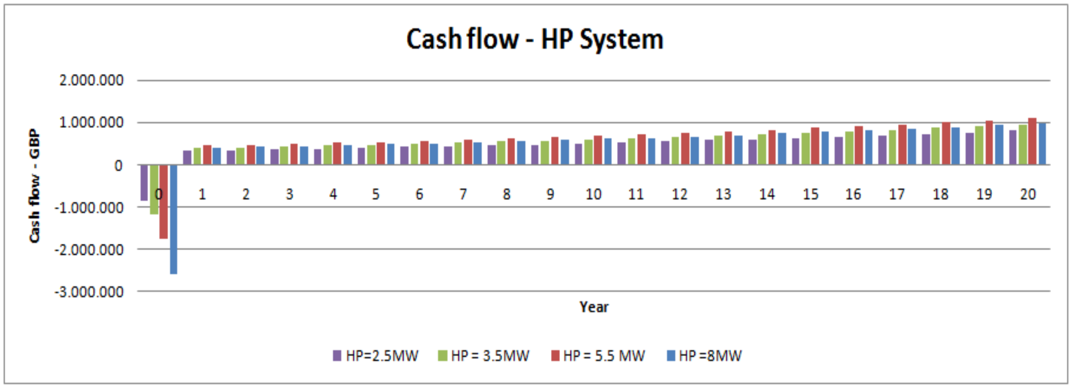

Figure 30 - HP cash flow

The 8 MW HP seems to be related with smaller savings then the 5.5 MW. In part it is related with the fact that its operational and maintenance cost is higher but is mostly related with the indication that it is oversized for the site load. Remembering the load duration curve, it is easy to understand that most of the time the load demand will be well below the 8MW. When switched on, the heat pumps tend to work for a short period at reduced efficiency. This efficiency reduction becomes more evident when the heat pump is switched on and off at short period of time, which is what happens when they are oversized and is what happens with the 8MW one in this example. Its lower efficiency makes the energy savings be smaller than the one of a 5.5 MW heat pump.

As commented before, where relevant, 20% of renewable participation will be the target to be achieved. All the configurations above are over this value, so the IRR will be plotted just against the CO_2 emission savings.

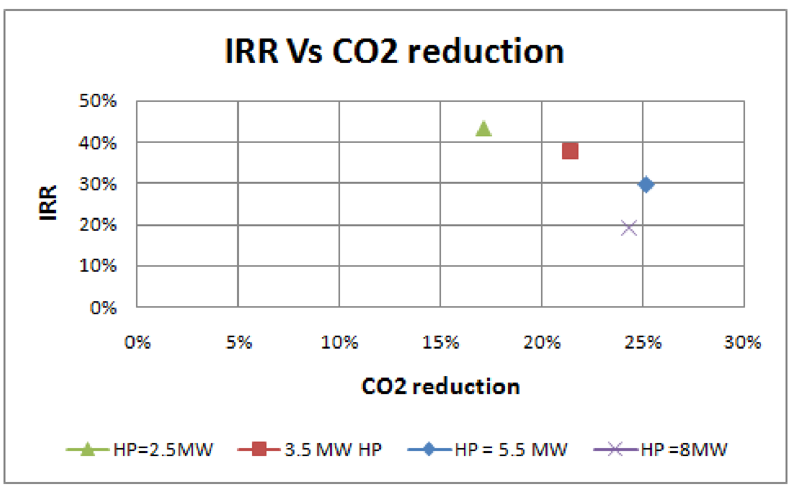

Figure 31 – Heat pump: IRR vs. CO_2 reduction

The extra energy savings of the bigger heat pumps, compared with the smaller ones, are not enough to overcome the price difference between the initial investments, resulting into lower internal rates of return. The disadvantage caused by over sizing the heat pump is also evident when comparing the 8 MW one with all the others. The same CO_2 reduction can be achieved with smaller machines that, requiring smallest initial investment, may achieve higher internal rate of return at the observed period.

The 2.5 MW heat pump, although presenting the best IRR, is below the target of 20%, not leaving many options over what can be done to improve its CO_2 emissions. At this stage, the best option is to utilize the 3.5 MW heat pump.

It might be also interesting to observe all the IRR and CO_2 reduction of the systems simulated until the present moment.

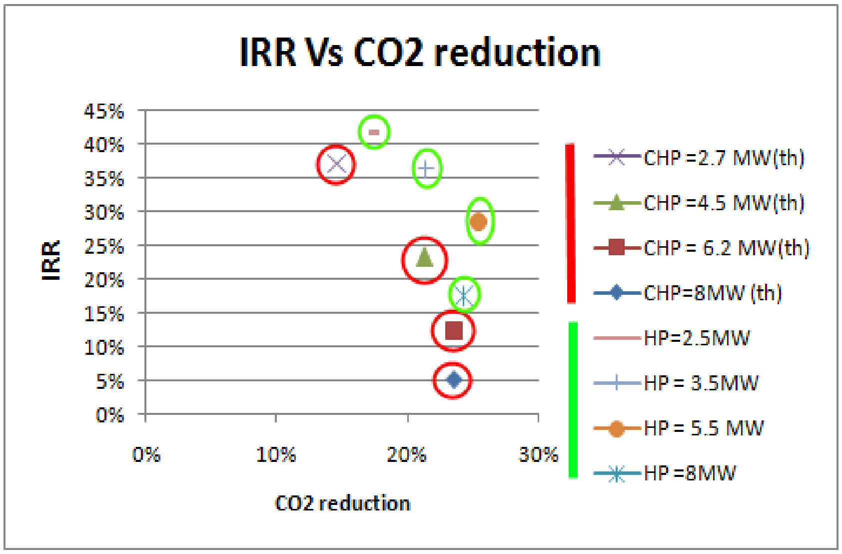

Figure 32 - CHP and HP IRR vs. CO_2 reduction

If no target of renewable participation is set, utilizing CHP to reduce CO_2 emission seems to be a better option. Even with the bigger machines, a higher IRR of return, when compared with the heat pumps, is achievable. Is important to also highlight here that many companies apply the CO_2 displacement factor (-0.568 kg of CO_2 per kWh) for all the electricity generated by the CHP, not just in case of production overcoming the generation as how was done during the calculations here present, which may result into even higher CO_2 emission reduction.

The next stage is to observe how a hybrid system involving a CHP engine and a heat pump behaves supplying the local load.

4.1.3. Hybrid CHP + HP system

The hybrid system will work as below:

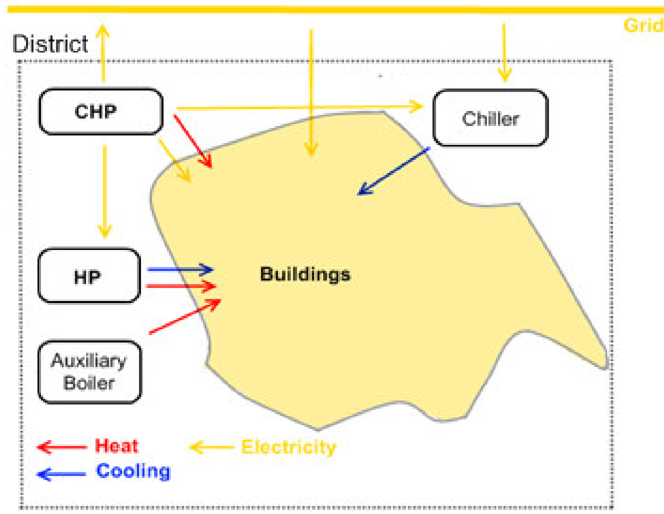

Figure 33 - Hybrid system supplied district

Three different sizes of heat pumps and CHP engines will be utilized. Based on the previous results it was decided that the lower limit for the heat capacity of the heat sources will be 2.5 MW and the upper limit will be 5.1, keeping the system below the 8MW capacity, at which the system gave clear signs of being oversized. The remaining heating load will be supplied by the auxiliary boiler.

The exact sizes are shown below:

CHP (heat capacity)	Heat pumps (heat capacity)
2.5 MW	2.5 MW
2.8 MW	2.8 MW
5.1 MW	5.1 MW

Table 9 - CHP & HP heating capacity

Unlike the previous cases, there will be changes not just at the size of the engines, but also at how they will be controlled, defining when each one will be supplying the heating or cooling demand.

The studied configurations are the following:

4.1.3.1. 2.8 MW heat pump + 2.8 MW(th) CHP

This system will be utilizing the heat pump and the CHP engine with the same heat capacity. Both systems will be connected at the load with their participation over the load controlled by the water flow through each system storage tank. The controls are:

Same share

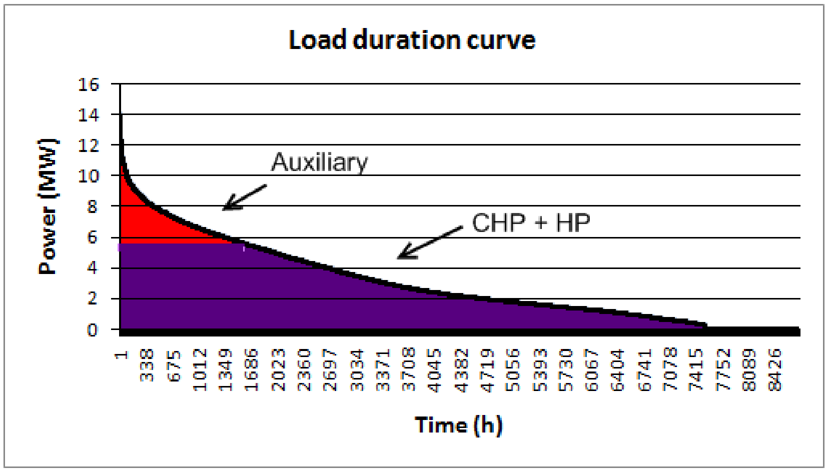

Figure 34 - Same share configuration*

At this configuration the CHP and the heat pump will be supplying equally the total demand. This means that if the total load is of 4 MW, for example, two will be supplied by the heat pump storage tank and two by the CHP one. This control is done keeping the water flow from the load to each tank always equal. When the total load is above the CHP+HP capacity, the auxiliary heaters are turned on.

In case of heating and cooling demand, the first one will be supplied exclusively by the CHP system (no water will return from the load to the HP storage tanks), with the heat pump giving priority to the cooling load. This observation is valid to all the configurations here present.

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

CHP Leading

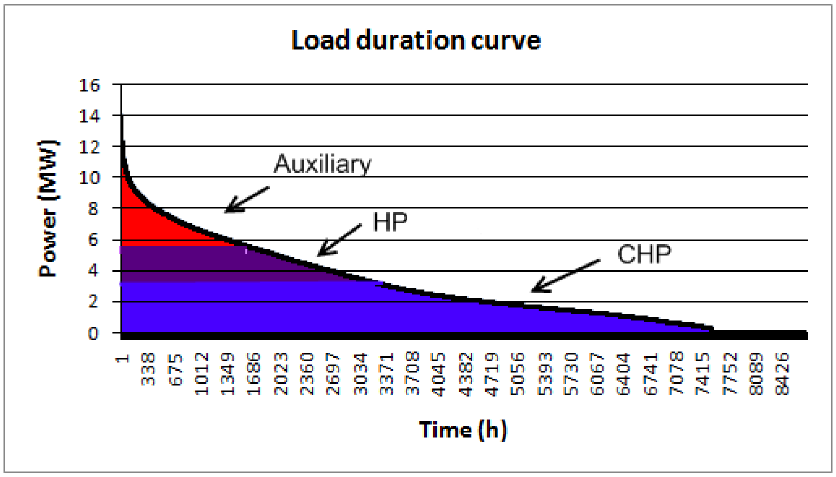

Figure 35 - CHP leading configuration*

CHP leading means that the control system will let the CHP supply the load alone, until its maximum capacity is reached, when the heat pump system starts to help with the demand. At this point each one will be supplying the same amount of energy. When the total load is above the CHP + HP capacity, the auxiliary heaters are turned on.

The control is done through the water flow from the load to the storage tank of each system.

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

HP Leading

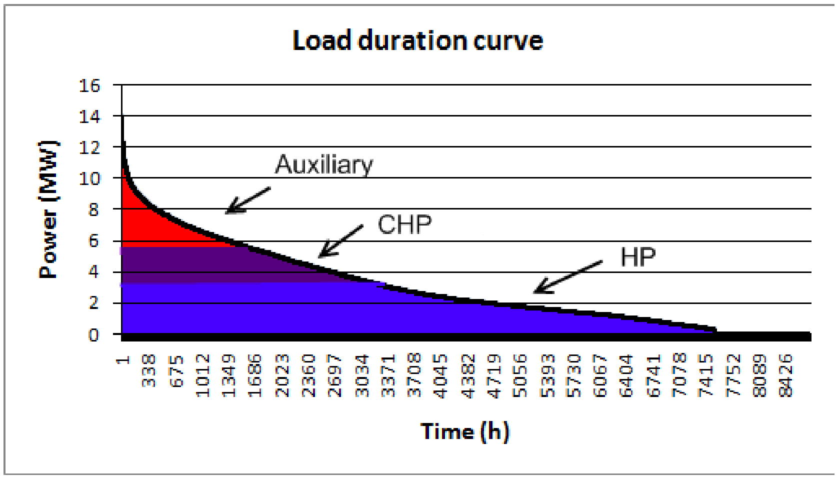

Figure 36 - HP leading configuration*

HP leading means that the control system will let the HP supply the load alone, until its maximum capacity is reached, when the CHP system starts to help with the demand. At this point each one will be supplying the same amount of energy. When the total load is above the CHP + HP capacity, the auxiliary heaters are turned on.

The control is done through the water flow from the load to the storage tank of each system.

4.1.3.2. CHP 2.1 MW(th) + HP 5.1 MW

The next set will be formed by a 5.1 MW heat pump and a 2.1 CHP engine.

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

HP leading

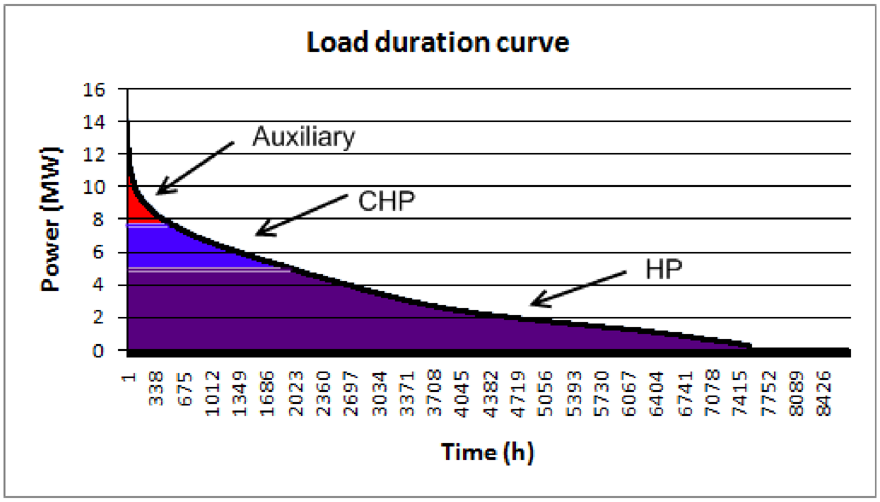

Figure 37 – 5.1 MW heat pump: HP leading configuration*

The only difference between this configuration and the previous "heat pump leading" one is that when both heat pumps are working, 60% of the load will be supplied by the heat pump system and 40% by the CHP.

CHP leading

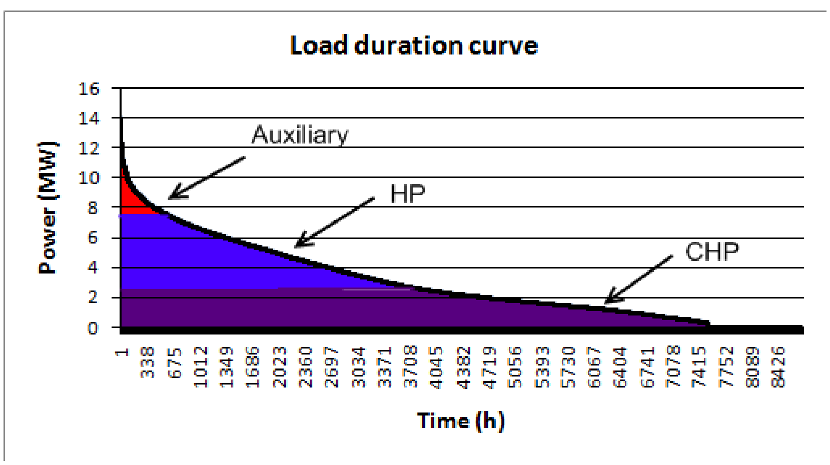

Figure 38 - 5.1 MW heat pump: CHP leading configuration*

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

This configuration will follow the same logic previously described at "CHP leading". The main difference is in the fact that, while both heat pump system and CHP are working, 60% of the load will be supplied by the HP and 40% by the CHP system.

4.1.3.3. CHP 5.1 MW(th) + HP 2.5 MW

The last configuration is formed by a 5.1 MW(th) CHP engine and a 2.5 MW heat pump.

HP leading

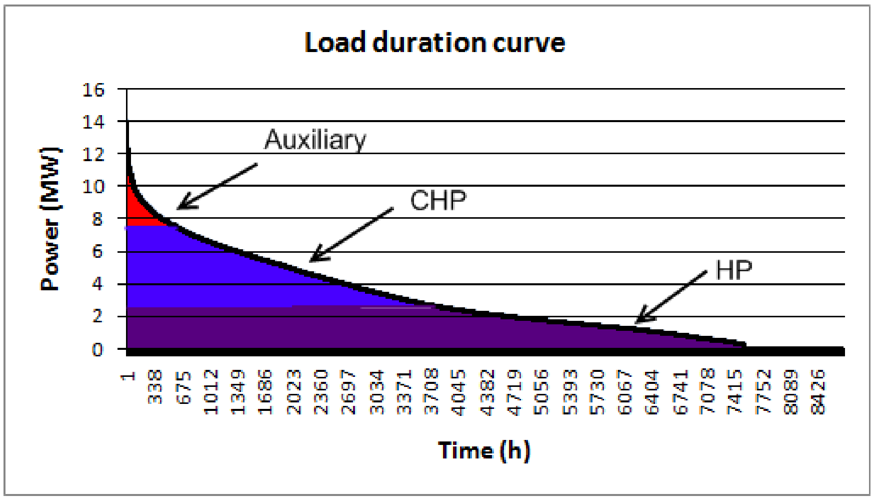

Figure 39 – 5.1 MW CHP: HP leading configuration[*]

The heat pump will supply the base load until the demand reaches 2.5 MW. Above this value the CHP system will supply 60% of the total required energy while the heat pump 40%. The auxiliary systems will supply energy when the demand reaches values above 7.6 MW.

[*] This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

CHP leading

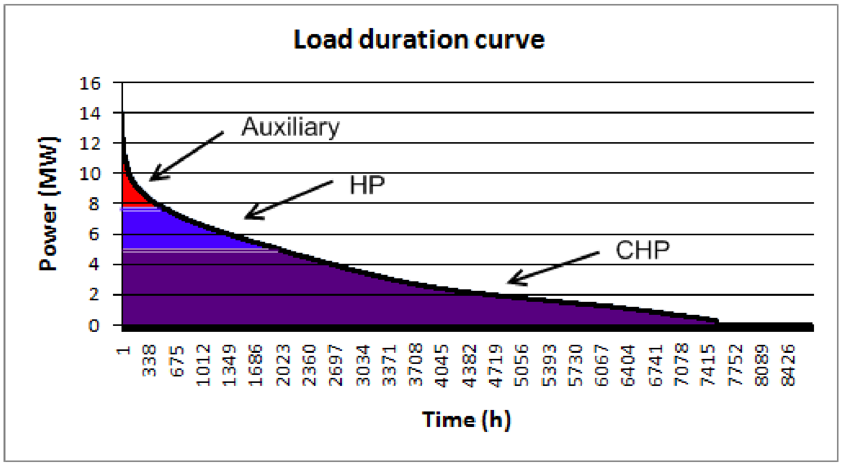

Figure 40 - 5.1 MW CHP: CHP leading configuration*

At this last case the CHP will supply alone the load as long as it remains below 5.1 MW. Above it, the heat pump system is joined to the previous one, supplying 40% of the total energy demand with the CHP system supplying the remaining 60%.

4.1.3.4. First round of simulation: results overview

The previous results may work as a guide to what is expected from the combination of the two technologies. The new hybrid system allows the designer to combine the benefits observed from each technology in order to try to achieve a given goal.

The renewable target of 20% will come completely from the heat pumps. It was observed that the participation of the heat pump over the load raises the final renewable participation, but this improvement does saturate if oversized. The CO_2 target seems to be easier to achieve since not just the heat pump is able to reduce the overall emission but the CHP also attested to have a great capacity to improve the savings.

Looking for the CO_2 emission savings of each configuration and the renewable share, the following graphic was generated. The colors were utilized to indentify each configuration easier.

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

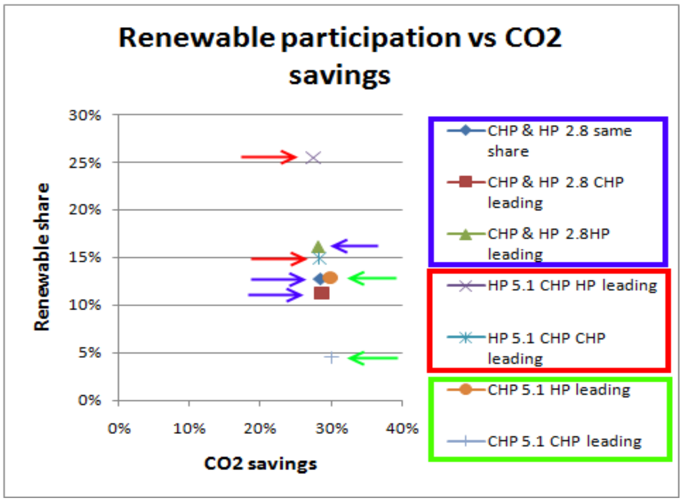

Figure 41 - Hybrid system: renewable vs. CO_2 participation

The first finding is that the CO_2 emission reduction had very low variation between all the configurations. All systems are above the 20% target previously established.

Two procedures were responsible to getting better renewable shares. The first is what was observed at the previous study (HP only) that is using bigger heat pumps, making them responsible for the higher amount of the supplied energy. The second is to let the heat pump supply the base load, making it run for more time during the year as is clearly observed with the 2.8 HP and CHP configuration. This allows the heat pump to cover a bigger area of the load duration curve than it would while working to supply just higher demands.

The cash flow graphic shows the energy savings and investments related with each configuration. It will be displayed just for 5 years for easier visualization, although the calculations were done for 20.

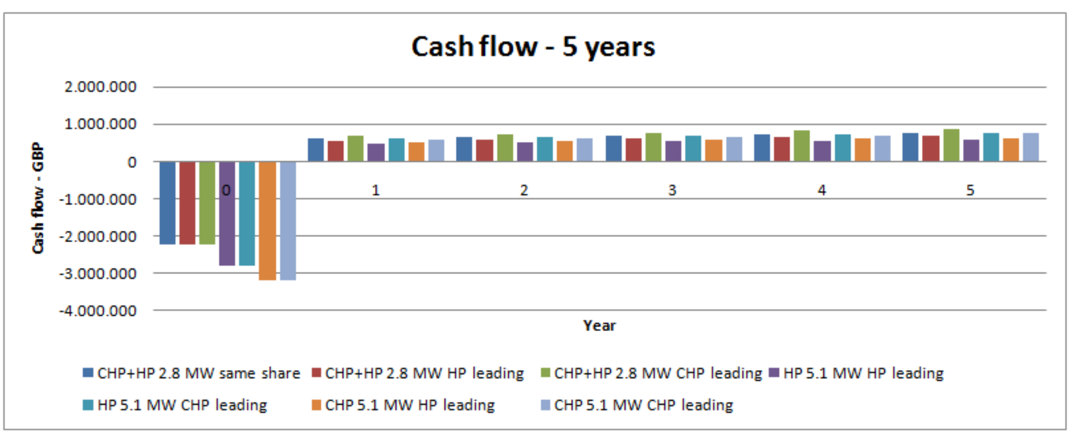

Figure 42 – Hybrid system: Cash flow

The cash flow does not present any dramatic difference between all the configurations. This will result into the initial investment being the main variable responsible for defining the best IRR. It can be observed though that the best savings are related with the configurations with higher participation of the CHP engine. The low price of gas and high price of electricity, that can be used on site or sold to the grid, are the main reason for it. Is also interesting to notice that the best savings involves the configuration with the smallest machines (CHP+ HP 2.8, CHP leading).

Since all the configurations have similar CO_2 savings and above the set 20% target, the internal rate of return will be plotted against the renewable participation. The circles with colors were utilized to make the visualization easier.

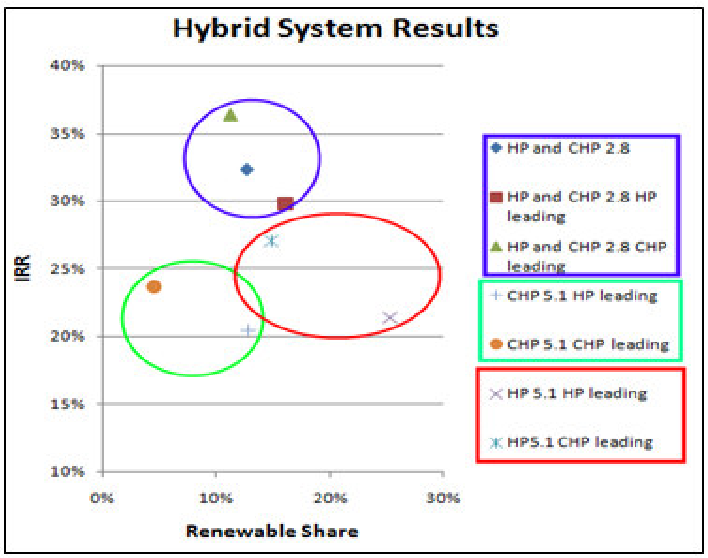

Figure 43 - Hybrid system: IRR vs. Renewable share

As possible to predict from the cash flow analysis, the configurations involving the smallest initial investments resulted into better internal rates of return. None of them, though, achieved the 20% target initially set.

It is interesting to observe how setting the heat pump to supply the base load makes their position into the graph move down at the IRR axis and right at the renewable share one. CHP supplying the base load raises the internal rate of return, reducing the renewable share. Better internal rates of return comes with the cost of reduction over the renewable participation at the final load may be the main conclusion extracted from this graphic.

As a direct result of the previous observation, the only configuration above the 20% target presents one of the worst internal rates of return, which makes it not so interesting. It may make the designer wonder if there is any change that can be done in order to move the configurations with best IRR to the right into the graphic. Even though it may be followed by it position lowering into the y axis. A good candidate for that may be the “2.8 CHP and HP, HP leading”. It presents the second best renewable share and is high into the IRR axis.

A first though may suggest as a good solution adding a new technology looking forward the improvement of the renewable share. Photovoltaic generation may be a good candidate, adding renewable energy into the electrical consumption. A first analysis indicated that an array of 15 000 m^2 would be necessary. It does sound huge value but when compared with the total area occupied by the buildings, it starts to look a bit more reasonable, as shown below.

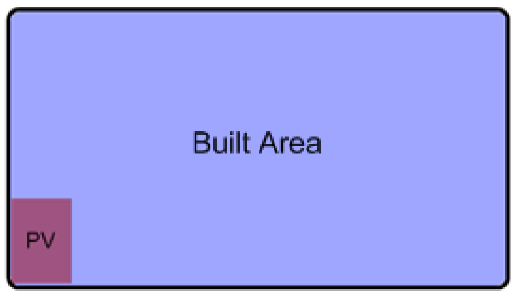

Figure 44 - District and PV array area

The array area seems acceptable, which is good news since it will allow the 20% being reached. Running the simulation, the following result was found.

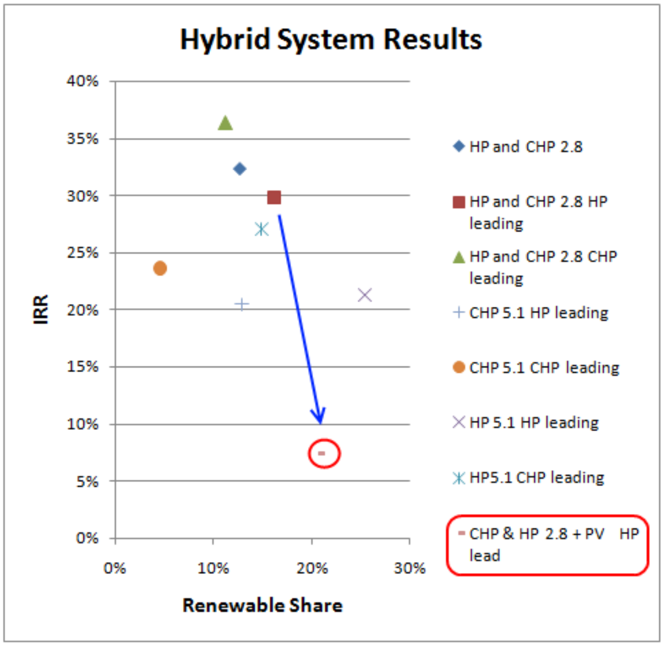

Figure 45 - Hybrid system with PV: IRR vs. Renewable share

Although the photovoltaic panels do add renewable and cheap electricity to the system, the required initial investment is rocketed. It was utilized the Sanyo model HIP-200BA3, with peak capacity of 200 W. The capital, operational and maintenance cost are listed below, followed by the cash flows of the same system, with and without the PV array.

- Capital cost (installation + equip): £ 568 per 1 m^2 (18) (19)
- O & M: £ 0.02 per kWh (20)

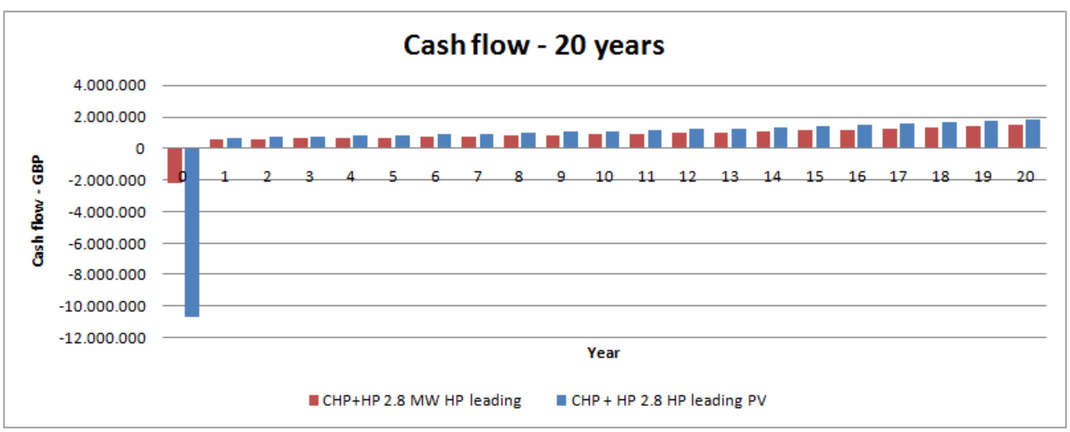

Figure 46 - Hybrid system: Cash flow with and without photovoltaic

The photovoltaic panels produced extra 2 480 MWh per year. Although a big amount of energy, it is small compared with the total energy consumed on site, 55 MWh per year, making the extra savings not big enough to overcome the massive extra investment required.

It is clear now that, at this case, relying exclusively on PV technology is not an option to solve the problem of reaching the 20% of renewable share with an IRR above the one of the 5.1 MW HP system. But a solution may still be possible.

As seen before, changes over the control of each system did have an expressive impact at the outputs. This is one big characteristic of hybrid systems and can be used as an advantage. Through simulation these controls can be easily changed with the new results rapidly being observed, allowing the system optimization.

The previous simulations highlighted how raising the heat pump participation improves the renewable participation of each system. It was also said before how, in all cases, it was set a command that would make the HP system supply energy exclusively to the cooling load, in case of heating and cooling demand at the same time. This was made in order to avoid a situation where both storage tanks require refilling at the same time. But depending of the timing of the loads, duration and magnitude, this situation may not happen. The best option is to run a new simulation, taking out the “exclusivity” command and observe what would happen.

The change implied no alteration into the quality of the heat being supplied to the load. It is a positive result which allowed the inclusion of this new configuration between the previous one and the recreation of the “IRR vs. Renewable share” graph, shown below.

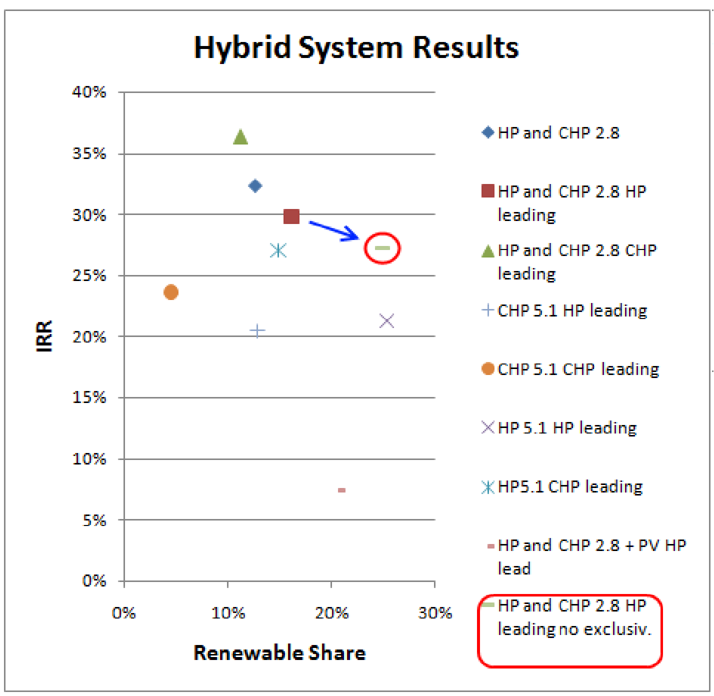

Figure 47 - Hybrid system no cooling priority: IRR vs. Renewable share

The 20% target was achieved with an internal rate of return above 25% thanks to the flexibility of controlling the hybrid system. It is important to inform that the new configuration did change the CO_2 emission reduction value to 20%, exactly the target previously set.

The capacity of changing the controls and observing how the entire system behaved at each case, proved a useful ally to achieve this result.

All the simulations above were made taking a liberty that may not happen in a real situation, like unlimited water heat source capacity or no extra losses related with different configurations. This made the non hybrid system involving just heat pump and gas boilers the best solution found. This partly results from the simplifications explained above and also from the very ambitious target of 20% renewable share. Given such an ambitious target, hybrid system configurations with solar thermal collectors might have provided a better economical performance.

The project design team informed us that two water sources were available and that it was possible to extract 2 MW of heat from each, through an open loop system in the first case and a closed loop the second one. They also decided to run each system independently, avoiding extra losses caused by high transmission distances. These limitations will be explored in the next set of simulations where the analysis method will also be observed.

4.2. Second round of simulations – Hybrid systems with three different heat sources.

The following simulations will reproduce the situation where the water source will limit the heat pumps sizes. On the studied site two water sources can, and will, be explored. Each one is able to supply up to 2 MW of heating power. The remaining required energy will be supplied by a third heat source, a CHP engine with a heating capacity of 1.8 MW(th).

4.2.1. Loads

Since these sizes of heat pumps and CHP engines would require a large participation of the auxiliary system around the year, the configuration changes were presenting not so expressive impacts over the results. It was then taken the liberty to scale down the load, making one of the three heat suppliers to become almost an auxiliary system. This allowed an easier observation of the configuration's capacity to alter the outputs (CO_2 emission, renewable participation, etc) while supplying the energy demand on site.

The main changes regarding the loads are explained next.

4.2.1.1. Heating

The total energy consumption for heating will be of 15 000 MW per year with a peak demand of 8.1 MW during the coldest day.

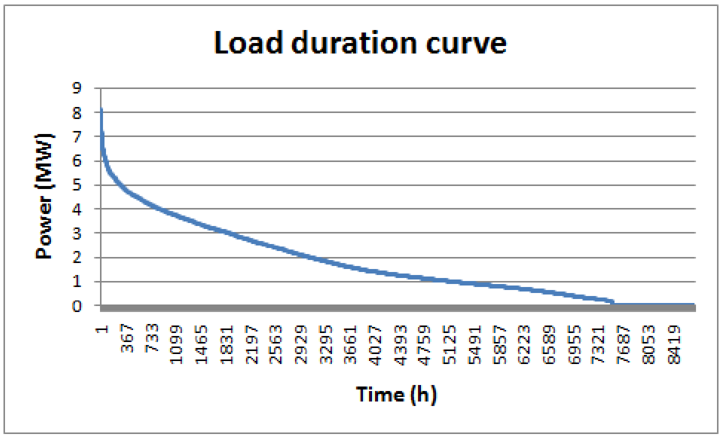

Figure 48 - Modified load duration curve

4.2.1.2. Cooling

The total energy demand for cooling will be 4 600 MWh per year with a peak demand of 4.5 MW.

4.2.1.3. Electricity

The total electrical demand will be of 15 500 MWh per year.

4.2.2. First case: Independent circuits

The first simulation will observe the system as if each heating circuit is completely independent and supplying energy to similar and also independent loads, with peak values of 2.7MW, like shown at figure 10.

This configuration may reduce transmission losses of the heated water, given the fact that each heat source may feed just the closest loads, reducing the transmission distances. It won't be considered a hybrid system (although the presence of auxiliary heaters and chillers may classify the system as it).

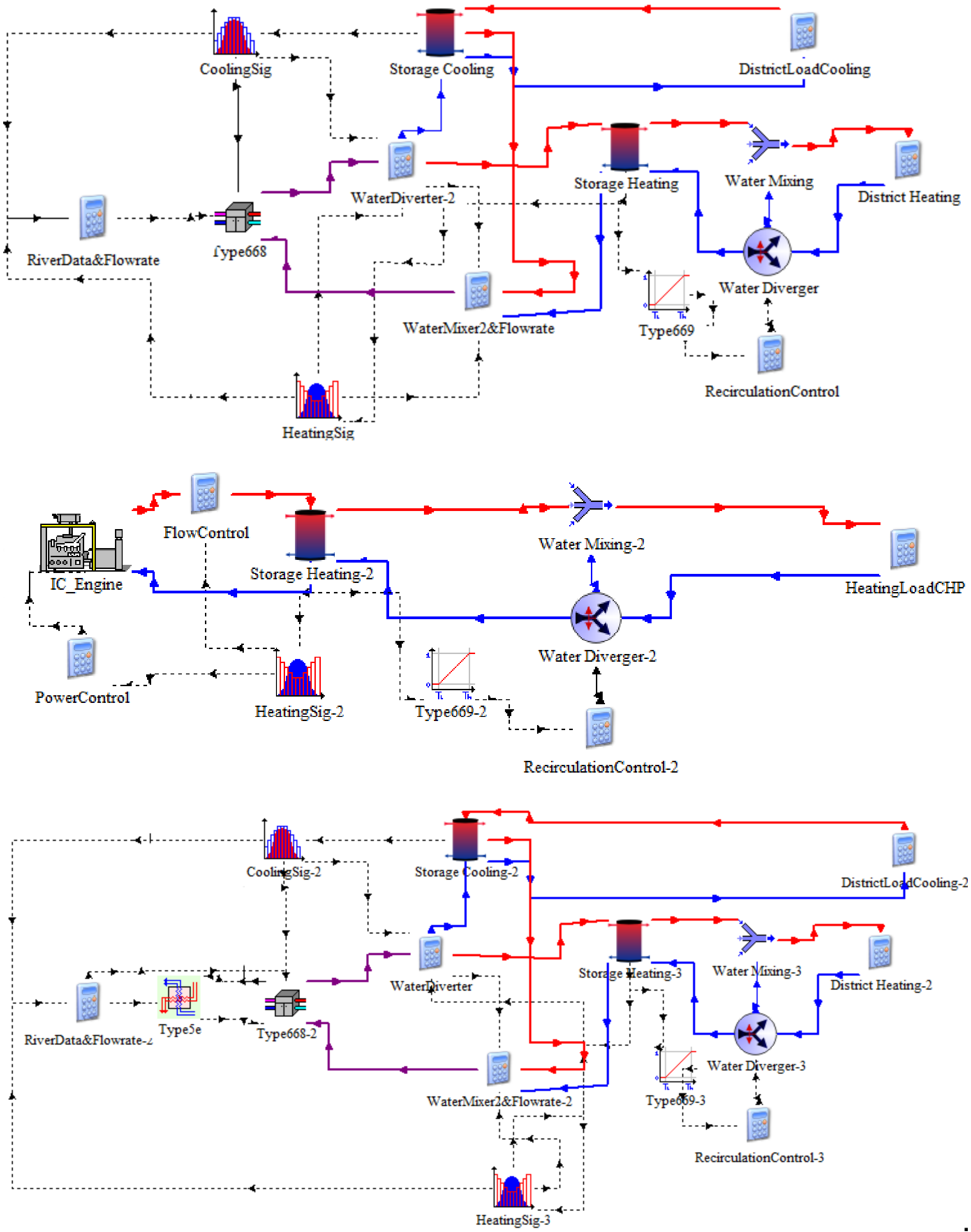

Figure 49 – TRNSYS model

4.2.3. Second case: Interconnected circuits equally feeding one load.

At this moment the three circuits will be connected at the feeding point. There will be just a single big load of 8 MW peak. The heat sources will equally supply the energy demanded, each one contributing with one third of the total amount (figure 50).

The cooling circuit will also be interconnected and operate in a similar way.

The main changes expected to observe at this point may be related with the extra transmission losses added. Especially at the moments of low load, where just one or two heat sources will be operating, higher distances between source and load will apply when compared with the previous case. Because of it, an extra 10% of heating requirement over the loads was applied (extra losses). This value will be applied to all hybrid systems.

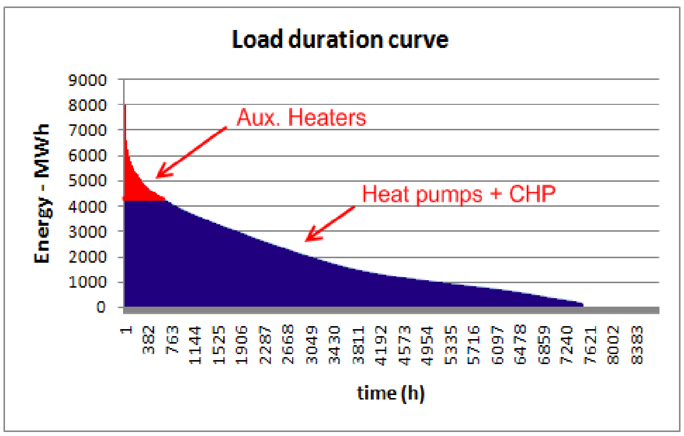

Figure 50 - Three sources: same share configuration*

4.2.4. Third case: Interconnected circuits with higher heat pump participation over the load.

At this configuration, the following control commands took place:

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

Heating

- If the total system load is under 1.5 MW, the demand will be supplied by the open source heat pump.
- If the total system load is between 1.5 and 3 MW, the demand will be supplied by the two heat pumps
- If the total system load is above 3 MW, the demand will be supplied by the heat pumps and the CHP system, which will also be generating electricity.

Cooling

- If the total cooling load is below 1.4 MW, the total demand will be supplied just by the closed loop heat pump. In case the demand is above 1.4 MW, the open loop heat pump will also enter the circuit.

There will be priority for the cooling load. In case of cooling and heating being required at the same moment and with high demand, meaning that the energy of just one heat pump won't be enough, the heat pumps will supply the cooling load, leaving all the heating for the CHP and auxiliary heaters.

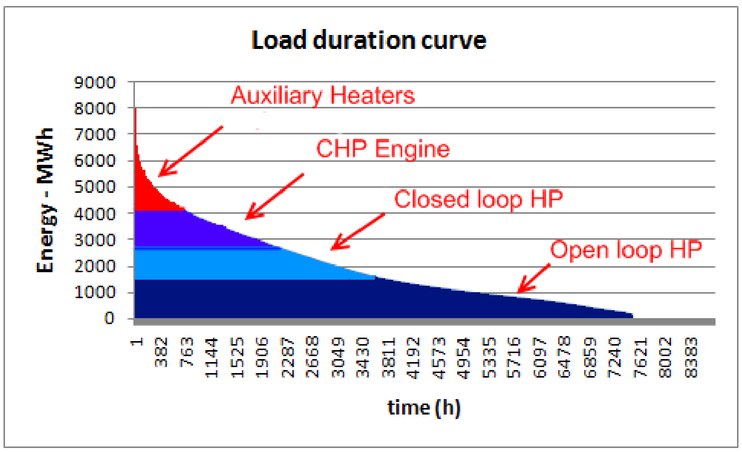

Figure 51 - Three sources: HP leading configuration*

4.2.4.1. First Results

At this stage the analysis will start slower, making possible to observe how the assumptions done can affect the final results.

At first the outputs will be examined through the monthly results: consumption and supplied loads. It will be evaluated how useful this data

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

may be to optimize the system and how precise can be dealing with this format of information.

Independent Loads (Energy in MWh)

Month	Time (h)	HP - P. to load	HP - P. consumed	CHP - P. to load	CHP - Electrical p. generated	CHP - P. consumed	HP closed - P. to load	HP closed- p. consumed	Auxiliary heaters
Jan	744	664	146	756	433	1,257	657	146	221
Feb	1,416	596	129	682	390	1,134	588	129	159
Mar	2,160	567	121	626	358	1,040	563	121	126
Apr	2,880	452	94	510	292	848	443	92	103
May	3,624	272	54	317	181	526	271	54	70
Jun	4,344	849	130	173	99	287	837	128	58
Jul	5,088	806	120	76	44	127	808	120	28
Aug	5,832	837	122	108	62	180	833	122	38
Sep	6,552	206	40	215	123	357	202	40	50
Oct	7,296	345	74	386	221	642	339	73	88
Nov	8,016	532	116	588	337	978	527	117	131
Dec	8,760	603	133	675	387	1,123	595	132	201
Sum	**8,760**	**6,727**	**1,280**	**5,113**	**2,926**	**8,499**	**6,664**	**1,274**	**1,273**
		COP	5.3	Total Energy	8,038.8		COP	5.2	

Table 10 - Non hybrid: energy distribution

Hybrid System – Equal share of loads (Energy in MWh)

Month	Time (h)	HP - P. to load	HP - P. consumed	CHP - P. to load	CHP - Electrical p. generated	CHP - P. consumed	HP closed - P. to load	HP closed- p. consumed	Auxiliary heaters
Jan	744	680	150	878	502	1,459	687	154	274
Feb	1,416	609	133	793	454	1,318	616	136	197
Mar	2,160	575	124	808	462	1,343	585	127	116
Apr	2,880	422	89	710	406	1,180	434	93	71
May	3,624	253	52	455	260	756	267	55	49
Jun	4,344	977	151	255	146	425	696	111	51
Jul	5,088	954	143	109	63	182	658	102	25
Aug	5,832	974	143	149	85	248	690	105	24
Sep	6,552	199	40	291	166	484	193	39	36
Oct	7,296	322	71	561	321	932	327	72	62
Nov	8,016	526	118	767	439	1,275	546	123	109
Dec	8,760	617	138	822	470	1,367	624	140	224
Sum	**8,760**	**7,108**	**1,351**	**6,598**	**3,776**	**10,968**	**6,323**	**1,258**	**1,238**
		COP	5.3	Total Energy	10,373.5		COP	5.0	

Table 11 - Hybrid same load share: energy distribution

Hybrid system – Heat pumps higher participation (Energy in MWh)

Month	Time (h)	HP - P. to load	HP - P. consumed	CHP - P. to load	CHP - Electrical p. generated	CHP - P. consumed	HP closed - P. to load	HP closed- p. consumed	Auxiliary heaters
Jan	744	837	193	794	455	1,321	683	155	220
Feb	1,416	752	171	713	408	1,185	601	133	148
Mar	2,160	756	166	628	360	1,045	581	127	120
Apr	2,880	638	134	417	239	694	462	98	114
May	3,624	538	109	107	61	177	294	60	93
Jun	4,344	862	128	431	246	716	656	103	15
Jul	5,088	906	134	188	108	313	635	97	5
Aug	5,832	896	128	281	161	467	666	100	10
Sep	6,552	463	94	22	13	37	186	38	73
Oct	7,296	584	127	190	109	315	360	78	111
Nov	8,016	706	159	567	325	943	546	123	134
Dec	8,760	762	176	732	419	1,216	615	142	191
Sum	**8,760**	**8,700**	**1,718**	**5,070**	**2,902**	**8,428**	**6,285**	**1,254**	**1,235**
		COP	5.1	Total Energy	7,971.6		COP	5.0	

Table 12 - Hybrid heat pump leading: energy distribution

The information above was displayed in a graphic form, making easier the visualization. These values include electricity, cooling and heating.

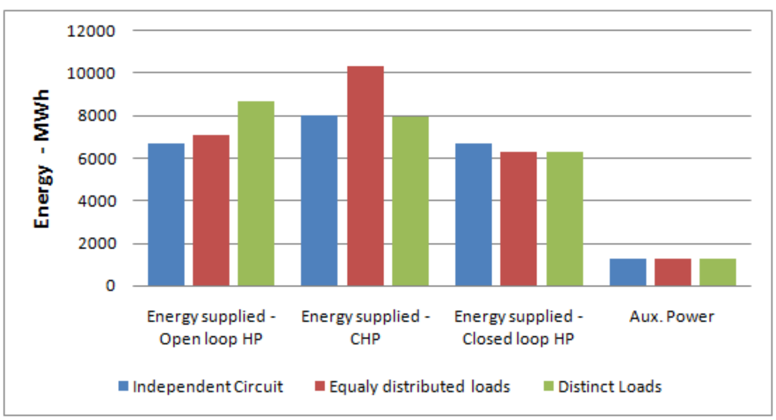

Figure 52 - Energy distribution

While the system was formed by three independent circuits, the participation of the different sources was very close from each other.

As the circuits were connected and a single load took place, with each source equally contributing to supply the energy requirements, the previous balance changed. At the first case, during the summer, while the heat pumps were working at the cooling mode, any heating requirement of their circuits would be ignored until they were once more available for heating. At the hybrid system, the CHP engine, with help of the auxiliary heaters, was the responsible for supplying heat for the system while the heat pumps were operating at the cooling mode. This, as consequence, raised the amount of energy supplied by the CHP system.

With the control change, where the heat pumps will have priority over the load, the amount of energy supplied by them raised. In all cases the bar representing the power supplied by the CHP is higher than the one representing the closed loop HP. It is due to the fact that, at the first, is also added the amount of electricity supplied.

The renewable share obtained was the following:

System configuration	Renewable share
Non hybrid	16%
Hybrid – Similar load distribution	15%
Hybrid – Heat pumps higher participation	19%

Table 13 - Renewable participation

The information present at figure 52 can be seen reflected at the renewable share results. The improvement at the amount of energy supplied by the CHP on the second case resulted into a reduction over the renewable share. The hybridization of the system gave the opportunity to create a control scheme that improved the contribution of the heat pumps at the load. The rise of the column representing the open loop heat pump energy production works as an indication that more renewable energy is being transferred into the load. The other heat pump column did slightly reduce. It is due to the fact that part of the cooling load previously supplied by it is now being supplied by the open loop heat pump.

The next step is to observe the financial aspect of each result, like was done before.

Although the data offered previously does give enough information to observe how the control configuration is acting over the final energy share, it lacks data about the moments where the energy is being produced and consumed, which is directly related with the system costs and related emissions.

There are different approaches to quantify the total emissions and costs based on the monthly data displayed previously. One of the options is to use data contained at the SAP-2005 (10) and define emission and energy costs looking for the demand side of the system, as long as it is known which technologies are supplying this load. For the present analysis, it will be observed the fuel consumption instead of the load, following the assumptions described at section 5. Making the analysis through the demand data might be interesting if one does not have access to details of the generation system, but is too generic. For a heat pump, for example, the table will assume that it is always working at a COP of 3.5, and based on that, define the energy consumption and related costs and emissions.

As explained at section 5, to have precise information about CO_2 emissions one must know if the energy generated may be internally consumed or constitutes energy surplus. This will depend of instantaneous values of generation and load. With just the information at the tables 6 – 8, assumptions based on personal experience or simple guess needs to be done.

For now, the following assumptions were made:

- It will be assumed that all the electricity generated by the CHP will be always sold to the grid.
- All the electricity used by the heat pumps will be purchased from the grid.
- The electricity purchased from the grid will cost 7.2 pence per kilowatt hour and when sold to the grid will pay 5.7 per kilowatt hour (10)
- The gas consumed will cost 2.1 pence per kWh (17)
- The emissions were calculated through the amount of energy consumed and its source. For gas, it was assumed the value of 0.194 kg of CO_2 per kWh consumed, and for electricity, 0.422 kg of CO_2 per kWh consumed from the grid. Electricity sold to the grid will save 0.568 kg of CO_2 per kWh (10).

Based on these assumptions, the internal rate of return versus the renewable share over the load generated the following graphic.

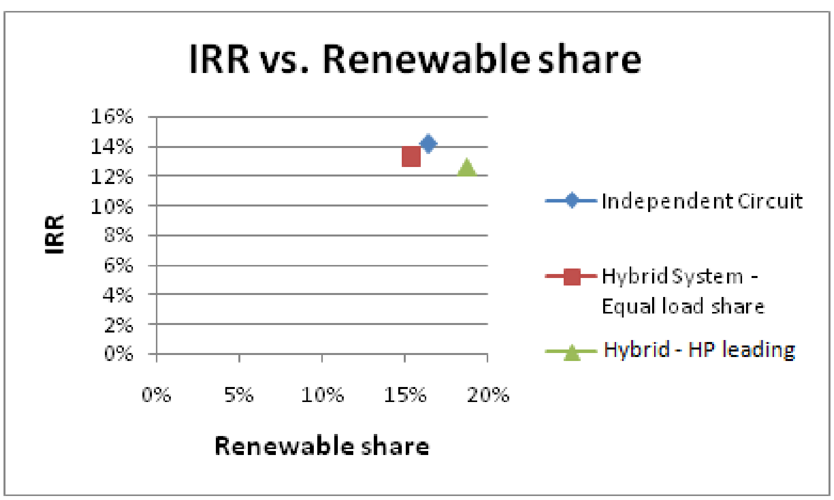

Figure 53 – Three sources: IRR vs. renewable participation

It can be observed that the hybrid systems present the worst IRR. This is, in part, due to the fact that the extra losses add cost to the energy being supplied. Even with a higher participation of the CHP than at the non hybrid case, which, as seen on the first series of simulations, tends to improve the savings with energy, the equal share configuration was not able to improve the IRR.

Although not applicable at the present case, is interesting to observe what would be the result if the hybrid system was not related with expressive extra transmission losses, which may be the case at smaller systems.

The graphic "energy cost against energy losses", for the "higher heat pump participation" configuration, is plotted below. It gives an idea of how much the cost of energy raises as also raises the **heat** transmission losses.

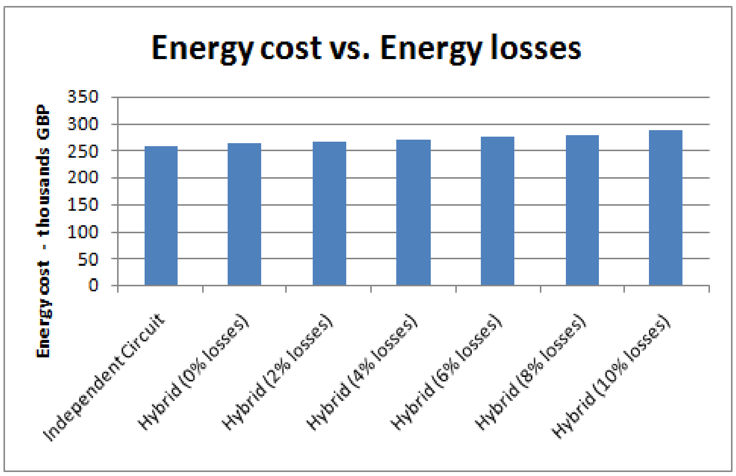

Figure 54 - Energy cost vs. heat transmission losses

It can be seen that the amount of money spent in a year with energy does not improve expressively. Looking for the IRR and given the fact that the energy reduction is small compared with the initial investment, that is equal for all cases, the changes are even less expressive.

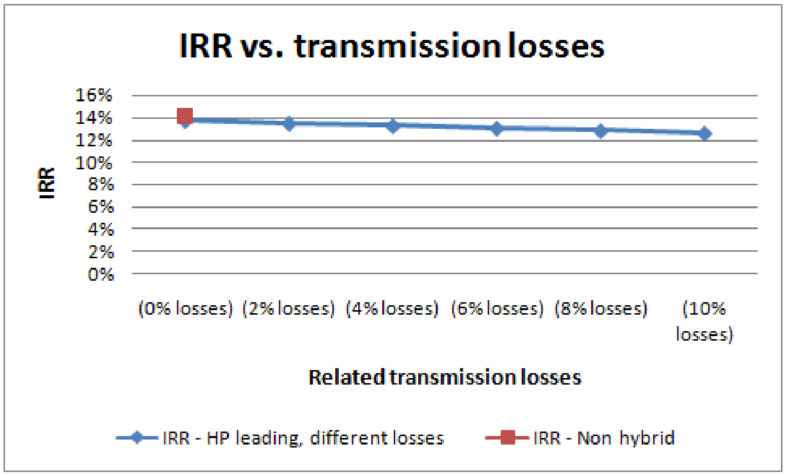

Figure 55 - IRR vs. heat transmission losses

The last point to be observed is the CO_2 emission reduction in each case.

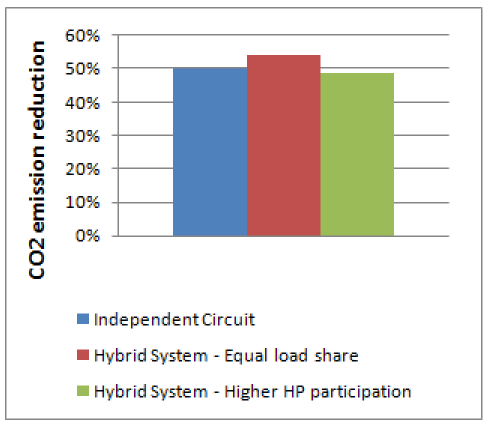

Figure 56 - CO_2 emission reduction

As said before, this analysis does present a flaw: The assumption of all electricity being sold to the grid, as it was electrical surplus. This gives amazing advantage to CHP engines as CO_2 emission reducers. The configurations with higher CHP participation over the load presented the best reductions. And in all cases, the reductions were massive, above 40%. It is relevant to know how much of the electricity sold to the grid could be internally used, which is impossible unless generation and demand are compared at an appropriate time step.

The power of simulation becomes evident at these moments, allowing to have the results based at the instantaneous values, whenever necessary.

Through Trnsys, a routine able to compare at every 3 minutes the electrical generation and consumption of the system was created, permitting to observe the origin of the utilized energy or, in case of generation, it destination.

The table with the utilized energy prices is shown below (10).

Energy	Profit (pence per kWh)
Electricity sold to the grid	5.7
Electricity sold to the buildings	7.2
Electricity sold to the heat pumps	0

Table 14 - electricity selling price

<u>**No** electricity will be sold to the grid if there is still internal load to be supplied.</u>

Looking now for the internal energy consumption, the following prices will be applied (10) (17):

Energy	Cost (pence per kWh)
Electricity purchased from the grid	7.2
Electricity purchased from the CHP	0
Gas consumed by the CHP	2.1

Table 15 - purchased electricity price

CO_2 emission:

Energy	Coefficient (kg of CO_2 per kWh)
Electricity from the grid	0.422
Electricity sold to the grid (surplus)	-0.568
Electricity from CHP	0 (it will be counted at the gas consumption)
Gas	0.194

Table 16 - emission coefficients

A new profile can now be built. The graphic below will compare the amount of energy internally used and sold to the grid from the previous assumption with the new method to calculate the energy flux.

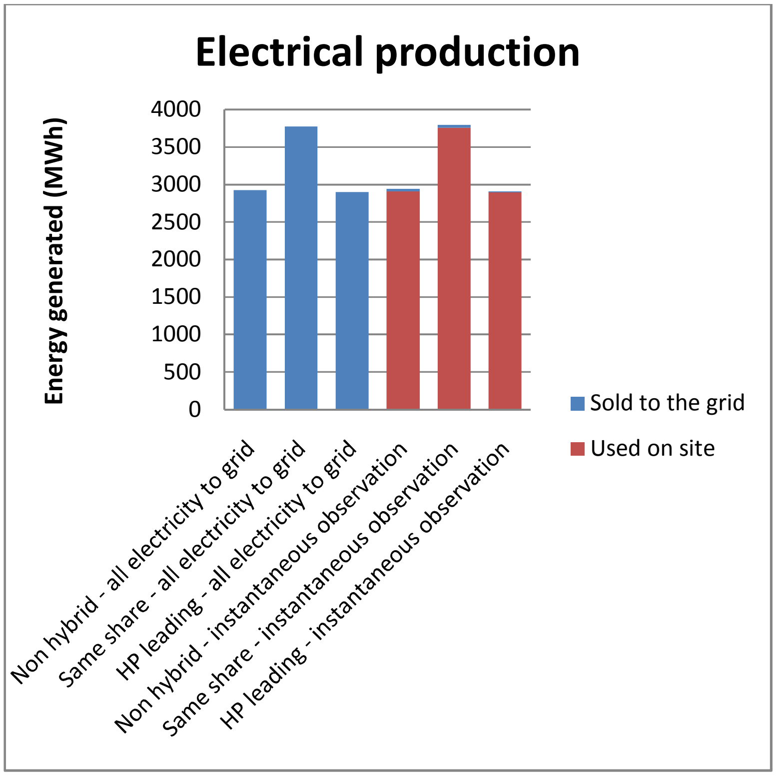

Figure 57 - CHP electricity destination

Comparing both analysis is evident the change over the results obtained initially and the new ones. The high electrical consumption of the site makes that almost all the energy internally produced be also internally consumed. This new analysis will cause a reduction over the CO_2 savings, given the fact that a very small portion of the electricity generated will be considered as displacing energy produced somewhere else. The new values for CO_2 reduction and renewable participation are shown below.

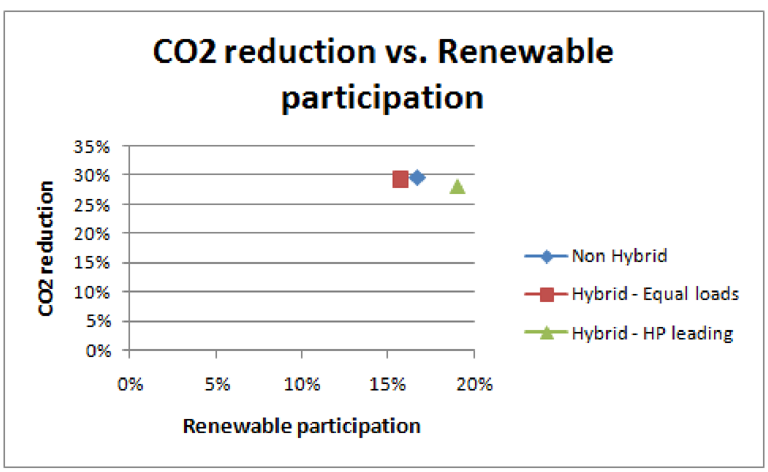

Figure 58 – Three heat sources: CO_2 reduction vs. renewable participation

The CO_2 reduction level, once the instantaneous analysis took place, made the savings calculated drop from around 50% to 30%. This highlights the importance to make clear whether the CO_2 displacement factor can be applied by any generated electrical energy or must be applied just in case of surplus. At the previous analysis one of the hybrid configuration did had a better CO_2 reduction than the non hybrid one. This difference is not evident at this moment anymore. Although the CHP production is still higher, the moments where it is generated ended up balancing both results. Timing the heat generated not with the heating demand but based at moments of the day where the electrical consumption is low may be an option to improve CO_2 emission savings, if needed. It would raise the chance to have electrical surplus, which can be sold to the grid and get the bonus of CO_2 displacement.

There were no changes over the renewable participation once it does not depend of the instantaneous value of any output or input.

Having all the options of CO_2 reduction above the selected target (20%) the analysis of the internal rate of return will be done against the renewable share.

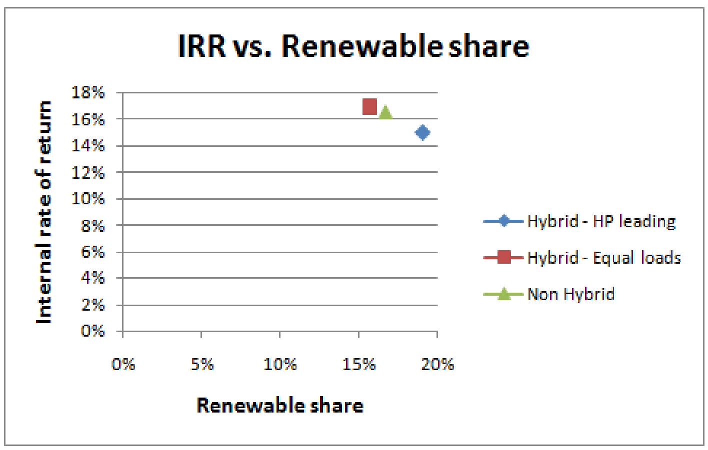

Figure 59 – Three heat sources: IRR vs. renewable share

During all the results it was seen how running the CHP for longer periods results on better energy savings. It is reflected at the graphic above. With similar initial investment, the difference between the internal rates of return depends almost exclusively of the energy savings. With almost all the electricity being used internally, money is being saved. It costs 7.2 pence per kWh purchased from the grid, while selling pays 5.7 pence per kWh. Economically, is more desirable to use the internally generated electricity than buy it from an external source. This explains why the IRR calculated at this time is higher than the previous ones.

It is also interesting to observe how renewable energy and costs are related. The higher the amount of energy extracted from the ground, the lower the internal rate of return. It is not exactly a linear relationship but may be kept in mind while creating a control configuration.

Changing the cooling priority, as done before, may be a solution to move the previous configurations to the right at the horizontal axis, closer to the 20% target. But another interesting change, in case the target of renewable participation is not so high, is to improve the CHP participation at the load, looking forward a better internal rate of return or even CO_2 emission reduction.

To observe how this last control option may affect the results, a new system was created, as detailed next.

4.2.5. Fourth case: Interconnected circuits with higher combined heat and power participation over the load.

The new system will have the following main characteristics:

Heating

- If the total system load is under 2MW, the demand will be supplied by the energy generated by the CHP engine.
- If the total system load is between 2 and 4 MW, the demand will be supplied by the CHP and the open source heat pump, equally.
- If the total system load is above 4 MW, the demand will be supplied by the heat pumps and the internal combustion machine, also equally.
- The electricity produced by the CHP system will be sold to the district buildings, heat pumps and, in last case, to the grid.

Cooling

- If the total cooling load is below 1.4 MW, the total demand will be supplied just by the closed loop heat pump. In case the demand is above this value, the open loop heat pump will join the circuit.

- There will be priority for the cooling load. In case of cooling and heating being required at the same moment and with high demand, meaning that the energy of just one heat pump won't be enough, the heat pumps will supply exclusively the cooling load.

The extra 10% heating transmission losses related with the higher distances between sources and loads is still being applied.

The load duration curve is shown below in order to make easier the understanding of how this new configuration will be working.

All the load distribution will be done controlling the water flow from the building to the storage tank of each system.

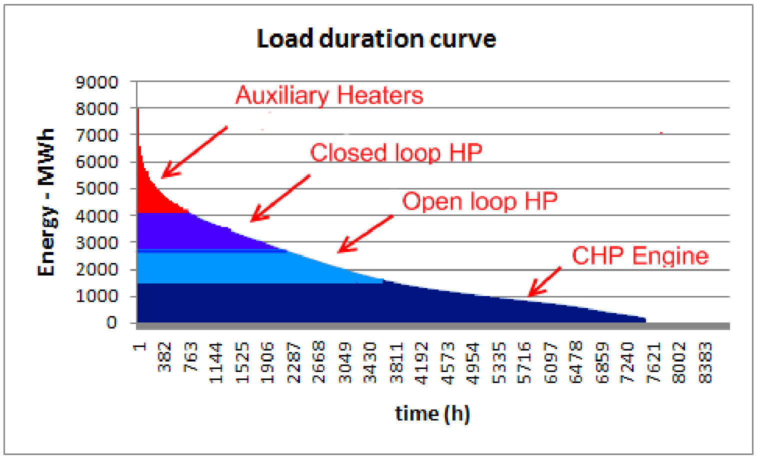

Figure 60 - CHP leading configuration*

4.2.5.1. Results

As before, the new configuration will be observed through its capacity to reduce CO_2 emission, compared with the base case, and to add renewable energy into the system.

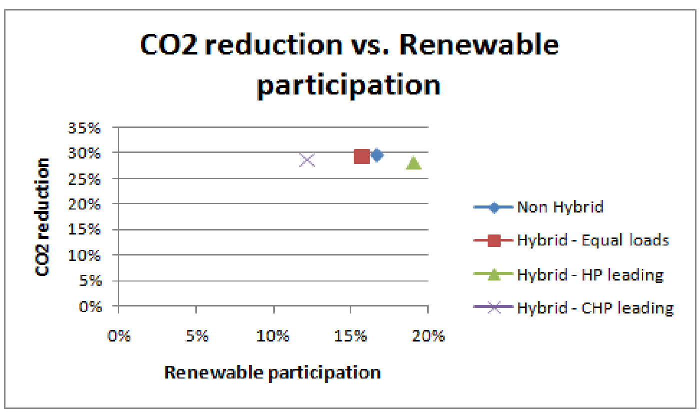

Figure 61 - CO_2 reduction vs. renewable participation

Unlike with what was expected, the raise over the CHP participation did not improve the CO_2 emission reduction. It is an interesting result and shows that the relationship between the CO_2 levels and CHP or even renewable participation is not so simple. Although this last system does reduce the

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

emission coefficient related with the internally consumed electricity, it raises the amount of gas being burned, improving the emissions related with the heat generation. The balance between all these variations seems to be better while CHP and HP are both supplying the same amount of heat during the year.

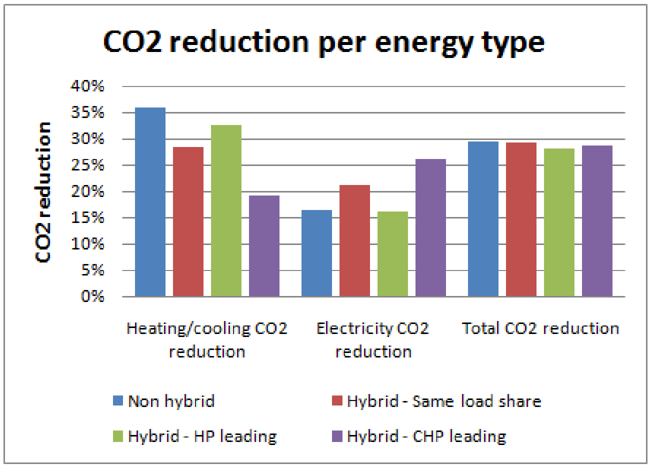

Figure 62 - CO_2 reduction per energy type

This graphic illustrates what was explained above. It was separated how much of CO_2 is being saved per kind of energy being consumed. The first case observed the emissions related with the heating and cooling consumption, the second focused on the electrical consumption emissions and the last combined both, giving the results observed before.

With these results, and with the renewable share being below 20%, running the system at the non hybrid mode seems to be a good option. Observing now the IRR against the renewable share, the following graphic was generated.

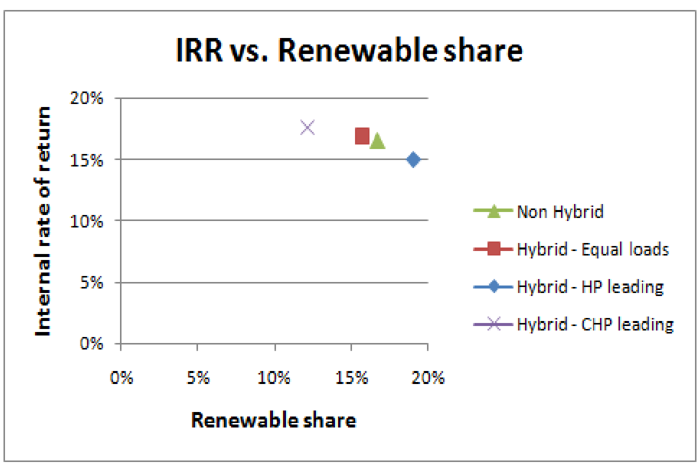

Figure 63 - Hybrid system new configuration: IRR vs. renewable share

The higher participation of the CHP system did return a better internal rate of return. A target of 10% of renewable participation, for example, would make the CHP leading configuration the best option between all the previous ones. It is true that the difference is not so expressive given the fact that the initial investment is set as the same.

A critic that may be added here is that, actually, the hybrid system would raise the complexity of the cooling/heating circuit, resulting into a higher initial cost. This extra value wasn't applied because of the lack of information over how much more the hybridization of the system would cost.

As observed before, looking for the renewable share target of 20%, a solution that may occur to a designer may be the introduction of photovoltaic panels to the system. It has already been seen that, for this district, the energy savings are not enough to overcome the raise of the needed initial investment caused by the high cost of the photovoltaic panels. It may be interesting to observe how much would be necessary to spend, and possible benefits, to achieve the 20% share with each configuration option through the addition of photovoltaic panels.

A fourth configuration will be also included.

4.2.6. Fifth case: Hybrid systems with photovoltaic cells.

This new case will observe the impact of photovoltaic arrays over the three previous hybrid system configurations and a fourth one.

Photovoltaic Panels

It will be utilized the Sanyo photovoltaic panel model HIP-190BA3, with peak capacity of 190 W.

A tilt of 55 degrees will be applied, facing south.

The fourth hybrid system configuration

The fourth control configuration will work by the following criteria:

Heating

- If the total system load is under 2MW, the demand will be supplied by the open source heat pump.
- If the total system load is between 2 and 4 MW, the demand will be supplied by the open source heat pump and the CHP system, equally.
- If the total system load is above 4 MW, the demand will be supplied by the heat pumps and the internal combustion machine, also equally.

- The electricity produced by the CHP system will be sold to the district buildings, heat pumps and, in last case, to the grid.

Cooling

- If the total cooling load is below 1.4 MW, the total demand will be supplied just by the closed loop heat pump. In case the demand is above this value, the open loop heat pump will join the circuit.

- There will be priority for the cooling load. In case of cooling and heating being required at the same moment and with high demand, meaning that the energy of just one heat pump won't be enough, the heat pumps will supply exclusively the cooling load.

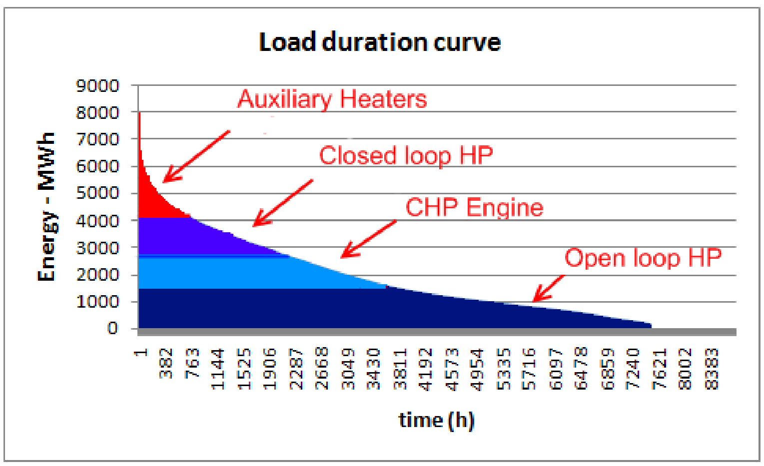

Figure 64 - HP-->CHP-->HP configuration*

4.2.6.1. Results

The photovoltaic panels were added in order to achieve the 20% renewable share at each case. The total area required by each configuration is shown below:

Control configuration	Required photovoltaic area

* This graphic is a conceptual representation created to facilitate the comprehension of the control configuration. It does not represent any result from the actual simulation or the precise load distribution.

Non hybrid	8,000 m^2
Similar share of the load	10,000 m^2
Heat pump leading	1,000 m^2
CHP leading	15,000 m^2
HP →CHP→HP	10,000m^2

Table 17 - required photovoltaic array area

The total renewable share and internal rate of return obtained is shown below, including also the values without the presence of any photovoltaic array.

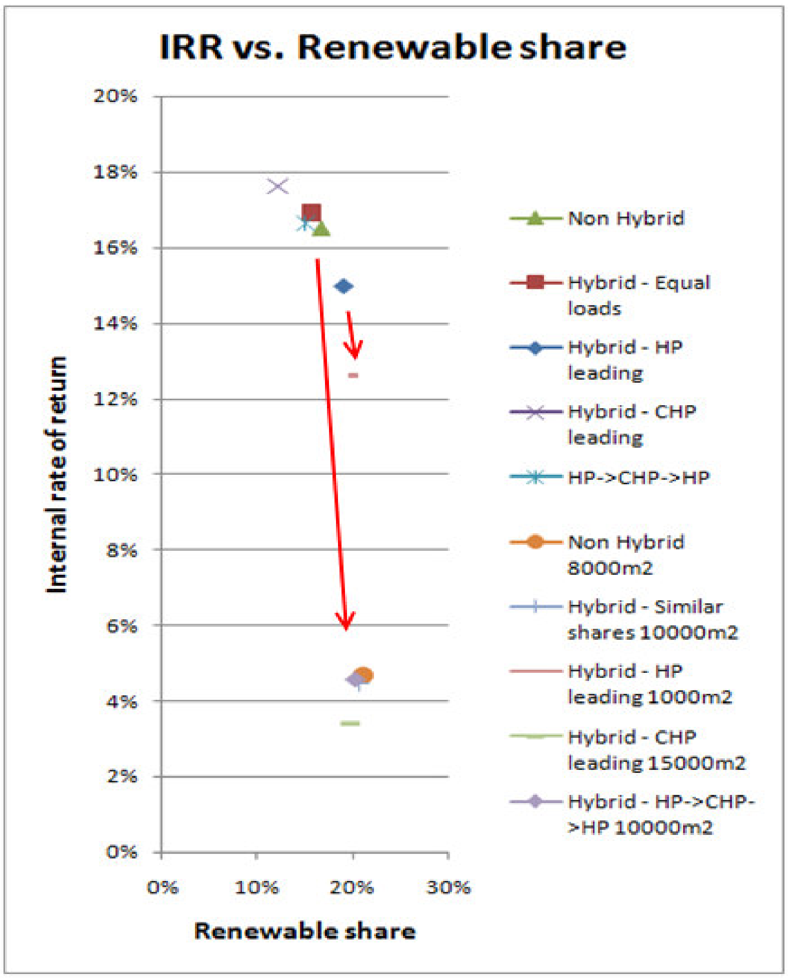

Figure 65 - Hybrid system with photovoltaic: IRR vs. renewable share

Using the photovoltaic panels to achieve the renewable target sunk the obtained internal rate of return of most systems with exception to the heat pump leading configuration, where a smaller amount of photovoltaic panels was necessary.

At this point, the advantage of utilizing the hybrid system over the non hybrid becomes evident. The possibility to improve the renewable participation through control configuration changes reduced the required investment needed to achieve the same share through a non hybrid system. Is still valid the detail that no additional cost related with the conversion from non-hybrid to hybrid was applied. But the final difference is high enough to suspect that even including this cost the results will still show advantage to the hybrid system. Plotting the expected cash flow during 20 years it becomes clearer the magnitude of the investments and savings for each case.

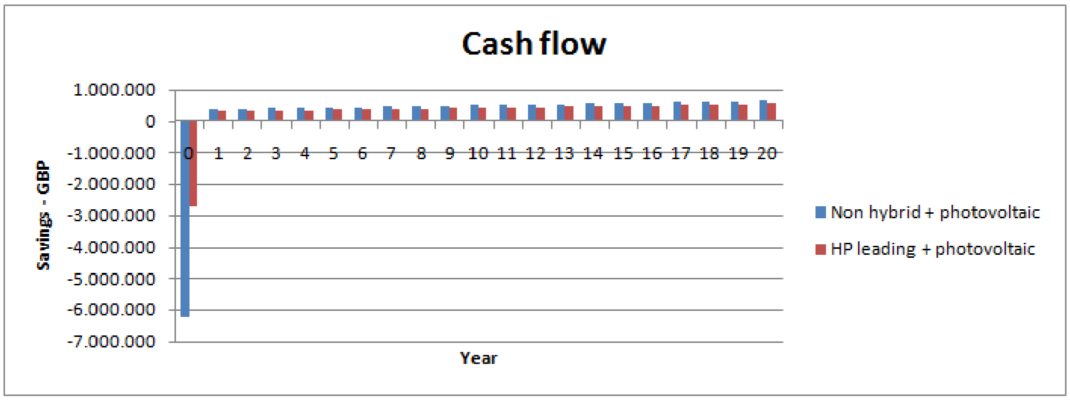

Figure 66 - Hybrid system with photovoltaic: Cash flow

It is also relevant to remind that the hybrid configuration is dealing with 10% more losses than the non hybrid one. At smaller systems, where these extra losses may be reduced, the hybridization may achieve even better results, also reducing installation costs.

To finalize, one last change over the control will be done, based on the knowledge achieved from the first series of simulations. The cooling priority will be taken out from the heat pumps. The result of such change at the HP leading configuration is shown below.

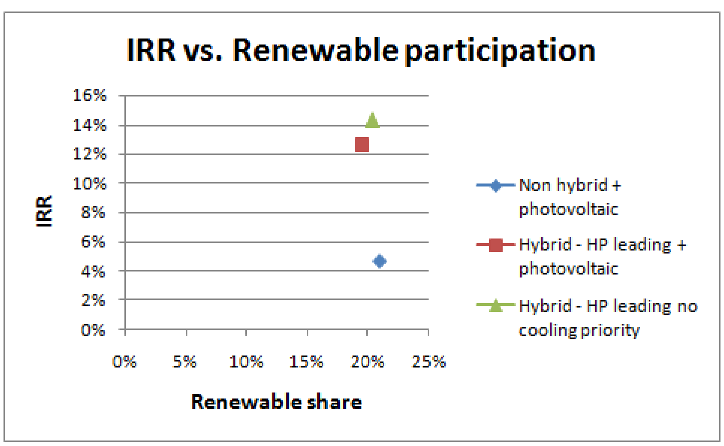

Figure 67 - Hybrid system no cooling priority: IRR vs. renewable participation

The graphic shows how the same target could be achieved through different methods and how the simulation indicated a possible best option. The capacity to analyze the results and how the load behaves for each change done at the system allows the designer to visualize the path that can be followed in order to optimize the system.

For the system being studied, this last configuration was able to provide all the set targets with the highest financial benefits and with a high difference from the non hybrid system.

5. Conclusion

The new energy policies adopted by several countries, where targets of renewable energy production and CO_2 emissions levels are set, created a new challenge for the energy suppliers: achieve those targets without compromising the reliability and profitability of the energy supply. This is especially the case in the UK, with building codes and local planning requirements imposing increasingly stricter targets. The thesis went through different steps of the design of a system aiming to achieve these targets for a real case study, observing, at the end, possible advantages brought by the utilization of a hybrid system. The performance of the different systems was simulated using the TRNSYS software, which allows a dynamic simulation of the complex interaction between component performance and control strategies.

The most relevant observations are:

5.1. CO_2 reduction and renewable energy fraction

A first point observed is the fact that, once these targets are set, is important to have the methods of calculating them very clearly defined. If these definitions are easy to misunderstand or present flaws that can be exploited, they will miss the point and not deliver the environmental benefits that were deemed to be necessary when the CO_2 and renewable energy targets were set.

A good example of this could be easily observed when, in chapter 3, different methods of calculating the CO_2 emission were compared. A difference of 20% could be seen in some cases, which is 100% of the savings imposed by the Edinburgh code for sustainable buildings, for example (3).

A more broad study over the sensitivity of the CO_2 emission calculated would be interesting, involving not just a particular location, as done at this thesis, but involving a series of consumers and producers. Maybe raising the total load involved could result at changes not so significant at the CO_2 emission calculated through each assumption.

A second point is the relevance of defining if heat pumps in cooling mode can be seen as a renewable technology or not. During the result analysis this unclear position led to the option of not including any possible benefit brought by a heat pump to the system while it is working in the cooling mode. In many cases, this forced the utilization of a second technology to achieve the renewable target, with a negative impact over the economic performance (as seen at figures 47 and 65).

With the current and expected growth of the UK heat pump market, this topic should deserve special attention from the government. A clear definition of renewable cooling is necessary, and might provide an extra boost to the heat pump market if they are included in the definition.

5.2. Advantages brought by combining technologies in a hybrid system

It became clear how powerful the heat pumps can be when trying to achieve the renewable targets or CHP while reducing the CO_2 emissions (especially if the reduction emission factor is applied to all the generated energy). At chapter 4.1 the best financial result, between the systems that achieved both CO_2 and renewable targets, was obtained with the system including a 3.5 MW heat pump + gas boiler as auxiliary heater. However, this solution was obtained by relaxing the constraints imposed by the real case study (the available flow from the nearby river does not allow to provide heat for such a large heat pump). Although interesting and useful to understand how each technology can contribute for each target, the result does not reflect the constraints of the location. But considering these constraints, which are common to all renewable energy technologies, reveals the interest and importance of hybrid systems.

Through the introduction of a hybrid system design, the targets that before were expensive to fulfil became more achievable. The ability to work with a more complex control creates the possibility to extract the most from each technology involved, without compromising the reliability of the system by depending from just one source.

In chapter 4.2, an attempt to use photovoltaic panels to meet the renewable energy target resulted, as expected, in an unacceptably low internal rate of return. Two options, though, achieved the target, reducing the IRR by a few points but requiring only some changes in the control strategy, without significant extra capital costs. The solution was a control configuration where the heat pumps were utilized for the longest period possible, with the CHP acting more as an auxiliary system when the heating demand was too high, with both technologies integrated into a hybrid system. The non-hybrid system based on the same two technologies did not offer the same flexibility in control strategies, and resulted in a more expensive solution.

5.3. Combined heat and power and heat pumps in a hybrid system

Another aspect observed is the benefits of running CHP engines in a hybrid system with water or ground source heat pumps. The first is able to not just reduce the emission levels of the system but also showed to be very flexible to accept the controls applied and with a helpful capacity to reduce the energy costs (in part caused by the high value paid for the electricity consumed from the grid).

The heat pumps do present a high efficiency but are limited by the ground or water source capacity to supply heat, making the CHP engine a good candidate to work as the complementary source. Given the significance of heat demand in the total energy demand in the UK, heat pumps present a real potential to deliver CO_2 savings and renewable energy to meet the country's objectives, even without taking into account any "renewable cooling".

5.4. The advantages of utilizing a simulation tool during the optimization process

It was very useful to be able to use a tool where, once a basic system was created, small changes, involving less complexity or time spent, could be done and the results of these changes rapidly obtained. The simulation tool was able to compare different system configurations, component sizing, and importantly different control strategies which could be simulated in detail.

Having a model of the whole system also allowed to reject solution that would have seem interesting from an economical point of view but proved to be technically unfeasible (i.e. not able to meet the load).

The discussion in chapter 3.1 revealed the relevance of taking into account the energy generation and consumption using short time steps. TRNSYS proved very flexible to not just work with the required low time steps (in this case 3 minutes) but also to accept routines that would already deliver, as result, the destination of the generated energy. It should also be noted that, although this was outside the scope of this study, it would have been possible to model the buildings together with the systems rather than using an estimated load profile.

The flexibility of the tool did have a cost which is the complexity involving its utilization. The learning curve is a steep one, and the use of such a program might be considered as too time-consuming for a designer dealing with tight deadlines. The program also requires a thorough understanding of the components and control strategies and does not offer the same level of user comfort as simpler tools that provide a unique answer to a design problem.

One interesting option for future work is to develop more user-friendly user interfaces based on basic systems configurations. Such interfaces would allow users not familiarised with a complex tool like TRNSYS to modify a few key design parameters, saving time during the design process and avoiding the need to train every designer in the use of a complex simulation tool.

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Appendix 1

EKW130 Heating Capacity Data (Full Load)

ELT	EST	Load Flow		Source 6.8 L/s							Source 8.5 L/s						
		Flow	PD	Heating						PD	Heating						PD
°C	°C	L/s	kPa	LLT	HC	kW	HE	COP	LST	kPa	LLT	HC	kW	HE	COP	LST	kPa
15.6	-1.1	6.8	21.4	20.2	127.6	22.8	104.8	5.6	-4.9	23.5	20.2	128.5	22.2	106.3	5.8	-4.2	34.4
		8.5	31.8	19.3	130.7	22.9	107.8	5.7	-5.0	23.5	19.4	131.9	22.4	109.5	5.9	-4.3	34.4
	4.4	6.8	21.4	20.8	144.6	23.7	120.9	6.1	0.1	22.8	20.8	145.7	23.2	122.5	6.3	0.9	33.5
		8.5	31.8	19.8	148.2	23.8	124.3	6.2	-0.1	22.8	19.9	149.5	23.3	126.2	6.4	0.8	33.5
	10.0	6.8	21.4	21.4	160.3	24.7	135.6	6.5	5.1	22.1	21.4	161.5	24.1	137.4	6.7	6.0	32.8
		8.5	31.8	20.3	164.2	24.8	139.4	6.6	5.0	22.1	20.4	165.7	24.3	141.5	6.8	5.9	32.8
	15.6	6.8	21.4	21.9	174.7	25.7	149.0	6.8	10.2	21.4	21.9	176.0	25.0	150.9	7.0	11.2	31.8
		8.5	31.8	20.7	178.9	25.8	153.1	6.9	10.0	21.4	20.8	180.6	25.2	155.3	7.2	11.1	31.8
	21.1	6.8	21.4	22.3	187.7	26.6	161.0	7.0	15.3	20.7	22.4	189.0	26.0	163.1	7.3	16.4	30.8
		8.5	31.8	21.1	192.2	26.8	165.5	7.2	15.1	20.7	21.2	194.0	26.2	167.8	7.4	16.3	30.8
26.7	-1.1	6.8	20.0	31.1	123.7	28.1	95.7	4.4	-4.6	23.5	31.2	124.6	27.4	97.2	4.5	-3.9	34.4
		8.5	30.1	30.3	126.7	28.2	98.5	4.5	-4.7	23.5	30.4	127.9	27.6	100.3	4.6	-4.0	34.4
	4.4	6.8	20.0	31.8	141.3	29.0	112.2	4.9	0.4	22.8	31.8	142.3	28.3	114.0	5.0	1.1	33.5
		8.5	30.1	30.9	144.7	29.2	115.5	5.0	0.3	22.8	30.9	146.0	28.5	117.5	5.1	1.0	33.5
	10.0	6.8	20.0	32.4	157.2	30.0	127.2	5.2	5.4	22.1	32.4	158.4	29.3	129.1	5.4	6.3	32.8
		8.5	30.1	31.3	161.1	30.2	130.9	5.3	5.3	22.1	31.4	162.5	29.5	133.1	5.5	6.1	32.8
	15.6	6.8	20.0	32.9	171.6	31.0	140.6	5.5	10.5	21.4	32.9	172.8	30.2	142.6	5.7	11.4	31.8
		8.5	30.1	31.8	175.7	31.1	144.6	5.6	10.3	21.4	31.8	177.4	30.4	146.9	5.8	11.3	31.8
	21.1	6.8	20.0	33.3	184.3	31.9	152.4	5.8	15.6	20.7	33.4	185.7	31.2	154.5	6.0	16.6	30.8
		8.5	30.1	32.1	188.8	32.1	156.7	5.9	15.4	20.7	32.2	190.5	31.4	159.1	6.1	16.5	30.8
37.8	-1.1	6.8	18.6	42.1	119.7	35.4	84.3	3.4	-4.2	23.5	42.1	120.6	34.5	86.1	3.5	-3.6	34.4
		8.5	28.3	41.3	122.6	35.6	87.1	3.4	-4.3	23.5	41.4	123.8	34.8	89.0	3.6	-3.7	34.4
	4.4	6.8	18.6	42.7	136.4	36.2	100.2	3.8	0.8	22.8	42.8	137.4	35.3	102.1	3.9	1.5	33.5
		8.5	28.3	41.8	139.8	36.4	103.4	3.8	0.7	22.8	41.9	141.0	35.6	105.5	4.0	1.4	33.5
	10.0	6.8	18.6	43.3	151.7	36.9	114.8	4.1	5.8	22.1	43.3	152.8	36.0	116.8	4.2	6.6	32.8
		8.5	28.3	42.3	155.4	37.1	118.3	4.2	5.7	22.1	42.3	156.8	36.3	120.5	4.3	6.5	32.8
	15.6	6.8	18.6	43.8	165.5	37.7	127.8	4.4	10.9	21.4	43.8	166.7	36.8	129.9	4.5	11.8	31.8
		8.5	28.3	42.7	169.5	37.9	131.6	4.5	10.8	21.4	42.7	171.1	37.1	134.0	4.6	11.7	31.8
	21.1	6.8	18.6	44.2	177.9	38.4	139.4	4.6	16.1	20.7	44.3	179.2	37.5	141.7	4.8	17.0	30.8
		8.5	28.3	43.1	182.2	38.6	143.6	4.7	15.9	20.7	43.1	183.9	37.8	146.1	4.9	16.9	30.8
48.9	-1.1	6.8	17.3	53.0	114.7	44.4	70.3	2.6	-3.7	23.5	53.1	115.5	43.3	72.2	2.7	-3.2	34.4
		8.5	26.5	52.3	117.4	44.6	72.8	2.6	-3.7	23.5	52.3	118.5	43.6	74.9	2.7	-3.3	34.4
	4.4	6.8	17.3	53.6	128.9	44.9	84.0	2.9	1.4	22.8	53.6	129.8	43.8	86.0	3.0	2.0	33.5
		8.5	26.5	52.7	132.0	45.1	86.9	2.9	1.3	22.8	52.7	133.2	44.1	89.1	3.0	1.9	33.5
	10.0	6.8	17.3	54.0	142.4	45.4	97.1	3.1	6.5	22.1	54.1	143.5	44.3	99.2	3.2	7.1	32.8
		8.5	26.5	53.1	145.9	45.6	100.3	3.2	6.4	22.1	53.2	147.2	44.6	102.7	3.3	7.0	32.8
	15.6	6.8	17.3	54.5	155.3	45.8	109.5	3.4	11.6	21.4	54.6	156.5	44.7	111.7	3.5	12.3	31.8
		8.5	26.5	53.5	159.1	46.1	113.0	3.5	11.5	21.4	53.5	160.6	45.1	115.5	3.6	12.2	31.8
	21.1	6.8	17.3	55.0	167.5	46.3	121.2	3.6	16.7	20.7	55.0	168.8	45.2	123.6	3.7	17.5	30.8
		8.5	26.5	53.9	171.6	46.6	125.1	3.7	16.6	20.7	53.9	173.2	45.5	127.7	3.8	17.4	30.8

Appendix 2

EKW130 Cooling Capacity Data (Full Load)

ELT	EST	Load Flow		Source 6.8 L/s							Source 8.5 L/s						
		Flow	PD	Cooling						PD	Cooling						PD
°C	°C	L/s	kPa	LLT	TC	kW	HR	COP	LST	kPa	LLT	TC	kW	HR	COP	LST	kPa
-1.1	10.0	6.8	23.5	-5.0	108.6	19.8	128.4	5.5	14.6	22.1	-5.1	109.4	19.4	128.8	5.6	13.7	32.7
		8.5	34.4	-4.3	111.2	19.9	131.2	5.6	14.7	22.1	-4.4	112.2	19.5	131.7	5.8	13.8	32.7
	21.1	6.8	23.5	-4.7	98.0	24.6	122.5	4.0	25.5	20.7	-4.7	98.7	24.0	122.7	4.1	24.7	30.8
		8.5	34.4	-4.0	100.3	24.7	125.1	4.1	25.6	20.7	-4.0	101.3	24.1	125.4	4.2	24.7	30.8
	32.2	6.8	23.5	-4.2	85.3	29.6	114.9	2.9	36.4	19.2	-4.2	86.0	28.9	114.9	3.0	35.5	29.2
		8.5	34.4	-3.6	87.4	29.8	117.2	2.9	36.5	19.2	-3.7	88.2	29.0	117.2	3.0	35.6	29.2
10.0	10.0	6.8	22.1	4.6	150.0	21.8	171.9	6.9	16.2	22.1	4.5	151.2	21.3	172.5	7.1	15.0	32.7
		8.5	32.7	5.6	153.7	21.9	175.6	7.0	16.4	22.1	5.5	155.1	21.4	176.5	7.3	15.1	32.7
	21.1	6.8	22.1	5.0	137.9	26.6	164.5	5.2	27.1	20.7	5.0	138.9	26.0	164.9	5.3	25.9	30.8
		8.5	32.7	5.9	141.3	26.8	168.0	5.3	27.2	20.7	5.9	142.6	26.1	168.7	5.5	26.0	30.8
	32.2	6.8	22.1	5.5	124.2	31.7	156.0	3.9	37.9	19.2	5.5	125.2	31.0	156.2	4.0	36.7	29.2
		8.5	32.7	6.3	127.3	31.9	159.2	4.0	38.0	19.2	6.3	128.4	31.1	159.6	4.1	36.8	29.2
21.1	10.0	6.8	20.7	14.3	188.4	23.7	212.1	7.9	17.7	22.1	14.2	189.8	23.2	213.0	8.2	16.2	32.7
		8.5	30.8	15.5	193.0	23.8	216.8	8.1	17.8	22.1	15.5	194.8	23.2	218.0	8.4	16.3	32.7
	21.1	6.8	20.7	14.7	176.6	28.7	205.2	6.2	28.5	20.7	14.7	177.9	28.0	205.9	6.4	27.1	30.8
		8.5	30.8	15.9	180.9	28.8	209.7	6.3	28.7	20.7	15.8	182.5	28.1	210.6	6.5	27.2	30.8
	32.2	6.8	20.7	15.3	161.4	33.5	194.9	4.8	39.3	19.2	15.2	162.6	32.7	195.3	5.0	37.9	29.2
		8.5	30.8	16.3	165.3	33.7	199.0	4.9	39.4	19.2	16.3	166.8	32.9	199.7	5.1	38.0	29.2
32.2	10.0	6.8	19.2	24.1	223.6	25.5	249.2	8.8	19.0	22.1	24.1	225.3	24.9	250.2	9.0	17.2	32.7
		8.5	29.2	25.6	229.1	25.7	254.8	8.9	19.2	22.1	25.5	231.2	25.0	256.2	9.2	17.4	32.7
	21.1	6.8	19.2	24.5	212.7	30.7	243.4	6.9	29.9	20.7	24.5	214.2	30.0	244.2	7.1	28.2	30.8
		8.5	29.2	25.9	217.8	30.9	248.7	7.1	30.1	20.7	25.9	219.8	30.1	249.9	7.3	28.3	30.8
	32.2	6.8	19.2	25.1	196.7	35.4	232.0	5.6	40.6	19.2	25.1	198.1	34.5	232.7	5.7	39.0	29.2
		8.5	29.2	26.4	201.5	35.6	237.0	5.7	40.8	19.2	26.3	203.3	34.7	238.0	5.9	39.1	29.2