# IMPROVING THE DESIGN OF HYBRID SYSTEMS USING DETAILED SIMULATION

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

Mahatma Gandhi

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# Abstract

Current stringent environmental legislations have driven energy system designers towards the challenge of providing systems with high renewable energy penetration without sacrificing reliability. System designs that provide the best answer to this challenge often require the combination of different technologies (so-called hybrid systems).

The aim of this project is to observe and exemplify how the design of a hybrid energy system benefits significantly from the utilisation of detailed simulation tools, as they can cope with the volatility of renewable energy supplies and the mixing of different quality (temperature) thermal sources with a thermal buffer, common in many hybrid systems.

For such, I created a new hybrid system design methodology and applied it to three case studies where the original hybrid energy system design was produced by a simplified energy analysis tool. Additionally, a performance analysis interface was also produced, reducing the time required to process and analyse all the time series data produced after each detailed simulation.

By applying the detailed simulation methodology to the first of the case studies, a typical residential heat pump system, it was possible to observe the impact that the control strategy adopted by the user will have in the system reliability and efficiency, factor currently ignored by the British heat pump design standards.

The outcome from applying detailed simulation to the case study two was an improved hybrid biomass and heat pump system design. The new system, unlike the original design, is able to achieve the performance targets defined by the customer. Additionally, the produced design proved to be flexible enough to meet possible future changes in these targets.

The performance of the hybrid system originally designed for the case study tree, a hybrid heat pump and solar water heating system, was highly sensitive to changes in the load profile. The outcome from remodelling and improving such system through detailed simulation was an energy system design that reduced by 13% the amount of $CO_2$ emission emitted and also is able to maintain constant performance levels even with considerable changes in the load profile.

# 1. Introduction

The driving force behind the work presented in this dissertation is derived from the current trend seen around the world towards higher energy efficiency in buildings and the growth of embedded generation. This trend is driven primarily from environmental legislation. For example, in the European Union the CO2 emissions of member states must be 20% lower by 2020 compared to 1990 levels. Additionally, at least 20% of all energy consumed should be produced from renewable resources (European Commission, 2008). To achieve such target, governments across Europe are instigating increasingly stringent energy efficiency legislation and developing mechanisms to encourage the uptake of low-carbon technologies at the small and large scale. The former is particularly important in the UK, where the domestic sector is responsible for 30% of total energy consumption with approximately 80% used for heating applications (BERR, 2009). Since 2008 all new dwellings in the UK are rated against the code for sustainable homes (Department for Communities and Local Government, 2009) and by 2016 it is expected that all new properties would be able to offset any carbon emission resulted from heating or cooling. This creates a formidable challenge to designers, who must integrate renewable technologies and overcome their weaknesses such as high capital costs and sensitivity to environmental (both external and internal) conditions.

System designs that provide the best answer to the challenges described above often require the combination of different technologies (so-called hybrid systems) such as heat pumps and solar water heating panels sharing the hot water demand of a residential building or biomass boilers connected to the same heat store as a combined heat and power engine. Popular hybrid systems frequently base themselves on bivalent configurations where one source has priority over energy supply and the second acts as backup. Due to their lower sensitivity to environmental conditions, fossil-fuel-driven technologies have typically been used as back up options but with more stringent emissions targets, as seen in the British code for sustainable homes(Department for Communities and Local Government, 2009), there is the need to find suitable mixes of low and zero carbon alternatives. Systems purely driven by low carbon technologies will achieve significantly lower CO2 targets (or higher renewable shares) than systems featuring a fossil fuelled back-up but their successful implementation and use also pose a greater engineering challenge to researchers, manufacturers and installers.

Evidence of this challenge is provided by the fact that even traditional hybrid energy systems installed to-date have performed poorly. For example, Hill (Hill et al, 2009) reviewed fifty five gas boiler and solar collector installations throughout the UK and observed significant variation in performance, even between similar systems. Sixty five per cent of installations were underperforming. It was concluded that the reasons for the lack of performance were user behaviour and poor implementation of system control. More often than not, the supposed back-up unit was acting as the primary energy source, supplying heat to the hot water tank even when solar radiation was still available.

Another example of poorly performing hybrid systems can be seen at heat pump installations. These are typically hybrid systems where the heat pump usually is designed to meet the base demand and a secondary heat source, such as an electric immersion heater, deals with the peak. In recent trials run by the Energy Saving Trust, 83 heat pump installations were monitored around the UK (The Energy Savings Trust, 2010). The results gave serious cause for concern, indicating underperforming systems as result of poor design and installation. The reasons for the poor performance were stated as over-simplified sizing methodologies and low attention given to the operation and control of the secondary energy (back up) source (most cases electric heaters). The initial response came from the Micro-generation Certification Scheme (MCS) (DECC, 2010) which reviewed the entire design methodology, defining a series of procedures that must be followed prior a heat pump installation. One of the case studies presented in chapter 6 indicates that including results of dynamic simulation and user behaviour/control into the design strategy could have made the standard more robust to a wider range of situations.

Finally, at larger scales, e.g. district heating systems, the CO2 reduction and renewable share targets, as for example the ones defined by the Edinburgh standards for sustainable buildings (The City of Edinburgh Council, 2010), are challenges for the designer. Traditionally, designers have relied on large thermal stores to which different heat sources may be connected and operate following a pre-defined schedule. Utilising low carbon energy units as one of the heat sources connected to this tank may be a viable to achieve the required targets. A major challenge lays in the fact that many design and feasibility study tools (such as Energy Pro, T-sol, HOMER) are ill-equipped to deal with system sensitivity to temperature changes. Factors such as temperatures of working fluids and stratification in thermal buffering are not considered in these tools, which may result into erroneous design and poor performance.

In the situations highlighted above, detailed dynamic modelling of the energy sources and thermal buffering system can give more a realistic picture of system performance as it can cope with the volatility of renewable energy supplies and the mixing of different quality (temperature) thermal sources with a thermal buffer.

The aim of this project is therefore to develop a methodology for the application of detailed energy modelling tools to the design of hybrid systems featuring renewable energy sources and then to apply this methodology in case studies featuring low carbon energy systems at different scales.

Specific objectives are:

- Identify design modelling requirements at different stages of a hybrid energy system design process.
- Define a methodology for the application of detailed modelling tools to a low carbon hybrid energy system design.
- Create tools that will improve the presentation an assessment of detailed simulation outputs.
- Apply the developed methodology and tools into three different case studies and highlight how detailed modelling contributed towards their improvement.

It is hoped that this project will assist in the on-going efforts around the world to properly integrate simulation into the design process and improve the quality of energy systems designs.

# 2. Hybrid systems review

The previous chapter described the drivers behind the growth in demand for hybrid systems in the UK, the poor performance of many existing systems and the shortcomings in the tools being used in the design of such systems.

Combining different renewable technologies, or even traditional energy sources within a single "hybrid" energy systems can have many benefits over mono-source systems such as improving the reliability and reducing the CO2 footprint (Deshmukh, 2008, Erdinc, O., 2011) . This chapter will overview which elements in technologies utilised for heating may be improved through hybridisation and give examples of how they may be coupled together, highlighting the design challenges and possible consequences from inappropriate implementation. All the selected technologies feature in the current British Micro-generations Certificate Scheme (Microgeneration Installation Standard: MCS 001,2011) .

## *2.1 Heat pumps – Air and ground source*

Heat pumps can be a valuable addition to an energy system due their capacity to turn low-grade energy into utilisable heat, their independence from fuel delivery or storage, their capacity to supply both heating and cooling demands and the fact that most of the heat energy they supply is renewable. Heat pumps effectiveness in energy system decarbonisation has been the focus of a number of studies (Miara, M., 2011, Energy Savings Trust, 2010, Delta Energy & Environment, 2011). In the UK the average system seasonal coefficient of performance found was around 1.9 for air source and 2.5 for ground, significantly lower than expected. The main responsibility over such poor results seems to be due to designers and installers, unable or unaware of how to best control and size the system (Energy Savings Trust, 2010).

The complexity in the design of heat pump systems is related with the fact that they are sensitive to changes in evaporator and condenser conditions. For example, the power output of most air source heat pumps drops considerably once the external air temperature falls below zero (Dimplex, 2012, Heat King, 2012, Kingspan, 2012). Added to that, the temperature at which they supply heat is also affected. Traditionally, to overcome such challenges, a second heat supply is included. Failing to precisely predict how the environment will affect the balance between the amount of energy supplied by the heat pump and the back-up unit may result in either an undersized system, where the back-up unit will have a higher participation than expected, or an oversized system where capital cost and system reliability may be affected (Lira et. al, 2011).

Ground source heat pumps efficiency and capacity tend to be more constant throughout the year due a more stable heat source. The down side tends to be higher design complexity and installation cost. The first is caused by the fact that the energy source (ground) is affected by the load and therefore must be carefully studied. Undersized boreholes may significantly affect the heat pump efficiency and heat capacity (The Energy Saving Trust, 2010). Boreholes and trenches can be expensive and available ground space can be a limiting factor. Hybridisation may raise the reliability of a ground source system by, for example, dumping excess heat from a second energy unit into the ground (Cui et. al, 2008 and R. Yumrutas et Al 2001). This will improve the recovery time of the ground and as a result add reliability to the system and potentially reduce the required ground area.

As is evident from the above, heat pump systems are quite sensitive to their environment, with efficiency depending from the conditions at both evaporator and condenser. Any simulation involving these systems must be able to combine these parameters as the different elements of the system start to influence each other.

## *2.2 Biomass boilers*

Biomass boilers are a popular alternative to expensive oil and LPG. They harvest the energy from fuel sources such as wood pellets or wood chips and convert it into utilisable heat. The system efficiency, appropriate design and control strategy is highly dependent of the quality and type of the selected fuel. For example, higher moisture content means lower turn-down ratio, efficiency and higher particulate emissions (Lundgren, J., 2004 and Demirbas, A., 2005).

Hybrid systems utilising biomass boilers are able to achieve low $CO_2$ emission levels, which is extremely useful when a specific target must be achieved. Unlike technologies like heat pumps or solar water heating panels, biomass boilers are not sensitive to the environment, working, in theory, quite well as an alternative to add reliability to a hybrid design during adverse weather conditions.

Adding a second heat supply to a system where biomass boiler is present may reduce the amount of fuel that needs to be stored, delivered and handled. It can be particularly relevant in areas where access can be restricted during periods of the year or storage space is limited. Additionally, depending of the quality of fuel utilised, the boilers will have limited turn down ratio (ratio between rated power and the minimum output it can modulate into) (Kirk, C., 2011). In order to reduce the energy wasted on the thermal lining during the start-up and switch off period, cycling should be avoided and a second energy source may be used to either supply the peak demand or the all of the demand during low energy requirement periods (such as summer).

## *2.3 Solar water heating*

Although seen as a simple method to harvest energy from solar radiation, solar water heating systems are sensitive to a series of variables such as ambient temperature, solar radiation magnitude and incidence angle, storage tank capacity and temperature, control strategy and user behaviour ( Laughton, 2007). The chosen design tool and methodology must be able to tackle these variables and observe how they correlate with the other parts of the energy system. Simpler design tools may give indicative values of what may be achieved through hybridisation but only detailed analysis can indicate how the system must be configured and controlled. The importance of such analysis can be observed in the results of a recent study (Hill et. al, 2009) where, after surveying a series of similar systems (same size, location, type and direction), no correlation between installed capacity and heat production could be observed. This result was attributed to inappropriate control strategies and system design, which didn’t consider the particulars of each load (such as number of residents and user behaviour).

If designed correctly, solar water heating panels may be utilised to reduce the total $CO_2$ emission of a given demand whilst improving the share of renewable energy supplied. Additionally, by combining this kind of system with other energy units, such as a ground source heat pump borehole field (Cui et. al, 2008 and R. Yumrutas et Al 2001) or an absorption chillers (Helm et. al, 2008 and Ali et. Al, 2008), it may be possible to give an output to the energy surplus resultant from high periods of radiation during periods of lower heat demand, maximising the solar energy participation over the load.

## *2.4 Combined heat and power – internal combustion engines*

The inclusion of micro CHP engines in the feed in tariff program (OFGEM, 2012) made the utilisation of this technology in the residential market more attractive to the end user. Care must be taken when predicting fuel savings and optimising control strategy since both values will rely in the assumed share between electricity utilised on site and exported (Gräßle, 2010, Eté, 2009). These parameters are directly related with electricity consumption, which, unlike heat, can vary extremely at very short period of times.

Although low $CO_2$ emission values can be achieved with a CHP engine by displacing grid electricity with high carbon content, natural gas driven CHP engines don’t count as renewable energy supply. This may be a problem if a specific $CO_2$ target must be met. Adding a renewable energy technology to the system may solve this problem but will require all the attention to detail already mentioned in the previous sections. Additionally, if combined with a technology that requires electricity to run, there may be an opportunity to boost independence from the grid and, as a consequence, considerably reduce the carbon content of the energy system. This may be the case of, for example, a system utilising a CHP engine in conjunction to a heat pump. Also, by sizing a CHP engine to deal only with the base demand, the period at which it will be running at rated capacity is maximised, without the undesired production of excess heat.

The fact that CHP engines do not necessarily rely on fuel delivery and storage can be seen as an opportunity to reduce the required storage and delivery frequency for an energy system such as an oil or coal system. It may also add reliability to the system at areas where supply may become a problem during extreme weather conditions.

## *2.5 Coupling Technologies – Energy storage*

A critical element in most hybrid systems is energy storage. Storage not only allows variable demand and supply to be accommodated but also acts as the coupling mechanism. The following section highlights common storage and coupling strategies used in hybrid systems.

### *2.5.1 Connection through heat sinks or sources*

Heat sinks may be utilised to connect a technology with significant energy surplus to a load that can extract this heat at a later moment. Considerable energy surplus may be seen, for example , on an array of solar water heating panels designed to supply a high share of the energy demand during low radiation periods (such as winter). During sunnier periods these panels are likely to be oversized when compared against the demand. To collect most of this energy through traditional methods, unfeasibly large tank sizes would be required (Hobbi, 2009). Diverting the energy surplus to a heat sink, which is also a heat source to a ground source heat pump, is a possible solution. The energy diverted into the ground may improve its recovery period and reduce the required field area, which direct impacts into the system capital cost. The amount of energy surplus may also have a positive effect in the ground temperature, improving the overall system efficiency. (R. Yumrutas et Al 2001 and Cui et. al, 2008).

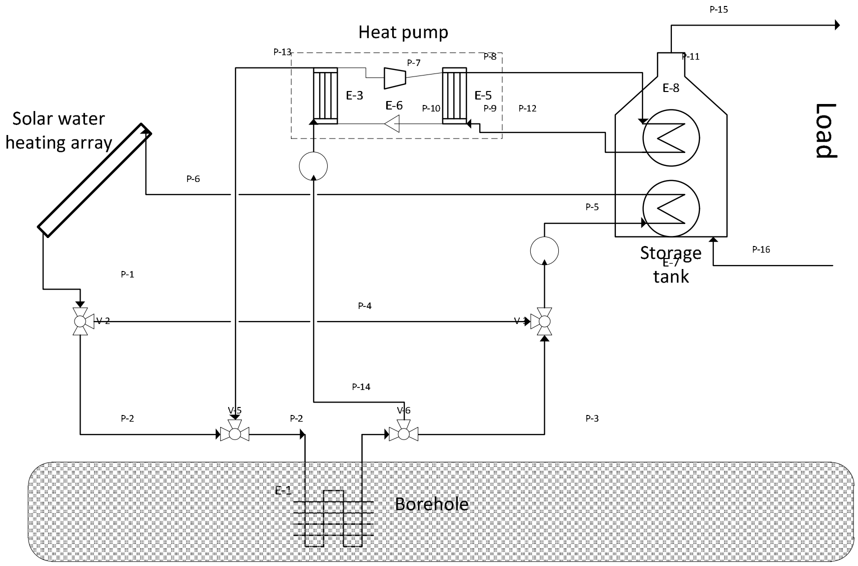


*Figure 1 - Hybrid heating system with heat sink- configuration 1 (R. Yumrutas et Al 2001)*

Alternative configurations may discard the heat sink as a means to couple the different technologies such as the one illustrated below.

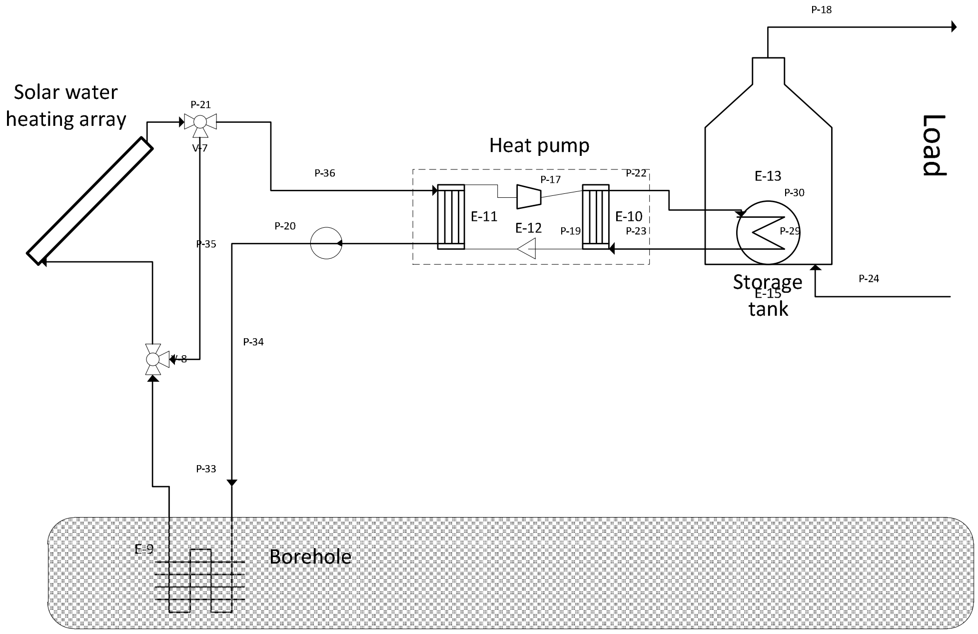


*Figure 2 - Hybrid heating system with heat sink-configuration 2 (Hepbaslib et Al ,2005)*

This design, which aims to improve the heat pump's efficiency by directly, raising the temperature of the fluid through its evaporator (Hepbaslib et al., 2005 and Guoying Xu et al. ,2009), will strongly rely on an appropriate design of the heat store since mismatch between periods of high solar radiation and demand may result into an ineffective hybrid system. The importance of storage tanks in hybrids systems is discussed in the next section.

### ***2.5.2 Parallel connection through heat store***

Combining two or more technologies through a common tank, as represented in Figure 3, is a popular hybrid system design found in different range of applications such as low carbon district heating networks (Green Watt Way, 2012) or even simple residential heat pump systems. In many cases, this configuration combines a primary energy source, usually expensive but efficient, to a backup one, cheap to install but expensive to run.

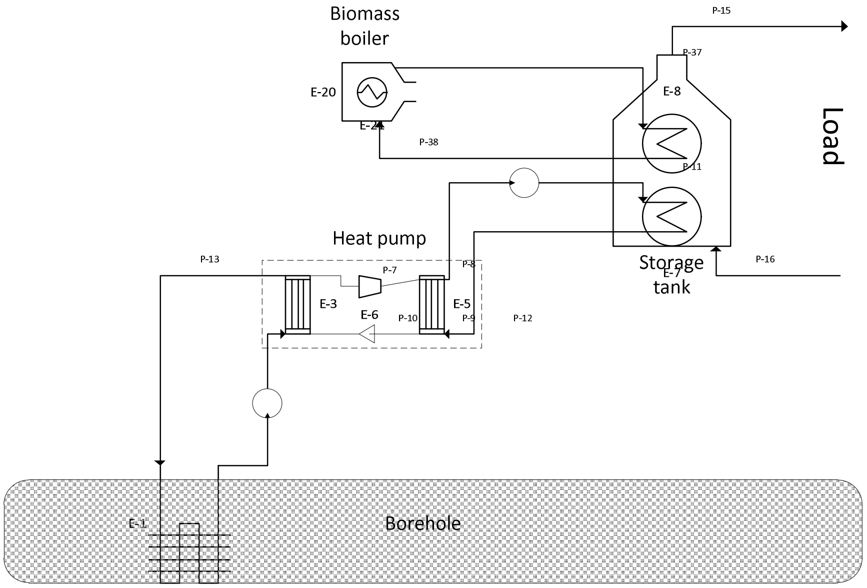


*Figure 3- Hybrid parallel heating system*

The challenge in designing this system lies in the fact that different technologies operate efficiently at different temperatures. For example, biomass boilers expect a return temperature around 60$^{o}$C whilst heat pumps efficiency drops significantly as the flow temperature rises. In many cases the unit will cut-out if return water temperatures achieve values above 55°C. As made evident in one of the case studies presented later in this dissertation, designer must be able to understand and make use of the tank stratification for the system to operate effectively.

The importance of proper understanding the interaction between storage and energy supply technologies can also be seen even in simpler and more traditional configurations. The Energy Saving Trust (Energy Saving Trust, 2010) highlighted in one of its field trials how electric immersion heaters, intended to work as back-up to heat pump systems, were one of the main causes of system inefficiency. In some of the studied cases, due to a poor control strategy, these units were constantly maintaining the system at temperatures above what normal heat pumps could achieve. The result was the immersion heaters acting as the base demand supplier, significantly reducing overall system efficiency. This example is an intuitive combination of technologies that most certainly did not go through a detailed simulation as part of the design process. Unlike fossil fuel based energy sources, renewable technologies are very sensitive to temperature and flow rate variations, which if overlooked may result in faulty (or undesirable) operation.

Understanding how different units operating together affect the tank's internal temperature requires a tool able to analyse its behaviour in detail. Simply counting the amount of energy transferred from A to B, as done by many steady state analysis tool, isn't enough; these tend to ignore the fact that, for example, 5kWh of thermal energy creates different temperature profiles inside the storage tank if done through heat exchangers in its top or bottom, which will have different effects in a second energy unit connected to it. Selecting the right design methodology and tools is therefore essential.

The next chapter presents evidence of poor performance in real life hybrid system installations throughout the UK and introduces a methodology that combines simple modelling tools and detailed simulation in the design of such systems. This methodology is then tested in three case studies presented at chapter 5.

# 3. Detailed modelling for hybrid system design

The previous chapter observed how different technologies may be combined together to form a hybrid system. The benefits of such systems do come at a cost: design complexity. Due the inclusion of renewables, these systems tend to be more sensitive to environment conditions than their fossil fuel driven counter-parts. A design tends to involve a larger amount of inter-linked parameters, adding complexity to the design process. A major challenge lays in the fact that many design and feasibility study tools, such as Energy Pro (EMD international, 2012), HOMER (Lambert, 2006 and NREL, 2012) and RETScreen (Natural Resources Canada, 2012 and Tristán,2011), are ill-equipped to deal with the now higher system sensitivity to temperature conditions. Factors such as tank temperature and stratification are not considered in these tools and may result into erroneous design and poor system performance. Evidence of such is given in the next two sections.

Detailed dynamic modelling of the energy sources and thermal buffering system can give a more realistic picture of system performance as it can cope with the volatility of renewable energy supplies and the mixing of different thermal sources with a thermal buffer. A design methodology which aims to minimise detailed modelling time requirement and yet maintain it as part of the process is presented later in this chapter.

## *3.1 The need for detailed simulation*

Different studies have analysed the cause of the poor performance observed in traditional hybrid energy systems in the UK. The next section describes two of these studies and highlights how detailed modelling could have avoided some of the problems identified.

### *3.1.1 Hybrid solar thermal system*

With 459 MW installed capacity, solar thermal systems are one of the most common hybrid energy systems in the UK (ESTIF,2011). In the residential market, a recent study indicated that these systems are currently under performing, with an astonishing 60% of surveyed properties achieving no more than 6% of potential savings (Hill et al. 2011). By investigating the causes of such discrepancy, the authors observed that system control had a significant impact in the observed results. This phenomenon was also highlighted by the latest Energy Saving Trust trial report on the topic (Energy Savings Trust, 2011). In almost every single property, the auxiliary boiler (most cases gas) was controlled just like it would be if a solar thermal system wasn't present.

Customers and, in many cases, installers were not made aware of the impact that the control of the energy system would have in its performance, which is also ignored by the current micro-generation certification scheme. Following its standards, the system design and potential savings are defined only by panel orientation, tank size, number of occupants and monthly weather data. The importance of detailed simulation became clear when the same systems were simulated using a detailed simulation tool, able to include user/control behaviour in the analysis. The results are shown below:

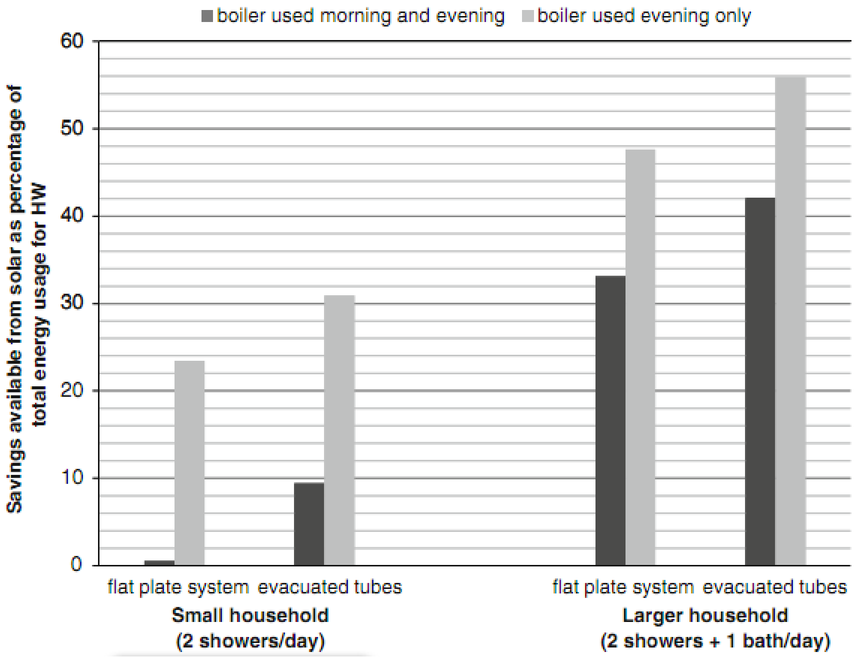


*Figure 4 - hot water system efficiency (Hill,2011)*

What the simple energy analysis ignores is how the user behaviour (or user defined control) affects the temperature profile in the hot water tank. Unnecessary intervention of a secondary energy source will keep the tank temperature higher than necessary, affecting negatively the efficiency of the panel, which is reduced as warmer fluid flows through its pipes, and also the capacity to store solar energy since safety devices will limit the maximum temperature the tank is allowed to reach. In systems so sensitive to environmental changes, the customer should be made aware about which assumptions (or expected behaviour) were taken into account when a given benefit was calculated. Alternatively, manufacturers or designer could use detailed simulation to design a system able to minimise the effects that changes in the environment or even user behaviour have in its performance. By achieving it, the energy savings assessment may be simplified. This possibility will be explored at chapter 5, as detailed energy simulation will be utilised to improve robustness of a system that combines two very sensitive technologies: Heat pumps and solar water heating panels.

### 3.1.2 Hybrid air source heat pump system

Typical residential heat pump installations usually depend of a secondary energy source to deal with extreme weather conditions. A challenge that the designer may face is to decide where the bivalent point (point where the load demand is higher than the heat pump capacity) should be. This point affects the system in two ways: the first by defining running costs, the second by defining system performance during milder weather conditions (Lira, 2011).

In a traditional hybrid heat pump system, a high bivalent point means that a considerable share of the total energy supplied comes from an expensive energy source such as an electric immersion heater or oil boiler. Moving this point to very low temperatures reduces the amount of times that the secondary source operates but also means that the heat pump may become considerably oversized during milder weather conditions, which affects system efficiency and reliability due over-cycling (unit switching on and off in a short period of time). The figure below compares both cases against a given demand, highlighting the point at which a problem may be observed.

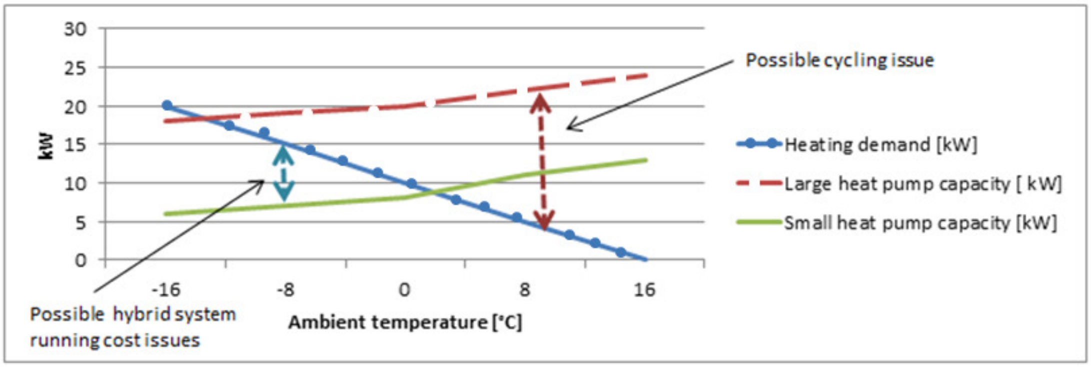


*Figure 5 - heat pump system output and demand*

In recent trials run by the Energy Saving Trust, 83 heat pump installations were monitored around the UK (The Energy Savings Trust, 2010). The results gave serious cause for concern, indicating underperforming systems as result of poor design and installation. The reasons for the poor performance were stated as over-simplified sizing methodologies and low attention given to the operation and control of the secondary energy (back up) source (most cases electric heaters).

In an effort to popularize heat pump installations and avoid many of the problems caused by bad design and control, a steering group working for the micro-generation scheme defined a simple design methodology. By this new standard the bivalent point (point at which a second energy source is needed) should be the temperature above which the outside temperature remains for

99% of the time in an average year. Effectively what it says is that, based on previous weather data, the heat pump should be able to supply all the building demand. As mentioned before, such a solution, although helping by reducing dependence in the secondary energy unit, may considerably raise installation capital cost and reduce system life span due excessive cycling (Lira,2011).

Instead of defining the bivalent point through a static solution, as above, dynamic simulation can play an important role over how a system is sized. By, for example, adapting the system control to external temperatures and/or user behaviour, the designer may be able to balance the energy share between different units in the system. This will be further investigated at chapter 5.

## *3.2 Proposed methodology and tools overview*

The examples above represent cases where the utilised design methodology ignored the need to include detailed modelling in the design of hybrid energy systems with high renewable energy penetration. Considering time as a resource of high value, designers may opt for simpler sizing methodologies that sacrifice flexibility and accuracy in exchange of reduced modelling time. This option was observed in half of the hybrid system design methodologies identified by Rubio (Rubio,2010) who analysed an extensive amount of hybrid system designs and classified the methodologies into four main groups:

- Probabilistic: Usually utilises one or two performance indicators as reference to judge a system. Simple energy supply and load models are combined to predict the expected system performance.

- Analytical: hybrid energy system performance is assessed for a set of possible system architecture and/or a particular size of components. Best configuration of a hybrid energy system is determined due to a multiple performance index of the systems analyzed. It needs long time series, usually 1 year, of weather variables for the simulations.

- Iterative methods: Is commonly utilised with detailed energy system modelling and the design improvement process is done by means of a recursive process which stops when the best configuration is reached according to design specifications.

- Hybrid methods: Combines different methodologies together. Usually applied in situations where a large amount of interrelated objectives are targeted.

This section introduces a new hybrid system design methodology, later applied to three case studies at chapter 5, where the design process combines three of the four methodologies identified by Rubio, divided into two stages: A feasibility study one, where simple energy system analysis and design tools are utilised to filter possible design solutions (probabilistic or analytical method), and the second, more time demanding, utilising detailed modelling to improve and analyse the best candidates (Iterative method). The reasoning behind this methodology is to just invest the time required by a detailed energy system modelling after a simpler and faster analysis indicated the feasibility of a given technology combination. In the next sections, appropriate tools and expected outputs at each stage are introduced.

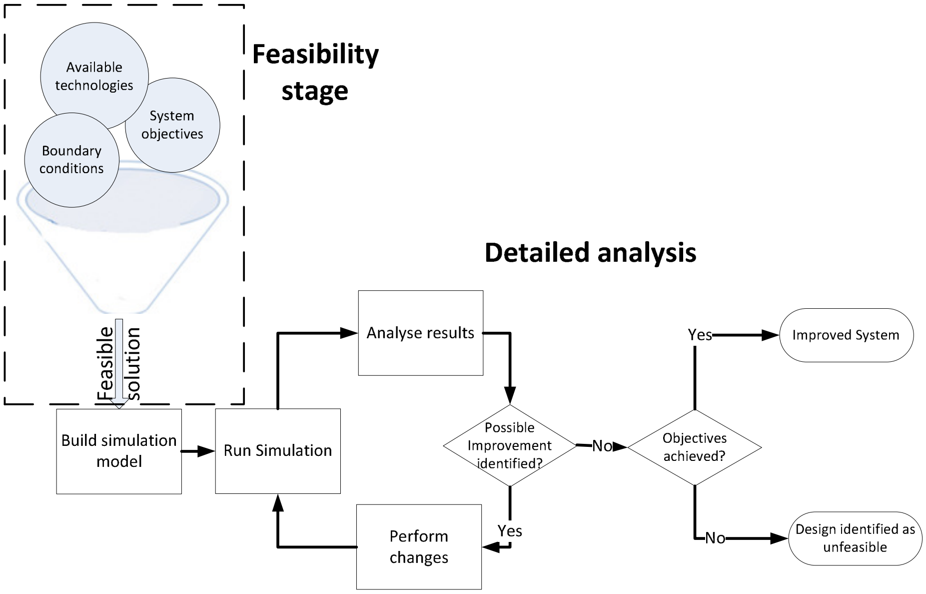


*Figure 6 - Stages in the proposed methodology*

### 3.2.1 The feasibility study stage

This is the earliest stage of a project and the main objective at this point is to, by utilising one or two performance indicators (such as running cost or $CO_2$ emission level), answer the simple question: Is the combination of two technologies a feasible solution to a given project?

At this stage data tends to be limited, which rules out detailed simulation as even the most powerful software will be unable to produce reliable information if inappropriate input data is utilised. Instead of bespoke figures, manufacturers' information, low resolution weather and energy demand data is desirable. Combining it with pre-set energy system templates gives the energy system designer indication of what may be achieved. The appropriate tool should give an overview of how each technology could contribute towards a defined goal but no detailed design and optimisation can take place.

At this stage it is recommended the utilisation of simple energy design tools such as HOMER (Lambert, 2006 and NREL, 2012) , Energy Pro (EMD international, 2012) or RETScreen (Natural Resources Canada, 2012 and Tristán,2011) where outputs are presented in simple tables and graphs, including data such as running cost, simple paybacks, internal rate of return and renewable share. In general, flexibility over what can be simulated is quite limited and the user must accept many of the embedded assumptions.

Due its limited customisation, this kind of tool won't be able to represent specific cases or allow the designer to perform significant changes into the energy system structure. In most cases the different elements of the system are seen as "black boxes" from which energy flows are observed. Temperature fluctuations and internal configuration changes are not taken into account and therefore also isn't the impact that they may have into the final system performance. As these two factors have great impact over the performance of a hybrid system with high renewable penetration, simple energy analysis tools can misrepresent the real behaviour of such structures. These tools represent a compromise between flexibility/accuracy and simplicity.

Regardless the limitations presented above, these tools can be of great importance in the design of a hybrid energy system if utilised to filter all the possible solutions to a given challenge and present to the designer the most feasible solutions, which shall be taken to the next stage in the design process where detailed modelling is utilised to define and improve the system design.

### 3.2.2 Detailed design / system improvement

At this stage, detailed modelling tools (such as TRNSYS (SEL,2012) or ESP-r (ESRU,2012) ) are utilised to improve and verify the design of the systems identified as feasible in the previous one. To improve the design of the energy systems presented at chapter 5, simple iterative process was developed as represented next. The loop between changes in the system and simulation runs is interrupted once the design objectives are achieved.

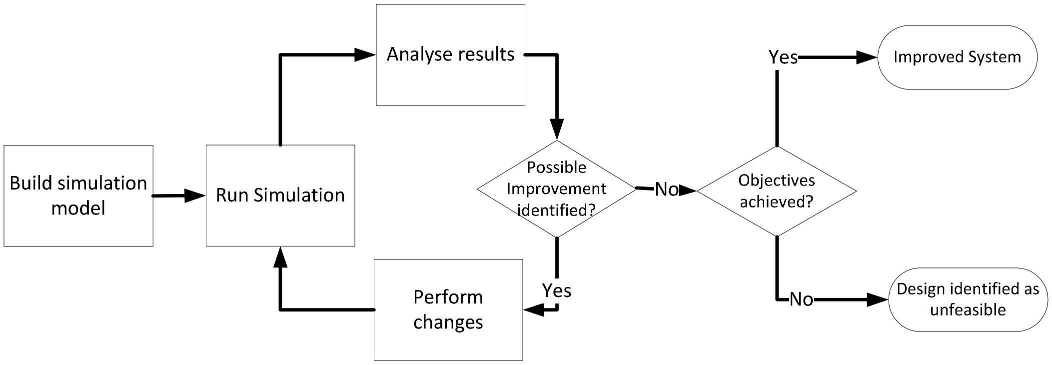


*Figure 7 - System improvement process*

An important element in this process, the duration of the simulation, was defined by the technologies utilised and the system objectives. Where storage tanks were not present and therefore the sizing methodology becomes a key factor, it may be acceptable to focus only in the coldest week of the year (MIS 3005,2012). Such methodology may, on the other hand, overlook issues this unit size may have during milder weather conditions. Due uncertainty regarding how the systems may perform during these weather conditions all the simulations here presented will run through the entire year and output, at every time step, information regarding key elements of the systems such as energy consumption, flow temperatures, tank temperatures, power output, weather condition and load demand.

The chosen resolution, monitoring points and simulation length can be used to identify punctual problems in the system but its ultimate objective is to define the overall system performance.

Due the large amount of outputs generated and to make the high level analysis faster and more reliable, an output interface had to be created. This interface is able to load the raw output from the simulation and represent it in a friendly format, focusing into parameters such as $CO_2$ emission levels, fuel consumption, renewable load share, running costs, payback period and internal rate of return (when compared against an alternative). Details about this interface and outputs are given at chapter 4.

As already mentioned, the long learning curve and required modelling time requirement is possibly part of the reason why softwares like TRNSYS and ESP-r are considerably more popular in the academic environment than in the commercial one. A possible solution may be the one presented by Ete (2009) where the detailed simulation once finalised is manipulated and turned into user friendly templates, based on the best solutions. The software is then utilized as a simple design tool where the interactions between different components are pre-defined.

## 3.3 Chapter conclusion

This chapter highlighted the importance of detailed modelling as part of the design process of a hybrid system. Two examples were given where common residential hybrid energy systems installed in the UK presented evidence of underperformance due poor design and installation. Detailed modelling will be utilised at chapter 5 to solve some of the problems presented in these examples and analyse its potential in the design of a hybrid energy system. It was, therefore, necessary to create a methodology for such.

The methodology presented in the second section of this chapter divides the design process into two main stages: Feasibility study and detailed modelling. The first stage works as a filter of feasible hybrid energy systems to be taken to the next stage. At this first moment, simple modelling tools such as RET Screen and H.O.M.E.R are recommended given their simple user interface and use.

At the next stage, a detailed model of the selected hybrid energy system is built and taken through an iterative design improvement routine, until the final design is found. For the case studies presented at chapter 5, the simulation tool TRNSYS was selected. Due the amount of outputs generated after each iteration, a performance assessment tool had to be created. Both TRNSYS and the new tool are detailed in the next chapter.

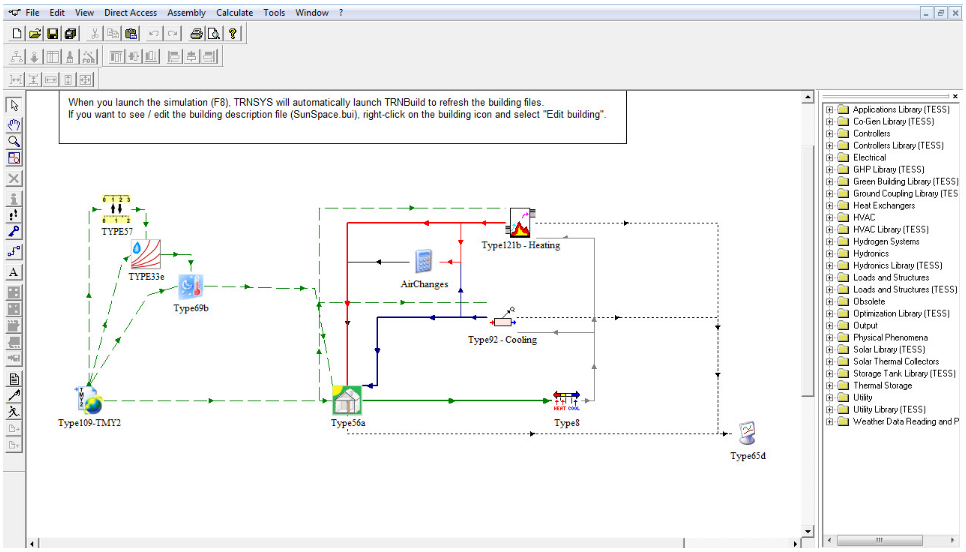
# 4. TRNSYS and the performance assessment interface

As stated in the previous chapter, the developed methodology will be applied to three case studies in order to analyse the benefits of detailed modelling in the design of hybrid energy systems and utilises TRNSYS as the modelling tool. TRNSYS is a transient system simulation software that utilises a modular approach to analyse systems whose behaviour is dependent of time. This approach simplifies the creation and analysis of hybrid energy systems yet maintaining the required level of flexibility and detail.

One of the challenges when utilising TRNSYS in the design of new hybrid systems is the amount of data generated in a format that doesn’t offer a concise way to analyse it. To simplify the data analysis process, a performance assessment interface was created. It is described in the second part of this chapter.

## 4.1 TRNSYS

TRNSYS is a transient system simulation software that utilises a modular approach to analyse systems whose behaviour is dependent of time. The modular approach refers to the fact that each element in the energy system is formed by an independent component (referred as “type”) whose inputs and outputs can be connected to a second, third or even fourth element in a manner analogous to piping, ducting and wiring in physical systems. The programmer supplies values for all the parameters describing the component to be used. These components can be found either in a provided library or created by the users. Once all the components and connections are defined, the program does the necessary simultaneous solutions of the algebraic and differential equations, which represent the components, and organizes the inputs and outputs (Duffie, 2006).

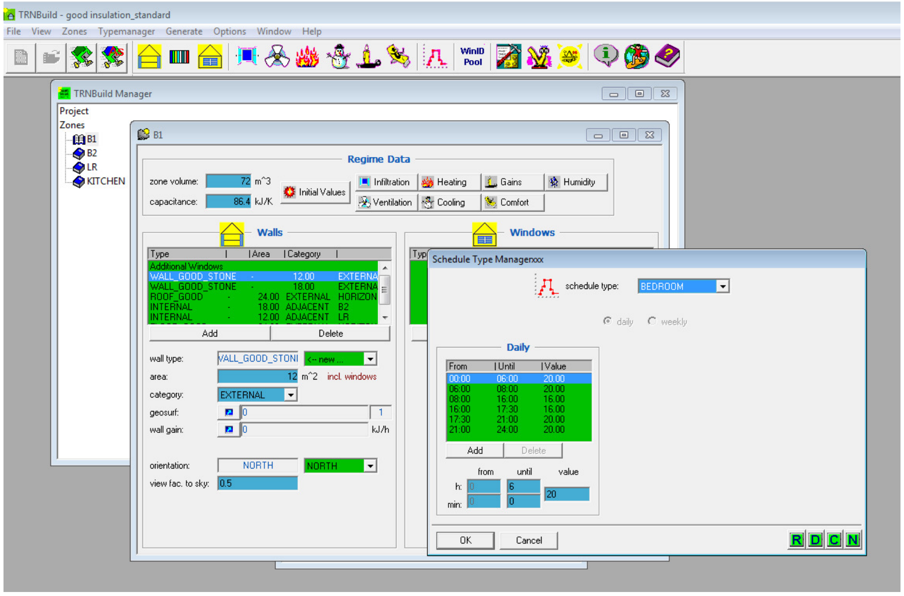


When you launch the simulation (F8), TRNSYS will automatically launch TRNBuild to refresh the building files.
If you want to see / edit the building description file (SunSpace.bui), right-click on the building icon and select "Edit building".

*Figure 8 - TRNSYS simulation studio interface*

TRNSYS consists of a suite of programs which includes the TRNSYS simulation studio and the building input data visual interface (TRNBuild), both utilised during this dissertation.

The simulation studio is the main visual interface utilized to create energy system models, which can be done by drag-and-dropping components to the workspace, connecting them together and setting the simulation parameters. In cases where multi-zone buildings are simulated, the TRNSBuild program is utilized to input the required data. It allows the designer to specify all the building structure details, as well as everything that is needed to simulate the thermal behavior of the building, such as windows optical properties, heating and cooling schedules, etc. Once all the information is inserted, TRNBuild creates a building description file, which can be imported by components in the simulation studio and integrated to other elements in the energy system such as heat supply units and environmental data.



zone volume: 72 m^3

capacitance: 86.4 kJ/K

| Type | | Area | Category | |
|---|---|---|---|---|
| Additional Windows | | | | |
| WALL_GOOD_STONE | - | 12.00 | | EXTERNA |
| WALL_GOOD_STONE | - | 18.00 | | EXTERNA |
| ROOF_GOOD | - | 24.00 | EXTERNAL | HORIZON |
| INTERNAL | - | 18.00 | ADJACENT | B2 |
| INTERNAL | - | 12.00 | ADJACENT | LR |

wall type: VALL_GOOD_STONI <-- new ...

area: 12 m^2 incl. windows

category: EXTERNAL

geosurf: 0 1

wall gain: 0 kJ/h

orientation: NORTH NORTH

view fac. to sky: 0.5

schedule type: BEDROOM

● daily ○ weekly

| From | Until | Value |
|---|---|---|
| 00:00 | 06:00 | 20.00 |
| 06:00 | 08:00 | 20.00 |
| 08:00 | 16:00 | 16.00 |
| 16:00 | 17:30 | 16.00 |
| 17:30 | 21:00 | 20.00 |
| 21:00 | 24:00 | 20.00 |

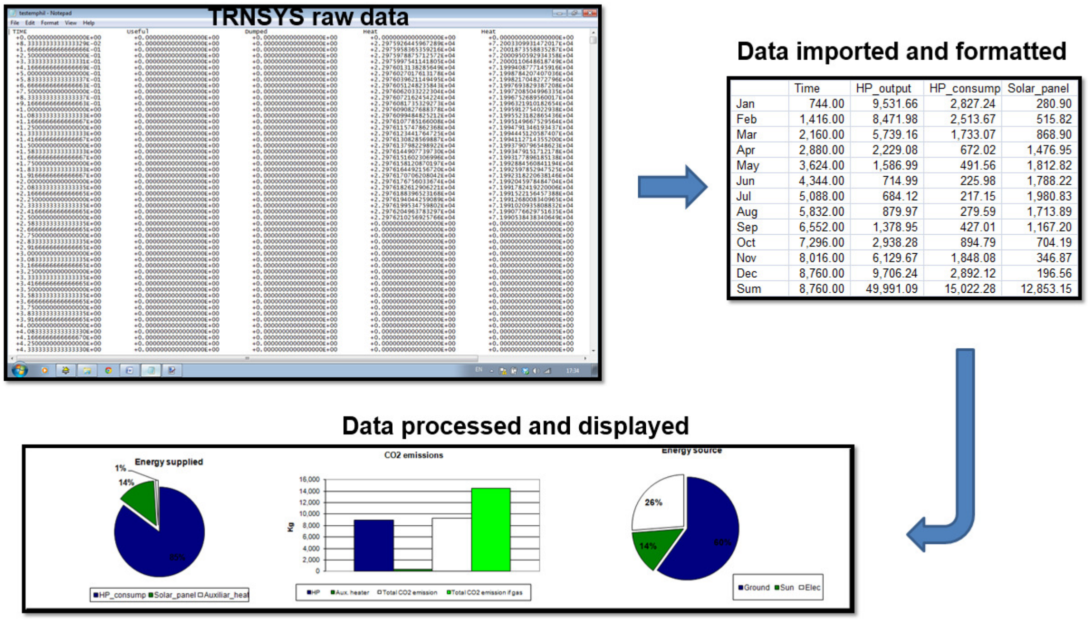
| | from | until | value |
|---|---|---|---|
| h: | 0 | 6 | 20 |
| min: | 0 | 0 | |

Figure 9 - TRNSYS simulation studio interface

A challenge when improving a complex energy system through TRNSYS is the fact that the amount of outputs generated may be overwhelming, and are presented in a time series format that does not represent a concise way to analyse the data. This makes the process of comparing performance after a series of interactions quite time consuming and with propensity to mistakes. To overcome such challenge an output analysis interface had to be created and is described next.

## 4.2 Performance assessment interface for TRNSYS

After each TRNSYS simulation, a group of outputs is generated and presented to the energy system designer as a group of time series. To analyse the data generated during the simulation of the case studies presented in the next chapter, it was necessary to translate these time series into a format that could be easily understood by the designer. The created performance assessment interface is able to import the data series generated after each TRNSYS simulation and translate it into a series of performance assessment data such as renewable energy penetration, running cost, $CO_2$ emission level etc. The interface also helps to identify energy balance issues during the simulation by comparing the amount of energy flowing through each component.



| | Time | HP_output | HP_consump | Solar_panel |
|---|---|---|---|---|
| Jan | 744.00 | 9,531.66 | 2,827.24 | 280.90 |
| Feb | 1,416.00 | 8,471.98 | 2,513.67 | 515.82 |
| Mar | 2,160.00 | 5,739.16 | 1,733.07 | 868.90 |
| Apr | 2,880.00 | 2,229.08 | 672.02 | 1,476.95 |
| May | 3,624.00 | 1,586.99 | 491.56 | 1,812.82 |
| Jun | 4,344.00 | 714.99 | 225.98 | 1,788.22 |
| Jul | 5,088.00 | 684.12 | 217.15 | 1,980.83 |
| Aug | 5,832.00 | 879.97 | 279.59 | 1,713.89 |
| Sep | 6,552.00 | 1,378.95 | 427.01 | 1,167.20 |
| Oct | 7,296.00 | 2,938.28 | 894.79 | 704.19 |
| Nov | 8,016.00 | 6,129.67 | 1,848.08 | 346.87 |
| Dec | 8,760.00 | 9,706.24 | 2,892.12 | 196.56 |
| Sum | 8,760.00 | 49,991.09 | 15,022.28 | 12,853.15 |

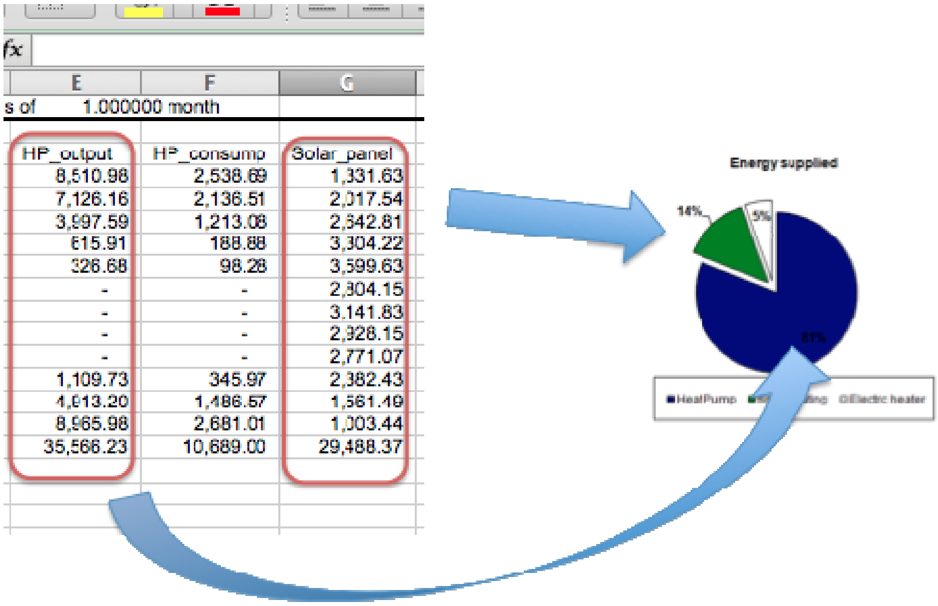
*Figure 10 - Data processing*

The figure above is an example of how the data, after processed, is displayed to the designer. The processed data was divided into two main groups, the first offering information regarding energy performance and emission levels and the second focused into financial parameters.

### 4.2.1 System performance interface

A full screen shot of this interface is presented at Annex 1. The following sections details some of the tool outputs that are useful during the design a hybrid system.

### *Overall energy share*



s of 1.000000 month

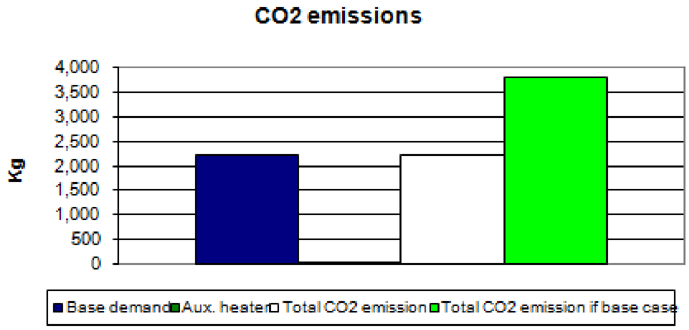
| HP_output | HP_consump | Solar_panel |
|---|---|---|
| 8,510.98 | 2,538.69 | 1,331.63 |
| 7,126.16 | 2,136.51 | 2,017.54 |
| 3,997.59 | 1,213.08 | 2,642.81 |
| 615.91 | 188.88 | 3,304.22 |
| 326.68 | 98.28 | 3,599.63 |
| - | - | 2,804.15 |
| - | - | 3,141.83 |
| - | - | 2,928.15 |
| - | - | 2,771.07 |
| 1,109.73 | 345.97 | 2,382.43 |
| 4,913.20 | 1,486.57 | 1,561.49 |
| 8,965.98 | 2,681.01 | 1,003.44 |
| 35,566.23 | 10,689.00 | 29,488.37 |

*Figure 11- Imported data converted into energy unit share over the load*

This simple chart (right hand side) represents how much of the total energy demand is supplied by each of the different energy units. It is a simple representation that allows the designer to easily track how the changes in the energy system are affecting the overall system behaviour. This same information is also represented numerically, showing exactly, in kWh, how much energy each unit converted.

## *$CO_2$ emission*

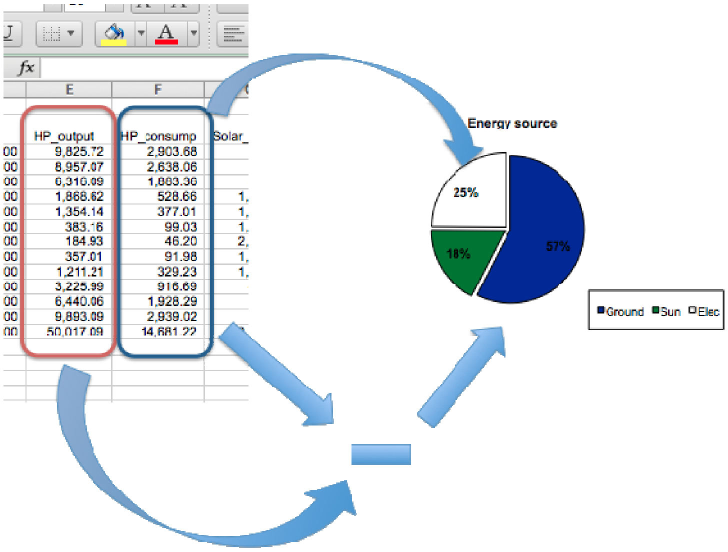
Important when trying to meet specific building regulations, the interface combines the information in the "energy consumption" columns, loaded from the simulation, with the emission factor defined by the user for that column and outputs the total $CO_2$ emitted by each energy unit. These values are displayed in a single graph and are also compared against a user defined base case.



| CO2 emission | | |
|---|---|---|
| Total CO2 emission | 2,228 | kg |
| Total CO2 emission if base case | 3,795 | kg |
| Difference | 41% | |

*Figure 12 – example of CO2 emission against base case*

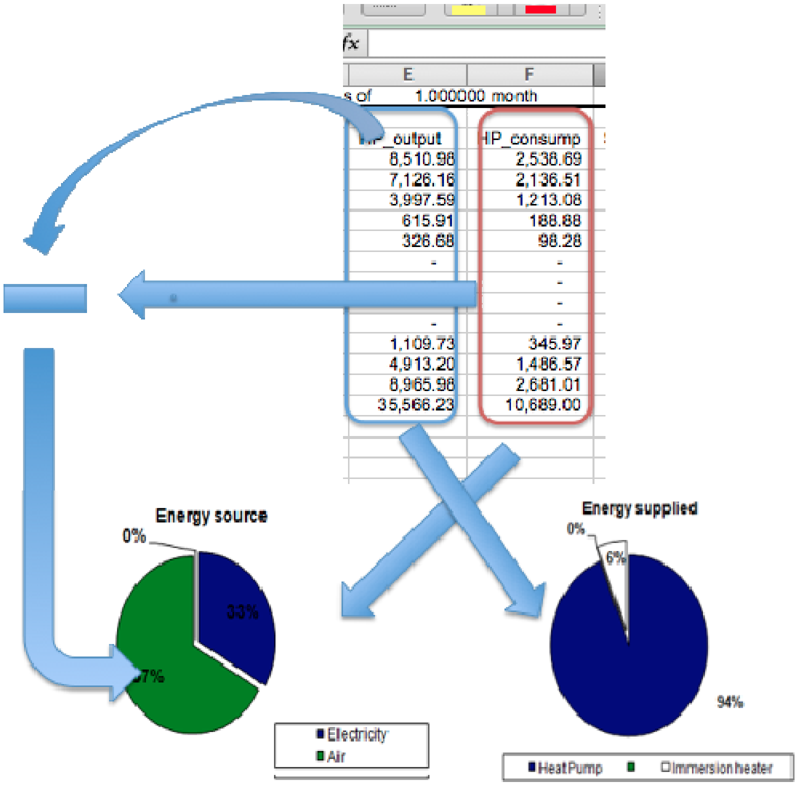
## *Energy Source*



| HP_output | HP_consump | Solar_ |
|---|---|---|
| 9,825.72 | 2,903.68 | |
| 8,957.07 | 2,638.06 | |
| 6,310.09 | 1,883.36 | |
| 1,868.62 | 528.66 | 1, |
| 1,354.14 | 377.01 | 1, |
| 383.16 | 99.03 | 1. |
| 184.93 | 46.20 | 2, |
| 357.01 | 91.98 | 1, |
| 1,211.21 | 329.23 | 1, |
| 3,225.99 | 916.69 | |
| 6,440.06 | 1,928.29 | |
| 9,893.09 | 2,939.02 | |
| 50,017.09 | 14,681.22 | |

*Figure 13- Energy source share over the load*

Although closely related with the first output described, the graph above displays the share of the different energy <u>sources</u> over the load. The calculation looks to the system as a single volume control where similar energy sources entering the boundaries are grouped together, regardless where, how and how effective it will be used. As a simple example, in a system formed exclusively by an air source heat pump plus immersion heater with a seasonal performance of 3, the "energy supplied" and "energy source" graphs would be as below:



| E | F |
|---|---|
| 1.000000 | month |
| _output | HP_consump |
| 8,510.98 | 2,538.69 |
| 7,126.16 | 2,136.51 |
| 3,997.59 | 1,213.08 |
| 615.91 | 188.88 |
| 326.68 | 98.28 |
| - | - |
|  | - |
|  | - |
| - | - |
| 1,109.73 | 345.97 |
| 4,913.20 | 1,486.57 |
| 8,965.98 | 2,681.01 |
| 35,566.23 | 10,689.00 |

*Figure 14- Energy source vs. energy unit share over the load*

This is an extremely relevant piece of information when specific building regulation targets must be met. The graph above disclaims that, although 94% of the energy supplied comes from the heat pump, only 67% is from a renewable source (heat from the air).

## *Fuel cost*

Following a similar structure utilised to calculate the total $CO_2$ emission, the designer is also able to define different fuel prices linked to each of the energy consumption columns, loaded from the simulation. Consumption and price are then processed together, outputting the total running cost of the system and also breaking it down to each of the energy units. The designer also defines a base case unit, against which the performance of the simulated system will be compared. If, for example, the base case is a gas boiler system, the designer can insert 80% in the "base case efficiency" field and "0.034 £/kWh" in the base case fuel price. The tool will work backwards, utilising the results from the simulation to define how the base case would perform.

The capacity to compare results against a base case is quite important when the financial analysis of the system is done. This feature will define factors such as investment payback time or internal rate of return as described next.

### 4.2.2 Financial analysis interface

The financial analysis screen, shown at annex 2, focus into the financial performance of the designed system. The difference from the interface presented in the previous sections is in the fact that the time series data imported is now linked to user-defined financial factors such as fuel cost (linked to the performance analysis interface), financial incentives (such as feed in tariff or renewable heat incentives, explained next), etc.

The financial characteristics for the base case scenario previously described are also defined in this interface, and works as a reference against which the financial performance of the new system may be compared.

#### Running cost savings

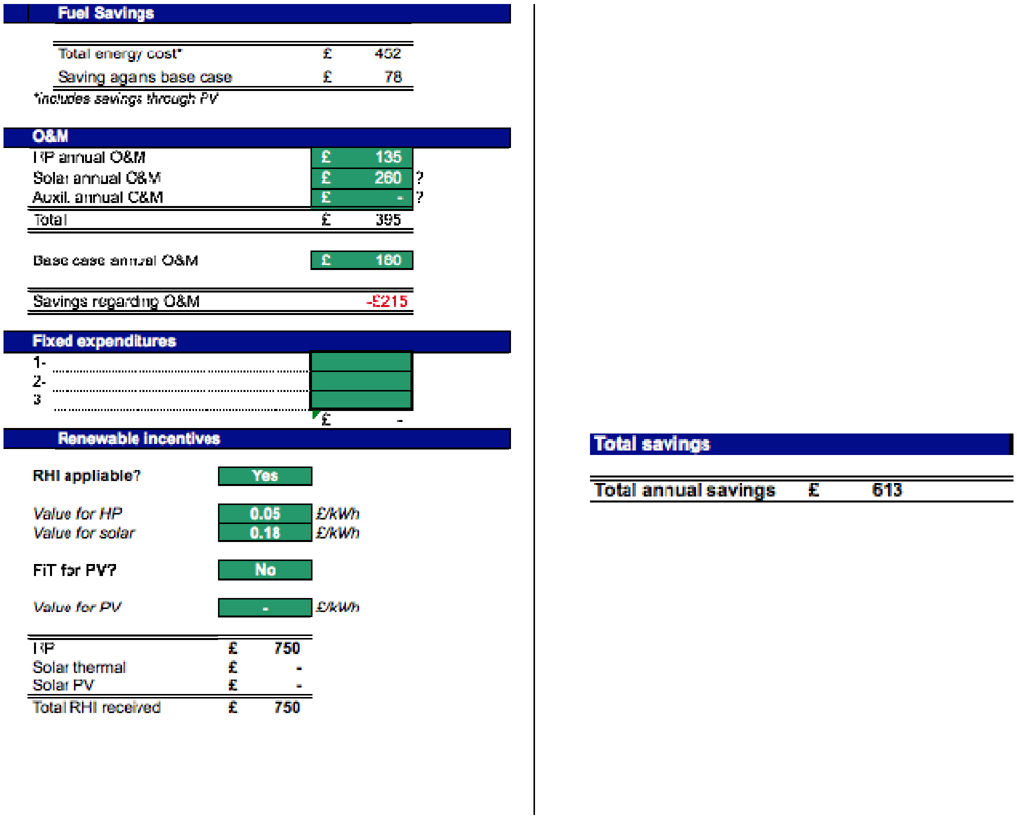
The savings from running the specified system instead of the base case one are defined by three different elements: Fuel cost difference, financial incentives and operation and maintenance cost.

The difference between the base case fuel cost and proposed system one defines the fuel cost savings.

The second element was built around a financial incentive structure where the energy user is financially rewarded for each kWh of renewable energy converted. For example, the UK Feed in Tariff pays a residential customer £0.21 per kWh of electricity generated through a photovoltaic panel installed on his/her roof. Similarly, the Renewable Heat Incentive (RHI) pays for the heat supplied by a low carbon technology. Combining the level of incentive with the total energy supplied by the relevant energy source defines the total annual renewable generation income.

The last element, defined by the user, refers to the O&M costs related with each of the involved energy supply units, including the one in the base case scenario. The difference between the proposed energy system O&M cost and the one from the base case scenario defines the system O&M savings (negative if the proposed system is more expensive to maintain).

Finally, by adding up all the three elements described above, the total Running cost savings is defined (negative if the new system is more expensive to run than the base case).



**Fuel Savings**

| | | |
|---|---|---|
| Total energy cost* | £ | 452 |
| Saving agans base case | £ | 78 |

*includes savings through PV

**O&M**

| | | | |
|---|---|---|---|
| HP annual O&M | £ | 135 | |
| Solar annual O&M | £ | 260 | ? |
| Auxil. annual C&M | £ | - | ? |
| Total | £ | 395 | |
| Base case annual O&M | £ | 180 | |
| Savings regarding O&M | | -£215 | |

**Fixed expenditures**

| | | |
|---|---|---|
| 1- | | |
| 2- | | |
| 3 | | |
| | £ | - |

**Renewable Incentives**

| | | |
|---|---|---|
| RHI appliable? | Yes | |
| *Value for HP* | 0.05 | *£/kWh* |
| *Value for solar* | 0.18 | *£/kWh* |
| FiT for PV? | No | |
| *Value for PV* | - | *£/kWh* |

| | | |
|---|---|---|
| HP | £ | 750 |
| Solar thermal | £ | - |
| Solar PV | £ | - |
| Total RHI received | £ | 750 |

**Total savings**

| | | |
|---|---|---|
| Total annual savings | £ | 613 |

*Figure 15 - Running savings*

### *Cash flow and internal rate of return*

| Simple bayback period | 8 |
|---|---|

| IRR | 12% |
|---|---|

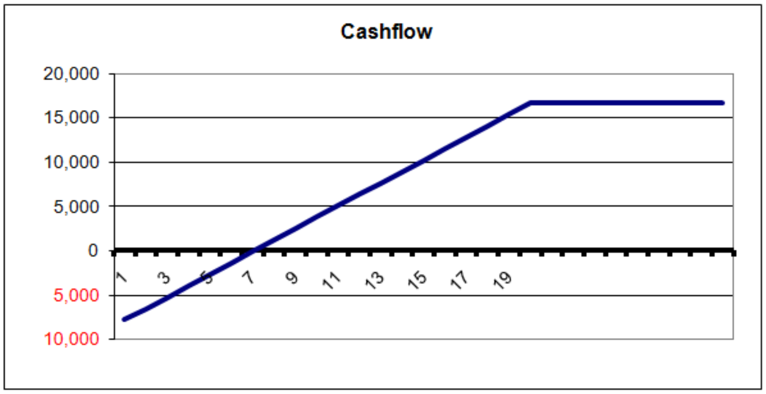


*Figure 16- Payback calculation output*

Before explaining the concept of internal rate of return it is important to understand the meaning of the **net present value** (NPV) of a given investment. The NPV defines how much a series of payments (or losses) would be worth today, assuming a given discount rate during the observed period.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \qquad [1]$$

Where t = time of the cash flow,

$R_t$= Total cash flow during period t (income positive, expenditures is negative),

i = the discount rate to be applied at each period between n and 0.

The NPV defines how much value an investment is adding to the investor.

The internal rate of return (IRR) is the discount rate that results into a net present value of zero for a series of cash flows. A net present value of zero means that the project repays the original investment plus the required rate of return. The higher the IRR the better is the investment.

Before calculating the internal rate of return it was, therefore, necessary to allow the interface user to input the capital cost related with the implementation of the proposed energy system and, if relevant, compare it against the base case one. Eventual break downs and replacement costs can also be defined at specific years.

With all information previously described it is now possible to combine the capital costs and running savings to create a cash flow analysis through the investment period. For each period, the cash flow is defined as below:

$$y = -Ci - Rc + Rs \qquad [2]$$

Where,

Y = cash flow for a given period.

Ci = Invested capital. Refers to the cost to install the proposed energy system including design, equipment and commissioning cost.

Rc= Replacement cost. If the replacement of parts of the energy systems are foreseen during the period analysed, this cost may be included here. The user is also able to define at which years it will occur.

Rs = Running cost savings, as previously described.

A graphical representation of cumulative cash is presented to the user as illustrated at Figure 14 and may be used as reference of how fast the money invested is being recovered. Additionally, once the cash flow associated to the proposed system is known, the IRR can be calculated. Microsoft Excel uses an iterative technique for calculating IRR. Starting with a guess, different discount rate values are tried until the value at which NPV equals to zero is found with an accuracy of 0.00001% (Excel 2007).

## 4.3 Chapter conclusion

The previous chapters highlighted the importance to utilise detailed modelling in the analysis of hybrid energy systems with high renewable energy penetration. Although able to replicate in details the thermodynamic relationship between different elements in a hybrid energy system, TRNSYS outputs information in a time series format without a concise way to analyse performance.

Motivated by the challenge described above, a performance assessment interface was created. This new tool imports the data series generated after each simulation and converts it into a format that designers can easily understand.

The interface outputs were divided into two main groups: energy performance analysis and financial performance analysis.

The first group informs the designer about performance parameters such as $CO_2$ emission levels, energy source or energy unit participation over the load, load share, etc. All the information is displayed in user friendly graphs and allows the user to create base case scenarios against which performance is compared

The second group focus into the financial aspects in the energy system. Additionally to running and capital costs, which also can be compared against a user defined base case, the tool allows the introduction of financial incentives based on the amount of renewable energy share over the load, such is the case of the feed in tariffs or renewable heating incentives. All these elements are combined together and converted into financial performance indicators, such as payback period or internal rate of return, which are commonly utilised in the decision making process regarding the feasibility of an investment.

In the next chapter both TRNSYS and the created interface are utilised as part of the design process of three energy systems. The benefits that detailed simulation brought to the final product will be analysed and compared against the original design.

# 5. Case studies

This chapter will analyse how some energy system designs may me be optimised by detailed energy system simulation. All three case studies here presented are based on real life projects within the UK to which access to the original design details were made available either through public publications or direct contact with original energy system designers. It is, therefore, assumed in the analysis that all the cases have already been through the first stage in the proposed design process: the feasibility analysis. This chapter will focus into the second stage, the detailed modelling and system improvement.

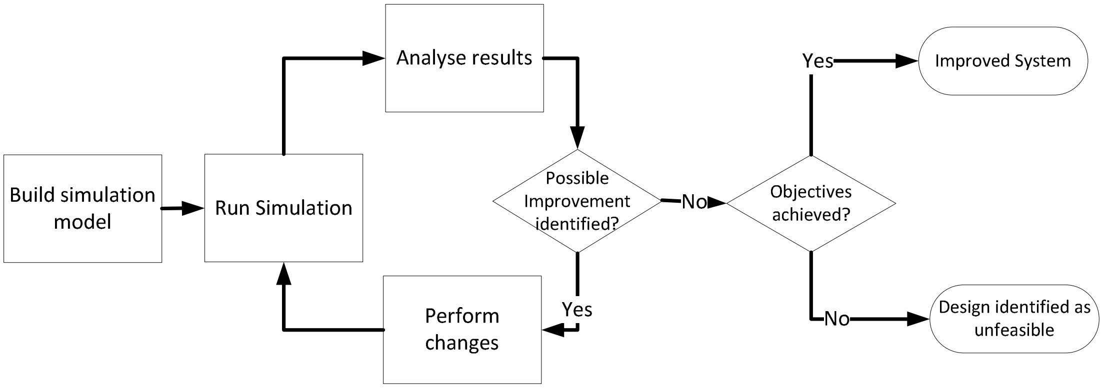


*Figure 17 - System improvement process described at chapter 3*

To each of the proposed energy system designs a TRNSYS model was created and key performance parameters defined. The performance assessment tool was utilised to quantify the benefit of proposed changes in the original design while more punctual data analysis, like storage tank temperature at different points throughout a day, supplied information that could identify problems or potential solutions.

In the end of each chapter a list of improvements and problems not identified in the original design will be presented, highlighting the benefits brought by the detailed modelling.

## *5.1 Caste study one – Individual residential system design: Sizing and control improvement*

### *5.1.1 Introduction*

In the UK around 3.4 million people currently live outside the gas network areas (Baker, 2011), relying traditionally on energy sources such as heating oil, liquefied petroleum gas (LPG) or electricity to heat their properties. The first two energy resources are not part of a regulated market, resulting into fuel prices considerably volatile with significant variation within months. In the past 3 years the average heating oil price in the UK doubled, going from 0.3 £/L to 0.6 £/L (DECC,2012).

The elements described above made alternative heating technologies quite attractive to homeowners and the retrofit market. As described at chapter 3, some of these technologies are, however, considerably more sensitive to the environment and user behaviour than their fossil fuel driven counterparts, indicating that design is critical to an effective operation.

It is unclear how current design standards, based on steady state analysis, affects system performance when different control strategies are applied or variable weather conditions are considered. This section will analyse a typical air source heat pump + back-up installation and through detailed simulation observe how the assumptions behind the design may affect system performance and capital costs and how it compares against current design standards.

### 5.1.2 The energy system

The proposed scenario replicates a representative UK detached dwelling (Kelly and Beyer, 2008) with main fabric elements highlighted below:

| **Structure** | **Details** | **U value [W/m2 K]** |
|---|---|---|
| External walls | Brick – cavity | 0.45 |
| Windows (13% of total surface area (DECC, 2009)) | Double glazing pre 2000 | 2.83 |
| Roof | Pitched | 0.3 |
| Floor | ($104m^2$) | 0.45 |
| Heating system | Radiators | N/A |
| Air infiltration | $13m^3/hr.m^2$ @50pa (DTLR,2000) | N/A |

*Table 1 – building details*

All the heat demand will be supplied by a combination of a heat pump and an electrical heating element acting as back-up as represented below:

The units will be initially operated based on the three main operation modes identified by The Energy Savings Trust's heat pump trial (The Energy Savings Trust, 2010):

**Operation mode 1 –** Intermittent heating: When unoccupied the heating in the building is completely switched off. During the occupancy periods the building temperature is set to constant 20°C.

**Operation mode 2 –** Set back heating: When unoccupied the building temperature is maintained above a minimum value. During occupancy periods it is raised to 20°C. For the modelled system it was observed that the setback temperature of 16°C gives a good balance between energy unit size reduction and annual energy consumption.

**Operation mode 3 –** Continuous heating: The building is maintained at 20°C through the entire day. This is quite usual with buildings where the thermal mass can be used towards its advantage but for refurbished buildings heated through radiators the result may be a significantly higher energy demand. Because the power output just needs to match the fabric losses this condition tends to lead to the smallest energy unit sizes.

Just like in real residential installations, the heat pump will be controlled by two main elements: room thermostats and the temperature of the water returning to the heat pump. The first defines when heat is required and therefore the heat pump must be switched on and the second element work as protection against undesired return temperatures, switching the unit off whenever it achieves values above 51°C.

Following current standards the back-up unit is controlled in such a way that, for Glasgow, it won't be allowed to act unless external temperatures are below -3.4 °C (DECC: MIS 3005, 2010). The sizing process must take it into context.

### 5.1.3 The energy system model

A TRNSYS representation of the proposed system was built as shown below:

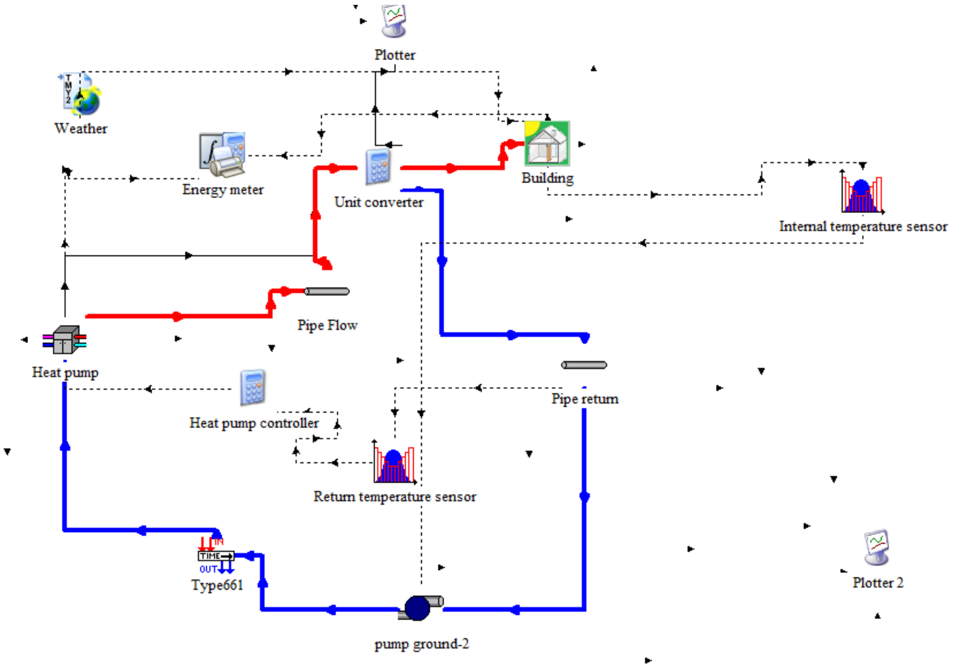


*Figure 17 – TRNSYS model*

It is formed by the following main elements:

**Heat pump**

The heat pump model simulates a real unit performance by reading, at every time step, inputs such as external weather temperature or returning water flow temperature and combining it against a pre-defined performance map. This map is user defined and indicates how the unit operates under different circumstances. The performance map was created based on manufacturer's performance data available in technical documents such as Dimple's planning manual (Dimplex, 2012).

**Building**

The building model follows the specifications presented in the previous section and was created through TRNSBuild, a TRNSYS interface utilised to create building models. The building is divided into four main volumes, individually controlled, and from which a call for heat signal is sent in case the internal temperature drops below a pre-defined set point.

**Back-up unit**

While in operation, the return temperature to the heat pump is monitored. If the outside weather temperature is below -3.4 $^{o}$C and the return temperature is below the expected value for more than 30 minutes, a 3kW back-up unit is activated, transferring extra energy to the property. The bivalent point was set based on current MCS Standards (DECC:MIS 3005, 2012)

**Plotters**

To allow punctual analysis of some key elements in the energy system, "plotters" were connected to some of the system outputs such as room temperatures, heat pump power output and energy consumption, weather temperature, etc. The "plotter" will automatically plot a graph representing the state of each of the linked outputs at every simulation time step.

### *5.1.4 The design improvement process*

The main challenge in this system is to identify the right balance between capital cost and system performance. Oversized systems may be unfeasibly expensive and financially unattractive while undersized ones would either not be able to achieve desired temperatures or become expensive to run due excessive action of back-up unit. Additionally, short cycles may have significant impact in the heat pump life cycle and performance and must, therefore, not be overlooked.

The improvement process will be divided into two stages:

**Unit sizing**

The simulation will define how much energy is required to achieve the set temperature during the coldest day in the year under different operation modes. In the case of set back and intermittent heating, the heat pump was started one hour prior to the desired temperature being required.

The required capital cost and annual running cost for each scenario will be combined in different financial parameters and utilised to define how effective each design is.

Following the procedure described at chapter three, if after the simulation of the proposed control strategies a potential improvement is identified, new simulations will be run until no more space for improvement is found.

**Reliability**

Although the analysis above defines how well the system will be able to cope with winter conditions it does not offer information about system efficiency under milder weather conditions and life expectancy.

Excessive cycling may reduce heat pump’s efficiency and life cycle and therefore the number of cycles will be utilised, at this stage, as reference over how damaging to the unit the selected strategy may be.

A final conclusion will be drawn from the combination of both results.

### 5.1.5 Result analysis

**Unit Sizing**

The model was first used to identify the size of unit required (based on peak demand) to attain the desired set point condition during the whole year.

Figure 18 shows the variation in the calculated peak thermal demand with the different operational strategies. This peak demand determines the size of the heat pump system to be installed. The intermittent operating strategy results in a unit size of 11kW heat output, almost twice the capacity of the unit required if a continuous heating strategy was adopted.

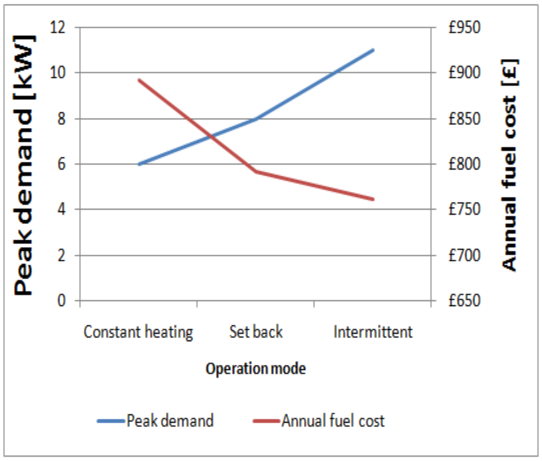


*Figure 18- Peak demand and running costs for different operation modes*

Figure 16 also shows the fuel cost associated with each strategy. To calculate it, a typical UK 'economy' tariff was applied, dividing the electricity price into two groups: low rate (7p from midnight- 5 am, 1pm-4pm, 8pm-10pm) and high rate (14.9p all other periods). Additionally, a standing charge of 16.3p per day was included. The resulting costs range from approximately £760 per annum for intermittent heating to around £900 per annum for a continuous heating strategy. The running costs are therefore significantly less sensitive to the operational strategy than the unit size.

The setback results and its position between the two other investigated conditions indicate that more feasible solutions may lie between the extremes. The previous analysis was, therefore, extended to 5 more intermittent heating conditions, but where a longer period of time is allowed between the heating system being switched on and the expected indoors temperature being achieved (pre-heat).

Figure 19 shows the effect of increasing the pre-heat time on the required unit size for the intermittent heating case.

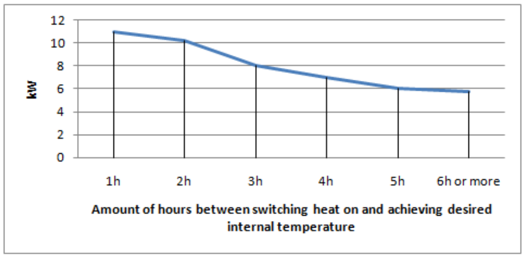


*Figure 19- Required unit size versus required heating time*

The unit sizes and running costs above only give a partial picture regarding the merits of a particular operating strategy, an appreciation of the likely capital cost is also required. Prices for a range of ASHP units were therefore gathered from a range of different suppliers. These indicated that installed cost of a domestic ASHP device can be placed between £900 and £1200 per kW (thermal) depending on the size of the unit. The relationship utilized here will be £1200 per kW for a 5kW installation and £900 per kW for 14kW installed unit. These prices include fitting and purchasing larger radiators sized for use with an ASHP.

Applying these prices to the calculated unit sizes for the different operating strategies, it can be observed that sizing an air source heat pump system for fast-response, intermittent heating is nearly 60% more expensive than trying to just meet the demand of a continuous heating system.

| Unit size | Estimated CAPEX |
|---|---|
| 11 kW | £10,500 |
| 10 kW | £9,800 |
| 8 kW | £8,300 |
| 7kW | £7,500 |
| 6kW | £6,700 |

*Table 2 - Required installation costs*

Comparing investments

The merits of the different operational strategies can be compared by plotting the net present value (NPV) for each investment. This analysis will observe a series of cash flows recurring from the initial investment in a new heat pump system and then expected savings from lower running costs over a period of 20 years. All systems will be compared against an oil boiler running cost and any fuel saving will be applied into an investment fund with annual return of 3%. The same fund will also take any savings from the installation of a smaller unit when compared against the largest and most expensive one (in this case, an 11kW (heat) heat pump). Figures for the calculations are shown below:

Electricity cost follows the economy 10 tariff previously described.

Oil price of £0.055 per kWh.

Inflation rate for fuel of 4%

Annual discount rate of 3% for NPV calculation

Individual Savings Account (ISA) interest rate of 3% per year.

The results are below:

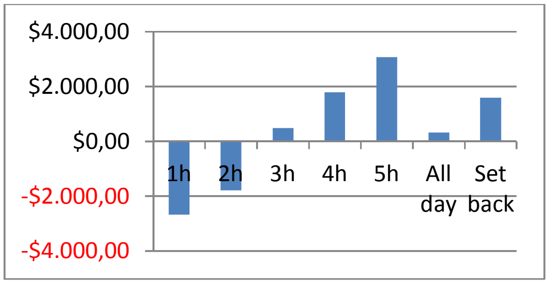


*Figure 20- Net present value*

The results highlight the fact that sizing the unit based on a slow heating mode represents the best investment from all the options observed. The difference between required investments is so significant that even a system more expensive to maintain, such as the "all day mode" is a better option than the installation of larger units. The slow heating modes, and in a certain level the all day and set back, are helped by the fact that between 1pm and 4 pm, a low electric tariff period takes place resulting in an interesting occurrence: Higher energy consumption but lower fuel bills. The 3, 4 and 5 hours preheating modes were particularly benefited by it, as shown below.

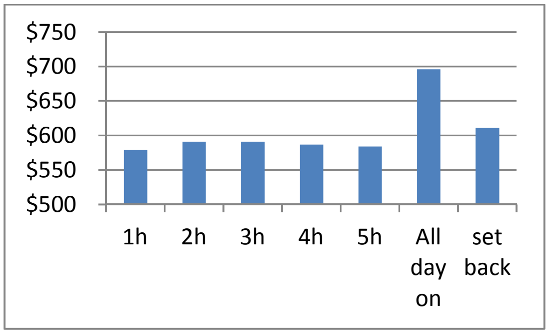


*Figure 21- Running costs for different heating modes*

**Reliability**

Another important aspect to observe at this stage is how the sizing methodology adopted affects the equipment's reliability. To evaluate the system's reliability the simulated compressor on/off cycles were observed and compared to the expected number of cycles over the lifespan of a compressor. Ideally, once the heat pump compressor is switched on it should be kept running for as long as possible to minimise cycling since its life span is closely related to the accumulated number of on/off cycles.

Note that the compressor being simulated can't modulate its output therefore the results are not applicable to inverter driven units. No buffer store was included into the simulation in order to emphasize the cycling effect from each control methodology.

| System type | Number of starts in 24h |
|---|---|
| Intermittent heating | 108 |
| Set back heating | 132 |
| 5h pre-heat | 68 |
| Continuous heating | 120 |

*Table 3- total cycles during a mild weather day*

Comparing the results above against a typical compressor with life span of 200,000 cycles (around 10 years lifespan) means that the best lifespan is achieved with the operational strategy that provides the best financial return: operating the heat pump intermittently but with a 5 hour pre-heat time.

Due the longer period of operation, the continuous and set back modes accumulate the highest number of cycles per day. In the latter case, the reduced internal temperature at which the building needs to be maintained during unoccupied periods (16$^{o}$C) results into the compressor cycling more often than if it was maintained at a higher value. Although being a financially interesting alternative, the setback mode in a retrofit property with low thermal mass can result into an early breakdown. It is an interesting result having in mind that most of customers in the EST trial were actually running the system in this mode.

It is worth to mention that, in all cases, cycling may be reduced by manipulating the dead band of the heat pumps' on/off controller (Karlssons,2008).

Finally it should be noted that intermittent operation (with no pre-heat) resulted in the shortest cycle periods; these tend to reduce the device efficiency due to factors such as refrigerant migration (vapour and liquid) into the evaporator, raising its initial temperature and affecting the heat exchange rate (McPherson, 1989).

### ***5.1.6 Simulation Review***

The series of simulations described above highlighted the impact that detailed modelling has in the solution of a “simple” energy system sizing. Current standards, based on steady state analysis, do not consider the impact that the customer behaviour and expectation should have in the system design.

For the proposed system, the size of the unit under current standards would be similar to the one found in the constant heating mode, where the unit only needs to match the current heat losses through the building fabric, not taking into account heating time. The problem is that, as highlighted in the Energy Savings Trust trials, most customers are oriented to run the system under the set-back mode. There is a mismatch between what is being sized and how the system is used. The customer isn’t oriented regarding required pre-heat time or impact that the proposed unit size / control could have into system performance. Unless a considerable thermal mass is present to act as a buffer, like is the case of an under floor heating system, the current sizing methodology combined with proposed control may lead to reduced life expectancy and negative customer experience.

The detailed modelling presented here suggests that the control strategy that best matches current standards is achieved by allowing a pre-heat time between 4 and 5 hours. If the customer is informed of such, his/her expectations can be managed and the system will be operated in a mode that benefits both its performance and customer’s need.

## 5.2 Case Study Two – Low carbon district heating: biomass boiler combined with ground source heat pump (GSHP)

### 5.2.1 Introduction

As mentioned at chapter 3, a key element in the design of hybrid systems is the method utilised to couple and control the different energy sources in the system. Due their simplicity, heat stores are good alternatives for such and was the solution applied in the zero carbon district heating networks used as case study in this section (Green Watt Way, 2010). Although the zero carbon nature is quite specific, the need to couple two low carbon technologies together in order to achieve a set $CO_2$ emission target is a challenge that new developments will be increasingly facing (Code for sustainable homes, 2010; BREEAM , 2010), making the chosen scenario relevant .

To minimise the $CO_2$ emissions related with heating the properties, the original project designers identified the combination of biomass boiler and heat pump as a feasible solution. It was defined that any $CO_2$ related with the heat pump utilisation must be offset by photovoltaic generation. It is, therefore, vital to keep the heat pump efficiency as high as feasibly possible since it will affect both running costs and the amount of extra investment required towards the installation of photovoltaic panels.

Although no specific target was initially set, it is known that due limited storage space and unregulated fuel market (making the price volatile), the biomass boiler use should be minimised. Meeting these requirements can be challenging since, as described at chapter 2, heat pump's efficiency is reduced by high water temperature through its condenser whilst biomass boilers require flow temperatures above 65$^{o}$C. For both units, short running cycles have negative effect in the performance, particularly in the biomass boiler, where considerable amount of energy can be spent during the start-up period. Detailed simulation will be used to observe how the combination of both units through a storage tank may be improved. The original design, created through simple simulation software (Energy Pro) is utilised as starting point.

An overview of the energy system is given next.

### 5.2.2 The energy system

The district-heating network is formed by 10 properties, each one built following passive house standards (Feist et al., 2005). The network connects to an energy centre into which four renewable heating technologies are available:

a biomass boiler, a ground source heat pump, an air source heat pump and solar water heating panels. As previously stated, this section will only analyse the hybrid system formed by the heat pump and biomass boiler.

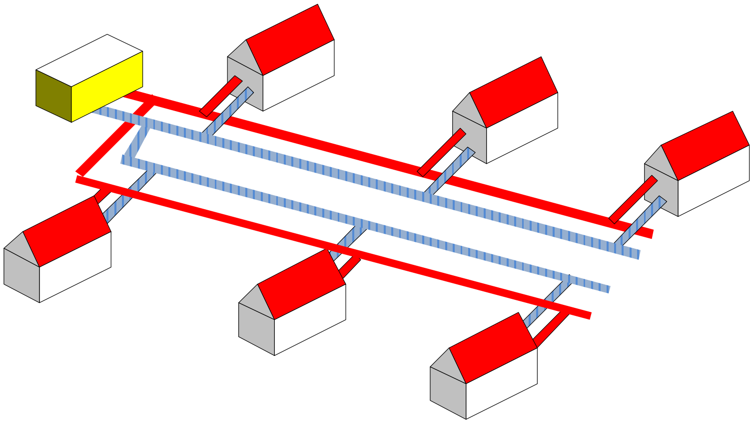


*Figure 22- District heating network*

A pair of heat exchangers allows the transfer of heat from the district-heating network to the radiator and hot water systems inside the property. Due the limited maximum temperature reached by the heat pump, both district heating network and heat exchangers are designed to work at 55$^0$C.

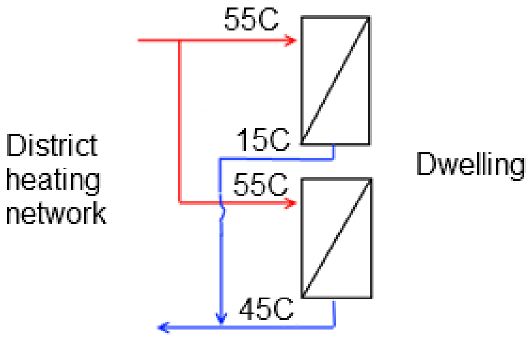


*Figure 23 - Heat exchangers inside each property*

Working as interface between energy units and the load is an 8000L storage tank built especially for this project. This tank has 5 pairs of inlets and outlets distributed evenly throughout its height.

The entire energy system is controlled by a management system able to observe a series of variables and perform the required actions based on pre-programmed instructions. The available inputs are tank temperature at 5 different points equally distributed through the tank's height, external air temperature, water flow temperature through the distribution system, solar radiation, time and season.

The simulated system operates with three thermostats placed into the heat store, as shown below:

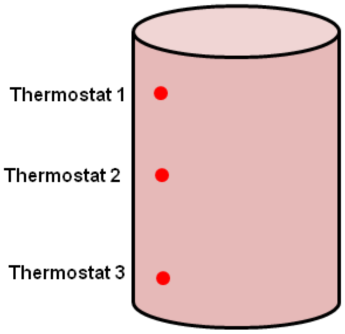


*Figure 24 - Hybrid system thermostat positions*

Sensors one and two control the biomass boiler, and are responsible for maintaining the temperature at the top of the tank always above 53$^{o}$C. The sensor three controls the operation of the heat pump, including fault protection against excessive return temperature. Both operations are demand (temperature) driven and no timer is utilized. The original design follows the strategy below:

- With the entire tank temperature above 55$^{o}$C, sensor one measures the internal temperature and once it detects a value below 52C, both units are activated.
- Biomass boiler runs until sensor 2, placed between its flow and return connection points, achieves 53C.
- Heat pump runs until temperature Thermostat 3 reaches 40C.

The next session describes how this system was translated into a mathematical model in TRNSYS.

### 5.2.3 The energy system model

The figure below illustrates the energy system model created to represent the system described above. Printers, controllers and data importers were removed from it to simplify visualisation.

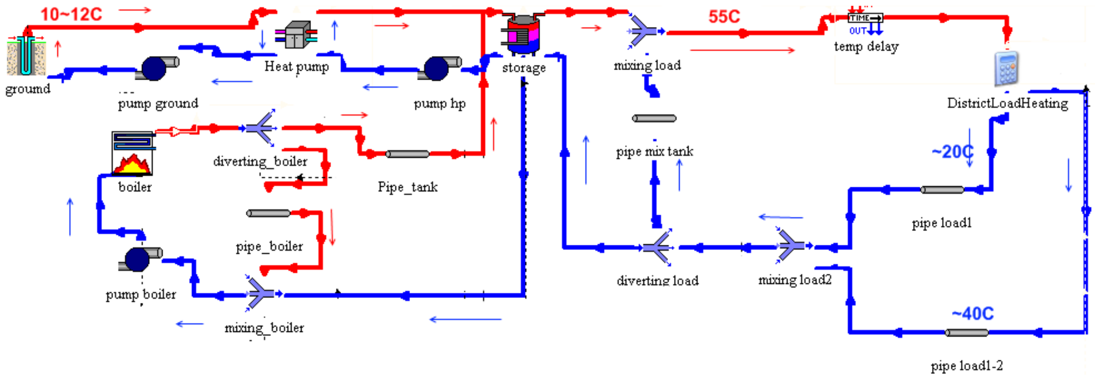


*Figure 25 - Energy system model HP + Biomass*

The TRNSYS model is formed by three key elements: The load, the heat store and the energy supply units.

## *The Load*

Unlike case study one, the load is connected to the energy supply units through a large storage tank, which also acts as a buffer. This reduces the effect that instantaneous change in the load has over the performance of the energy units and vice-versa. Because of this independence, each property wasn't explicitly modelled as in the case study one. Instead, time series from previous building simulations were imported directly into the model.

The total expected space heating demand behaviour for a typical winter day is shown below and was generated at a half hour resolution.

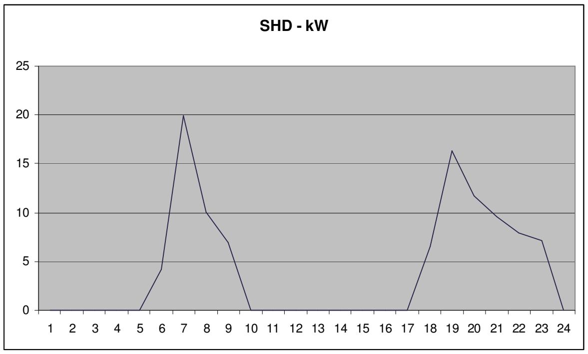


*Figure 26- Daily load profile*

Due the high insulation level in each property the hot water demand becomes a significant share of the total system energy demand. Like the space heating load, the hot water utilisation wasn't explicitly modelled in TRNSYS but time series were imported from external data generated by ECBS Annex 42(Knight, 2007). The original data was manipulated by receiving a random time shift between 0 and 15 minutes and each variation allocated to one of the 10 properties. Single bedroom flats received 100L daily draw off profiles, the two bedrooms 200L and the three bedrooms a mix of 200 and 300 litres profiles.

## *Heat Store*

As represented at Figure 25, the entire system converges to one main component, the heat store. Due the heat pump sensitivity to flow temperatures, the tank model must be able to replicate eventual tank stratification. This is achieved by employing the TRNSYS component type 534, which utilises a multi-node approach where the tank is divided into N nodes (equal volumes of water) and to which energy balance differential equations define the temperature levels as function of time.

An example of this representation is shown below for a three node tank. In this case, the tank connects to a single load and a solar collector. $\mathrm{F_i^n}$ is a control function defining which node receives water directly from the collector and is directly related with the utilized kind of inlets and diffusers. Usually just one of the control functions for each type of water source (in the case below, the collector $\mathrm{F_i^c}$ and the load $\mathrm{F_i^L}$) can be non-zero. In the model created for the hybrid system it was assumed that diffusers with baffle plates were utilised and therefore $\mathrm{F_i^n}$ for the respective inlet node is non-zero (e.g, if the inlet connects to the tank at node 2, $\mathrm{F_2^n}$ will be non-zero).

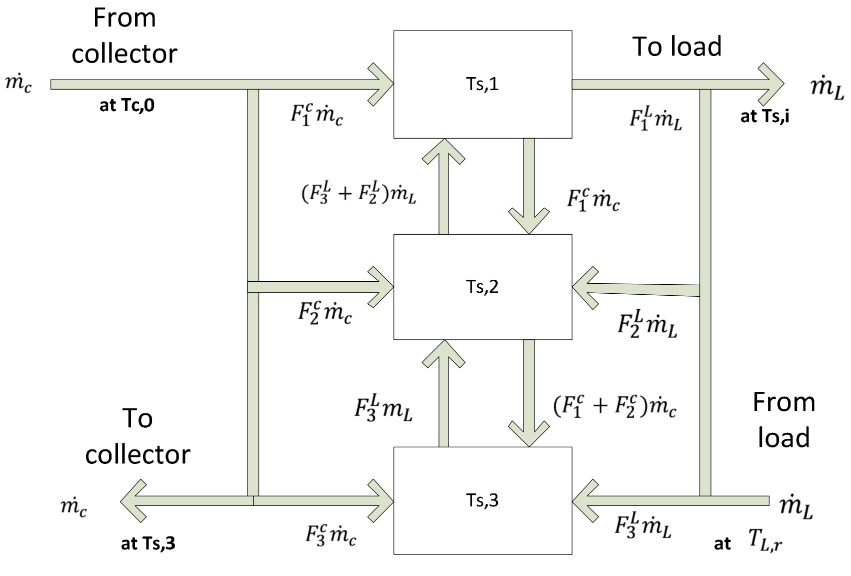


*Figure 27 - Energy flow through nodes (Duffie et al., 2006)*

It is convenient to represent the flow rates through each node as one single resultant flow, from node i - 1 to node i.

$$m_{m,i} = m_c \sum_{j=1}^{i-1} F_j^c - m_L \sum_{j=i+1}^{N} F_j^L \qquad [3]$$

Where:

$m_{m,1} = 0$ (it means that if the node observed is node 1, there will be no flow from a node above) and

$m_{m,N+1} = 0$ (no means that if the node observed is the last node, there will be no flow from a node below).

The differential equation, including tank losses, is then:

$$m \left(\frac{dT_{s,i}}{dt}\right) = \left(\frac{UA}{C_p}\right)_i \left(T_a' - T_{s,i}\right) + F_i^c m_c\left(T_{c,0} - T_{s,i}\right) + F_i^L m_L\left(T_{L,r} - T_{s,i}\right) + \begin{cases} m_{m,i}\left(T_{s,i-1} - T_{s,i}\right) \; if \; m_{m,i} > 0 \\ m_{m,i+1}\left(T_{s,i} - T_{s,i+1}\right) \; if \; m_{m,i+1} < 0 \end{cases} \qquad [4]$$

The number of nodes to be utilized generally depends of the application. Kleinbach (Kleinback et al., 1993) compared measured data against predictions and found that 10 nodes were satisfactory in predicting measure performance for domestic hot water cylinder while Oberndorfer (Oberndorfer et al., 1999), through the simulation and analysis of a series of different systems, concluded that for annual predictions no more than 10 nodes are necessary. Additionally, for annual prediction, the nodes temperatures will be utilised in this study to track the system behaviour at smaller time ranges, such as a day. This analysis will help to understand how changes in the system configuration are affecting overall performance and therefore indicate possible beneficial design changes. A sensitivity check was made and the 10 nodes approach also proved to be enough for such analysis. Larger amount of nodes would require considerably lower time steps to avoid possible mass balance issues. These errors may happen whenever a volume of water entering one node, in a time step, is higher than the node capacity.

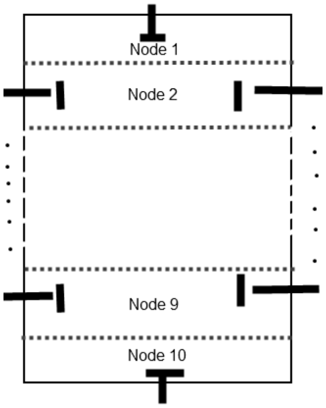


*Figure 28- Simulated tank nodes, inlets and outlets*

## The Energy Units

The next key components in the energy system models are the utilised energy units. For the biomass boiler simulation a normal gas boiler model from the TRNSYS library was modified to replicate a biomass one. From the same library a heat pump model similar to the one utilised at case study one was utilised. The main difference is the fact that this new unit is now connected to a borehole and therefore the ground temperature had to be also simulated. Details about each model are given next.

### Biomass boiler

The biomass boiler is represented by the combination of a TRNSYS water boiler model (Type 659) and a pair of controlled mixing and diverging valves whose behaviour were adjusted to simulate the studied technology.

The boiler model transfers a controllable amount of heat to a mass of fluid connected to its inputs. Following biomass boilers manufacturer's data, the original model was modified to allow a maximum turn down ratio of 3:1. The minimum boiler entry temperature allowed is 50°C with outputs between 65°C and 90°C. These values are maintained through the control of a bypass valve placed between the boiler's outlet and inlet, as below.

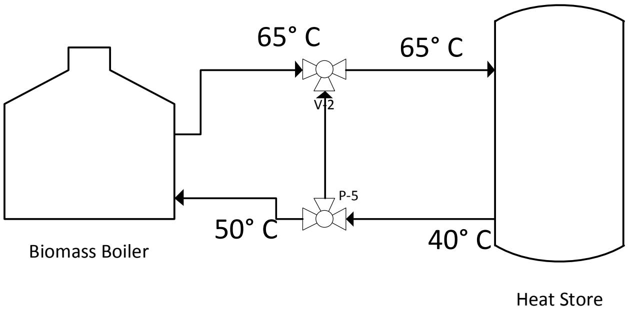


*Figure 29 - Simulated biomass boiler*

The feasibility study carried out by the energy system designers of the project suggested a 30 kW boiler as feasible solution. This will be the initial value from which detailed modelling will start the system improvement process.

<u>Heat Pump</u>

TRNSYS type 668 simulates a heat pump unit by comparing the temperature of the fluids connected to its inputs (source and load) against a performance map inserted by the user, as described in the previous case study. The main difference in this model is in the fact that the evaporator element must receive information regarding a different type of heat source, in this case, the ground. The chosen ground model represents a borehole field formed by eight one hundred deep boreholes heat exchanger (double U DN 32 pipes) allowing a total extraction of 105 MWh per year. The ground temperature follows the profile below:

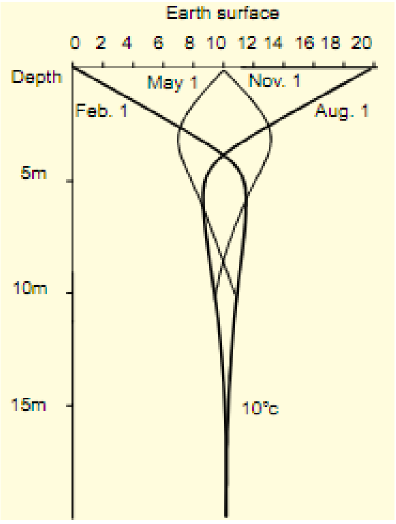


*Figure 30 - Ground temperature*

### System Control

In order to control all of the different elements in the system, from distribution system pumps to mixing valves and energy units operation, a bespoke control system had to be created.

The relevant outputs from each element in the system were connected to a series of equation solvers which are able to analyse the combination of different inputs and through a series of equations define the required action (output). Examples of outputs from these controllers are: heat pump on, mixing valve state and circulation pump speed.

## 5.2.4 The design improvement process

As previously stated, the challenge in this design is to balance the conflicting requirements from the different energy supply units and maximise the heat pump participation over the load. The improvement process was divided into four stages: Units sizing, configuration improvement, control strategy improvements and design refinement.

### Unit Sizing

The iterative process starts by simulating the original design defined during the feasibility study: a 30kW biomass boiler connected on the top of the heat store and two 17kW heat pumps connected in series to the bottom part of the heat store. By observing the overall load share during the year for each unit and the different nodes temperature through the tank in a typical week, it is possible to identify inappropriate unit size. The results from this first iteration will define new units sizes and possible changes into system configuration.

### System configuration

A second stage in the iterative process will observe how different connection points affect the system performance. Both annual performance, generated through the performance assessment tool, and more punctual data, such as heat store's temperature through a typical day, are utilised to identify how the changes may improve the system performance.

### System control

The next element to be improved in the system is the control strategy. Utilising the data from previous simulations, control improvements are tested and compared against each of the proposed system configuration.

**Design refinement**

The previous stages give the designer information about how the system reacts to changes into the unit size, control and positioning. The last system improvement stage will utilise this data to define final changes required to achieve an improved system.

### 5.2.5 *Result analysis*

**Unit sizing**

After simulating the original design, created through a simplified energy system design tool during the feasibility stage, it was observed that the system capacity was oversized for an efficient hybrid configuration. The detailed simulation was indicated that the original design resulted into excessive units cycling (consecutively switching on and off) and incapacity to control how much of the load was supplied by each of the units. The key issue identified is the fact that the oversized biomass boiler brought the tank temperature above the heat pump's operation threshold too fast, forcing it to shut off due high return temperature. By reducing the boiler capacity to 30% of the original value (30kW), the temperature through the tank became more controllable, allowing the heat pumps to operate as expected.

**System configuration improvement**

With the new biomass boiler size, different energy system configurations were compared against themselves regarding total running costs and $CO_2$ emission. The results are presented at Figure 31 where "B+HP X/x Y/y" means biomass boiler flow at node X, return at node x, heat pump flow at node Y, return at node y. Because the objective of the project is to offset any emission in the heating system by producing electricity through photovoltaic panels, a simplified approach, utilising SAP 2009 methodology to calculate the total electricity generated per square meter of panel, was adopted. The final area, in square meters, required to offset the heating system emissions is shown in Figure 32.

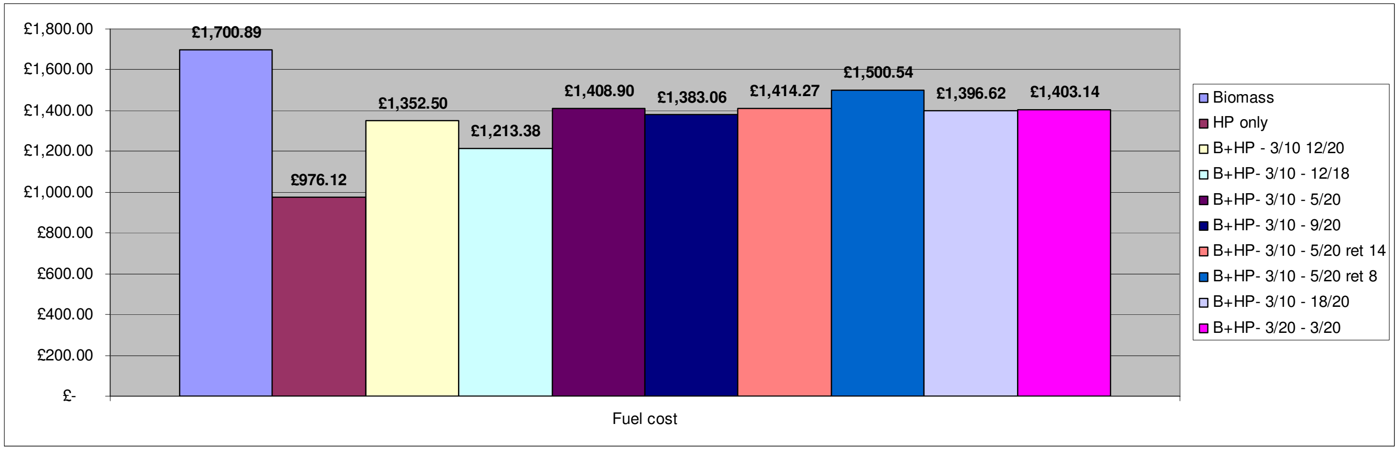


*Figure 31 -Running cost under different configurations*

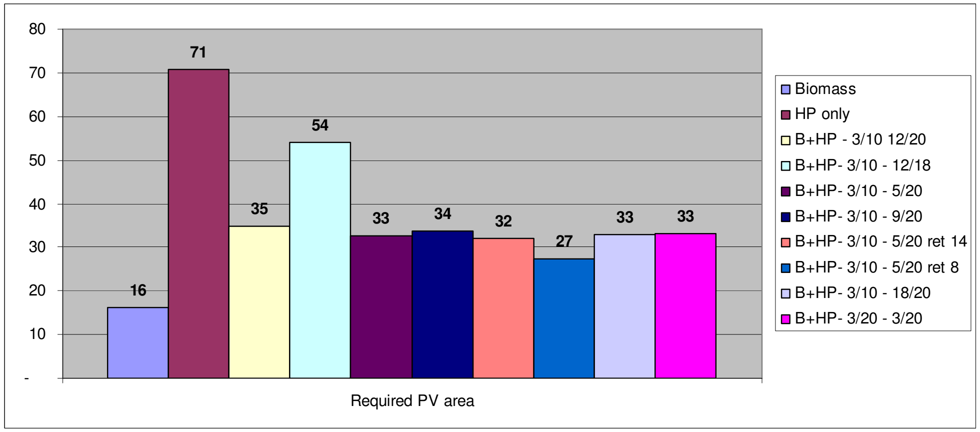


*Figure 32 - Required PV area ($m^2$) to offset emissions*

Among the hybrid systems, configurations B+HP 3/10 – 12/20 and B+HP 3/10-12/18 offered the best running cost results but diverged regarding total $CO_2$ emission levels. The performance analysis interface outputs aren't detailed enough to better understand how these two configurations could lead to a third, more effective, system. For this reason, a detailed study on the tank temperature at each configuration was carried out. The heat store temperature levels at different nodes were observed during a winter week.

As seen at Figure 33(right hand side), by moving the outlet that connects the tank to the heat pump away from the thermostat, the maximum return temperature through the heat pump is raised to 50°C, compromising its COP but allowing it to run for longer (raising its share over the total load). This indicated that the key point to maintain the heat pump COP under control is to maintain the position of thermostat 3 above the outlet feeding the heat pump. This option was implemented (left hand side of Figure 33) and resulted in emission levels similar to the 12/20 option but with higher heat pump share of the load.

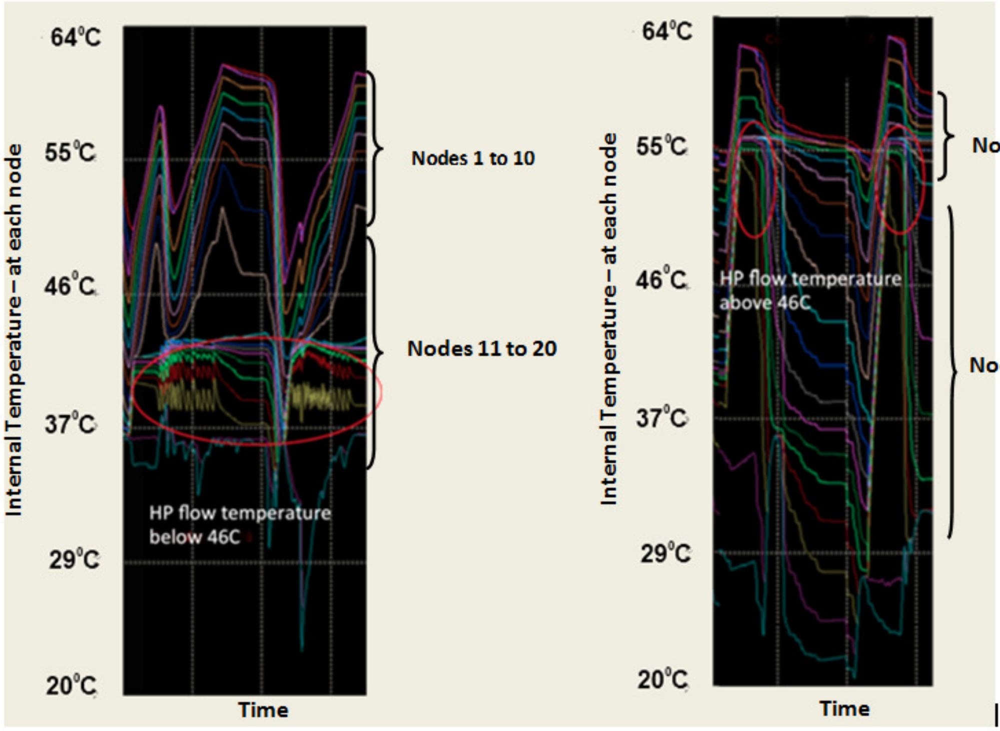


*Figure 33 - Simulated internal temperatures showing different tank stratification level for different control thermostat locations*

Further result analysis also shows that higher biomass load share results in lower emissions while higher heat pump share results into reduced running costs. It is worth mentioning that so far no restriction was given regarding how often the biomass boiler is allowed to run. As stated earlier in this chapter it is desired to minimise the biomass participation due limited fuel storage space and fuel price volatility. The next group of simulations will adjust the system control and focus into minimising CO2 emissions by improving heat pump seasonal COP but restricting biomass boiler participation to a maximum of 70%.

**Control Improvement**

Following the new objectives, the operation of the units was changed:

- With the tank charged and the energy units off, a thermostat at its top measures the temperature. Once thermostat one detects a value below 52C, the biomass boiler is activated
- Biomass boiler runs until thermostat 2, between its flow and return inlet/outlet, achieves 53°C.
- If temperature at thermostat 3 is below 36°C, the heat pump is activated.
- The heat pump runs until the temperature at sensor 3 achieves 40°C.

The main difference from the previous simulation is that under the new control strategy the energy units are operated independently. The best configuration found is illustrated below:

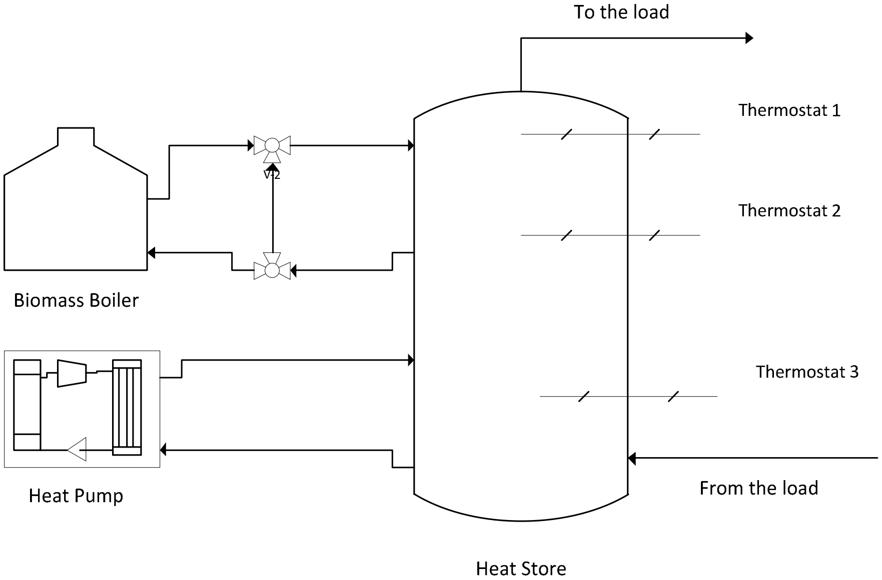


*Figure 34 - Hybrid system configuration*

Comparing the configuration above against a heat pump only solution, the obtained average heat pump COP went from 3.1 (HP only) to 4.2, with heat pump share of the load at 25% and, therefore, below the target of at least 30%, initially set. The COP rise was driven by the fact that under this configuration, the heat pump is operated at a significantly lower temperature with flow values hardly above 45 °C, as shown below.

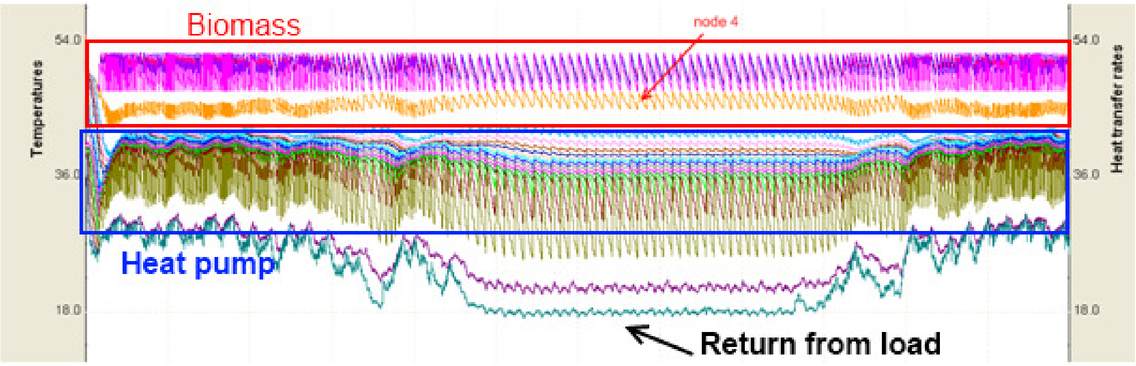


*Figure 35 - Internal tank temperature – HP return temperature constantly below 36°C.*

To achieve 30% load share target, new simulations were conducted for the summer period, the biomass boiler is kept off. This small change brought the heat pump load share to 45% but affecting its average COP, now at 3.8. The system efficiency was affected by the fact that, during summer, the heat pump does not act as a pre-heater, forcing it to operate at temperatures around 55°C, as required by the hot water demand.

**Design refinement**

The previous simulations were utilised to give the designer better understanding about how the system reacts to changes in the unit size, control and positioning. All this information is now utilised to define a final system design. Maintaining the system configuration and control utilised in the last section, a new unit size is proposed.

New heat pump capacity – 10kW

New biomass boiler capacity – 7.5 kW

With a capacity 75% below the original, it was possible to run the biomass boiler at its rated power and gradually reduce its capacity in order to maintain its flow temperature always around 65°C (instead of 90°C seen before), making the tank temperature more controllable. Running the new hybrid biomass/heat pump system through the entire year granted an average COP of 4.3 with heat pump load share of 43%. With the heat pump being the exclusive heat source during summer, the average COP dropped to 3.9 but share of the load rose to 55%.

Both cases above meet the 30% minimum heat pump share target defined earlier. As observed in the first group of simulations, if priority is given to reduced running cost, the solution with higher heat pump share should be adopted. If, otherwise, lower $CO_2$ emission levels are expected, the solution providing higher biomass boiler share over the load is the appropriate solution.

### *5.2.6 Simulation review*

This hybrid system may be an alternative to designers looking for a balance between running costs and $CO_2$ emission levels. The main challenge involving such system proved to be the management of different ideal operational temperatures. The "priority" technique utilized by some simpler energy system analysis tools such as E.Pro or RETScreen, where the amount of energy supplied by each energy unit follows their rated capacity and priority status, could mislead the designer that higher heat pump shares could be reached. It was observed that, regardless the unit sizes, badly positioning of the biomass boiler's inlet and outlet in the tank may force the heat pump to constantly operate at high temperature levels, which affect its efficiency and may lead to the heat pump shutting down due to a high pressure fault (high temperatures through condenser).

The capacity to observe the temperature changes through short time scales was key to understanding how the biomass boiler operational temperature would influence the heat pump performance and how different targets could be achieved by either repositioning the energy units through the tank or changing the control methodology.

## 5.3 Case Study Three- Ground source heat pump combined with solar water heating panels.

### 5.3.1 Introduction

The previous case study utilised detailed simulation to improve the design of two low carbon technologies combined through a heat store. A key characteristic in that system is the fact that only one of the utilised energy units, the heat pump, is sensitive to changes in the temperature levels through the storage tank. This last case study differs from the previous by combining together two technologies sensitive to tank temperature levels: A ground source heat pump and solar water heating panels. Both energy units benefit from colder water flows, which make finding the optimum balance between heat pump and solar water heating panels' efficiency the challenge to be overcome.

Once more, the system improvement exercise shall minimise any $CO_2$ emission related with the heat pump's operation by reducing the heat pump share over the load and by maximising its efficiency.

### 5.3.2 The energy system

The energy system follows a similar configuration described for case study two, differing in the fact that the biomass boiler is substituted by an array of solar water heating evacuated tubes installed on the top of the energy centre.

Additionally, the 8000 L heat store is provided with a group of automated valves that allow the connection points between the energy units/loads and the tank to be changed on demand (Figure 36). It is possible to, for example, move the heat pump's flow and return inlets and outlets from the upper volume of the tank to the bottom part without interrupting its operation. This feature is relevant due the fact that, unlike in the previous case, both energy units benefit from colder water flows, usually found in the bottom parts a stratified storage tank.

Traditional hybrid configurations place the solar water heating panel connections through the bottom of the storage tank, prioritising its efficiency over the heat pump's. Although it may indeed be reasonable during sunny periods, in the event of no or low radiation (common in UK) the reduced heat pump performance may compromise system's efficiency. This happens due the fact that, unlike a gas or biomass boilers, that can operate at flow temperatures as high as 90$^{o}$C, the heat pump maximum operating temperature, 55$^{o}$C, is already close to the minimum temperature allowed in the tank, 50$^{o}$C. Below this value the heat exchangers and radiators inside the properties are unable to deliver heat at the required rate.

The heat pump limitation means that less energy can be stored per m$^3$ of water and therefore moving the heat pump’s connection points towards the top of the tank will have a significant impact on the amount of energy stored and how often it will need to be replenished. Being able to move the heat pump’s connection points depending of expected weather may have a positive impact on system’s performance and will be explored during the simulations.

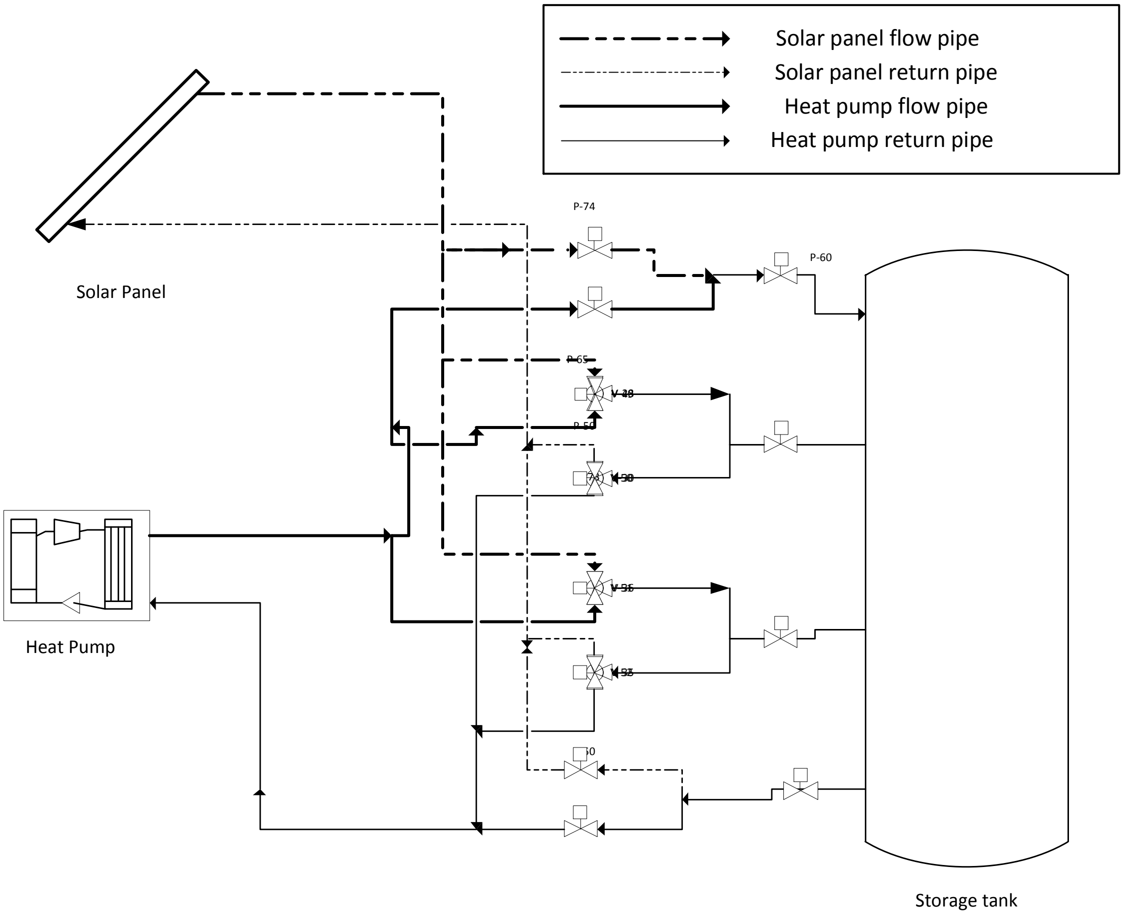


*Figure 36- Dynamic connection layout*

### 5.3.3 The energy system model

Although most of the energy system remains the same, the additional features in the tank and the consequently required controls added considerable complexity to the system as seen at Figure 37.

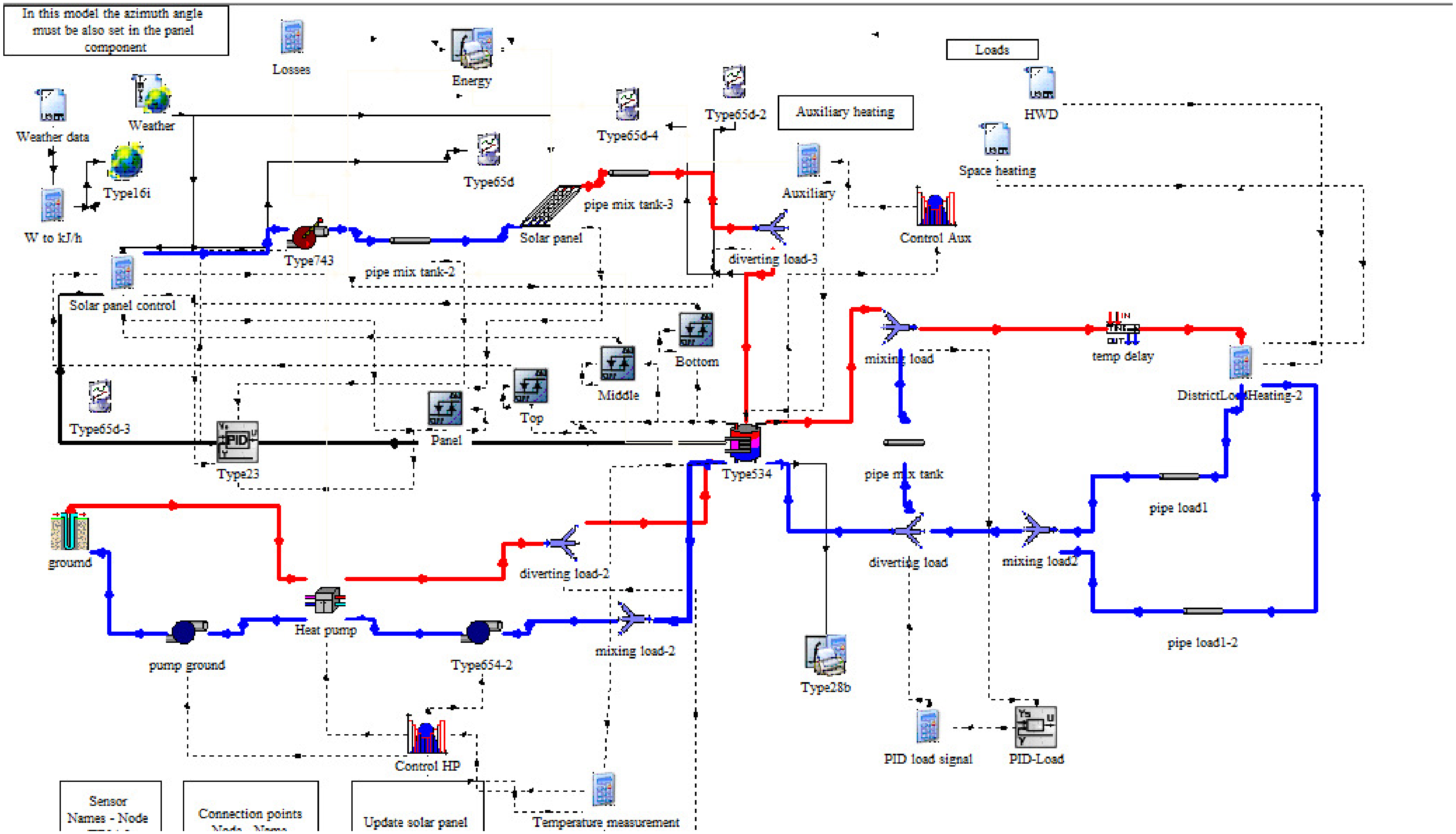


Figure 37 - Case study 3 model

The new elements in the energy system are described below:

### The solar panel model

Utilising the performance data from a popular manufacturer, the TRNSYS model type 538 simulates an evacuated tube solar heating system installed over the energy centre and connected to the heat store. The array size is limited by the amount of roof space available over the energy centre, allowing a 20m$^2$ array to be installed. At 2m$^2$ per property the total area isn't particularly high when compared against typical installation in the UK (CIBSE, 2007) and therefore the simulation won't consider smaller array sizes.

### Immersion electric heater

All simulations include a 10kW electric immersion heater in the upper part of the tank. Unless otherwise stated, it will become active whenever the temperature metered at node 1 is below 50°C, raising it up to 52°C before switching itself off. This heater will act as backup in case the heat pump is not able to maintain tank output temperatures at desirable levels.

### Basic control

Although susceptible to changes as the improvement process starts, the original system control follows the strategy below:

- Heat pump switches itself on whenever the temperature at node 3 (upper part of the tank) is below 50°C
- Once on, the heat pump monitors the temperature at the node above the one connecting the tank to the heat pump's return pipe. The system switches off once the temperature at this node achieves 54°C, providing overheating protection to the unit.
- The solar panel pump is off until the temperature difference between the node in the tank from where it draws water and the water inside the panel is above 8°C.
- Once on, the pump operates until the temperature difference between the points described above reaches 2°C.
- Whenever the temperature at node one (from where water to the load is drawn) drops below 50°C, the 10kW immersion heater is activated. Once this temperature is raised to 52°C the unit is once again switched off.

### ***5.3.4 The design improvement process***

The improvement process aims to reduce $CO_2$ emissions and once again will follow the structure described in the previous case study. Details about each stage are shown below:

**Energy unit sizing**

The fact that the heat pump is the only energy unit in the system able to supply heat on demand is a limiting factor regarding how it can be sized. The heat pump output must supply all the heating demand during winter conditions, assuming no solar participation.

Since the roof area is restricts the size of the solar panels, it will be assumed that the whole $20m^2$ roof space is utilised. This may be reduced in the unlikely event that significant energy surplus is observed.

**System configuration**

A second stage in the iterative process will assess how different system configurations affect the system performance. Both annual performance, generated through the performance assessment tool, and more punctual data, such as heat store's temperature through a typical day, are utilised to identify how the changes affects the system. This information is utilised as guidance regarding possible control improvements.

**Control Improvement**

The control improvement process will focus on the system's ability to change how the energy units are connected to the storage tank. Based on the results from the previous stage, possible control strategies will be defined and implemented. In all cases, reduced $CO_2$ emission is the main objective.

**Design refinement**

The previous stages will give the designer information about how the system reacts to changes into the unit size, control and positioning. The last system improvement stage will utilise this data to define final changes required to achieve an improved system.

### 5.3.5 Result analysis

**Units sizing**

As described in the previous section, the original design assumed the utilisation of two 17kW ground source heat pumps, connected in series to the storage tank, into which a total of 20m$^2$ of evacuated tubes are also connected, as illustrated below.

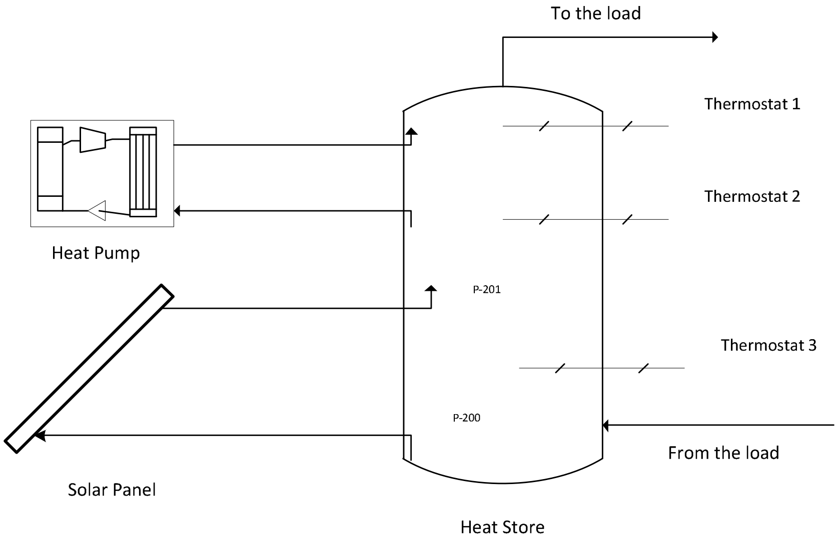
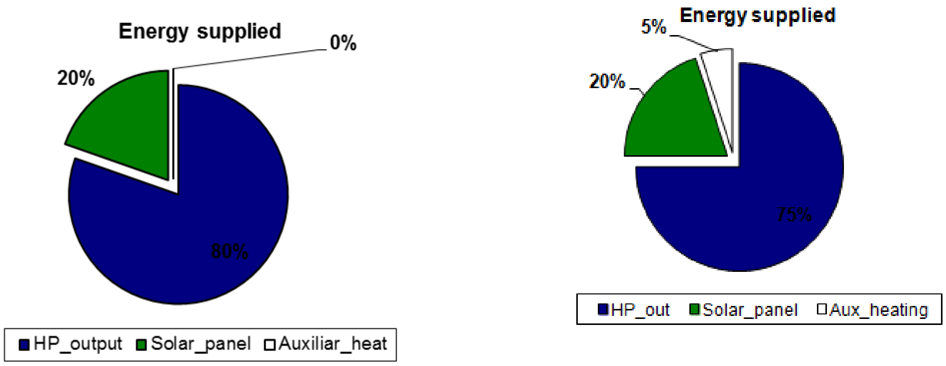


*Figure 38 – Energy system configuration (HP + Solar)*

The first results indicated that the presence of the second heat pump made the system significantly oversized, resulting into substantial cycling even during winter. By reducing the unit size to 17 kW the cycling issue was reduced but, during peak conditions, the 10kW immersion heater became necessary. The performance of both systems can be compared below

| | 2x 17kW Heat Pumps | 1x 17 kW Heat Pump |
|---|---|---|
| **Annual $CO_2$ emission** | *5.2 Tonnes* | *6 Tonnes* |
| **Solar energy converted** | *12 MWh* | *12 MWh* |
| **HP Average COP** | *3.2* | *3.2* |

*Table 4 - System performance - hybrid solar + heat pump*



*2x 17 kW HP system*

*1x 17 kW HP system*

*Figure 39 - Share of energy supplied by each energy unit*

Considering that any emitted $CO_2$ will be offset by photovoltaic panels, 15% more emissions is a significant increase in the total $CO_2$ levels. The two heat pumps solution, on the other hand, may affect the reliability of the units due excessive cycling (as described at case study one). To avoid it, the heat pump and electric heater back up option will be maintained and system configuration and control shall be improved aiming to minimise immersion heater utilisation.

### *Configuration improvement*

Utilising the unit sizes defined in the previous stage, 6 different system configurations were simulated. Overall system performance, generated through the assessment interface tool and more punctual data, such as tank temperature profile through a typical week, are utilised to identify the benefits brought by each arrangement.

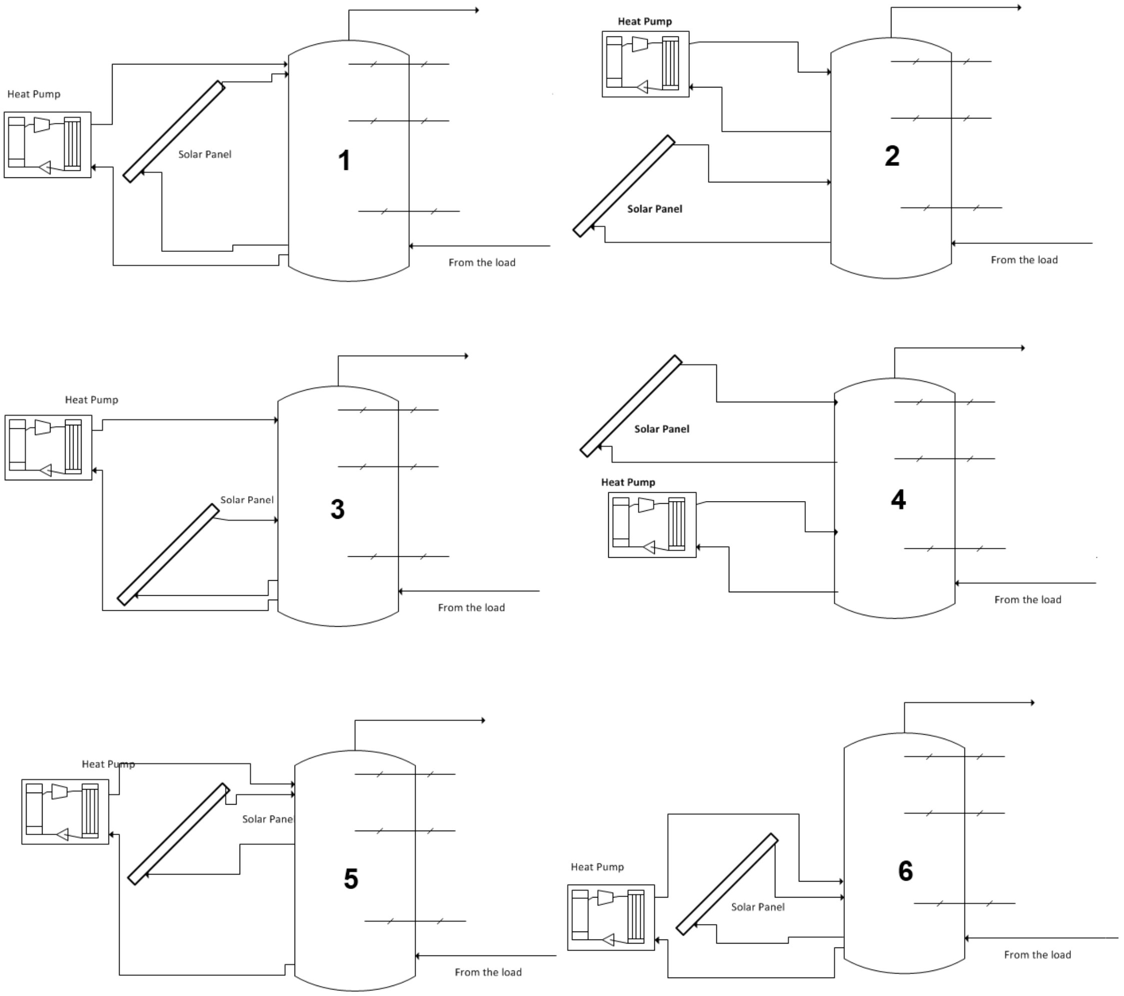


*Figure 40 - Connection points*

**Results discussion**

Focusing on the $CO_2$ emission levels, the results indicated a difference of 6% between the best case (number 6) and the worst (configuration 5). By analysing the tank temperature profile for each case and how it affected the behaviour of the energy units, it became possible to understand which variables contributed towards system efficiency and which reduced it. For example, it was noticed that by placing the heat pump at the top of the tank (configuration 2), the system became able to better react against temperature drops. This is due the fact that, being closer to the top, maintained at about $55^oC$, the temperature of the water circulating through the heat pump's return pipe remained at around $50^oC$. The $5^oC$ temperature rise, defined by the heat pump's rated water flow and power output, was enough to deliver heat at the required temperature as soon as it started to operate. By moving the return pipe towards lower parts of the tank, colder water circulates through the heat pump when it starts to run. It means that the heat pump flow temperature (water leaving the heat pump) will take longer to reach the expected 55°C, resulting into slower reaction time and therefore more frequent intervention from the backup unit.

Another feature observed was that, by placing the heat pump in the bottom part of the tank, it was possible to store significantly more energy. By comparing configuration 2 and 6 it was observed that, at the first, whenever demand was above 17kW, the electric heater had to act. However, with configuration 6, due the larger amount of stored energy, the auxiliary heater was just required during days where the <u>average</u> demand was particularly high, short peaks of demand had no impact on system performance. For the simulated load, the larger storage capacity proved more important than fast reaction to peak conditions. This resulted into configuration 6 presenting the lowest auxiliary heater participation of all the options, which was key to the lower $CO_2$ levels observed.

In all cases, maintaining the outlet feeding the solar panel at the bottom of the tank resulted into higher energy conversion.

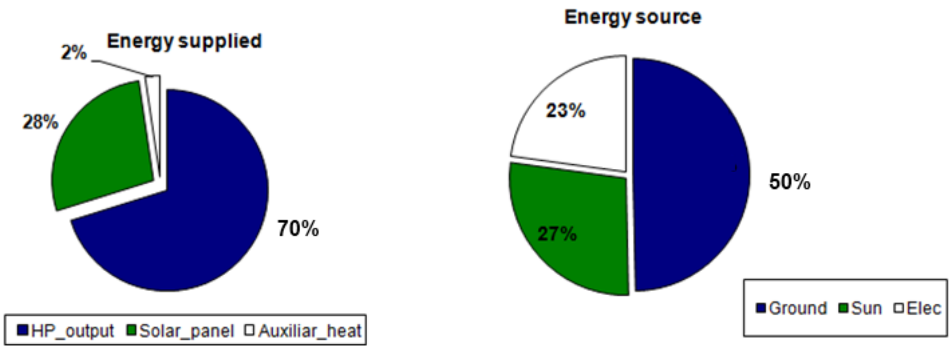


*Figure 41 - Supplied energy by unit and source – Configuration 6*

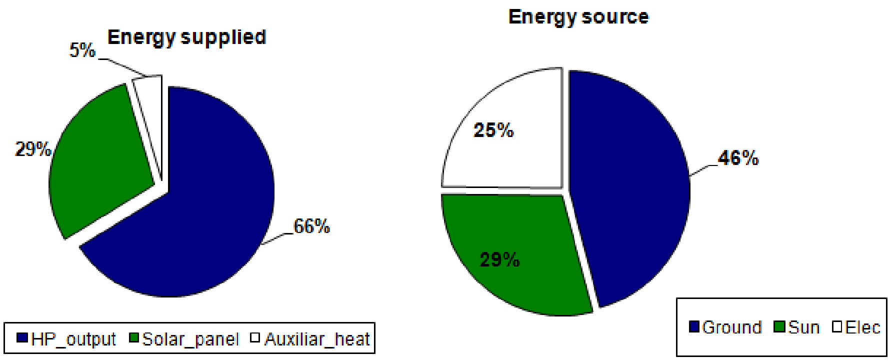


*Figure 42 - Supplied energy by unit and source – Configuration 2*

A natural question would be how sensitive are these solution to changes in the load profile (which could be caused by user behaviour changes resultant from new customers moving into one of the properties, for example). By reducing the peak to 80% from the original value it was observed that more even load profiles, such as the ones seen in continuous heating systems, did not benefit so much from configuration 6, making configuration 2 a better match. On the other hand, if the peak demand was 20% higher, configuration 6 became considerably better than 2. It may be concluded that the system performance is very sensitive to the load profile.

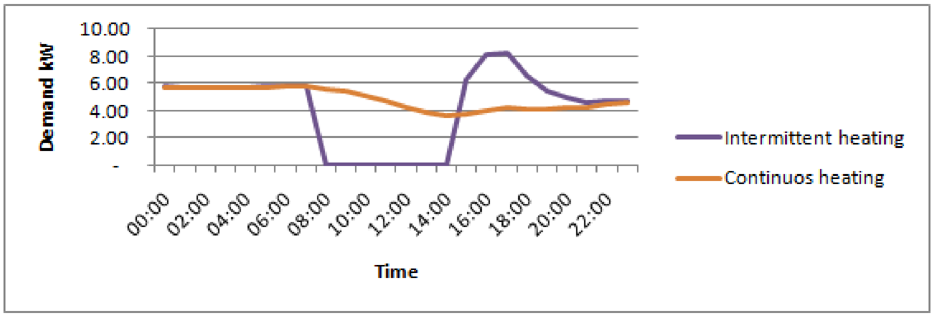


*Figure 43 - Impact of user behaviour in load profile (case study one)*

The next stage in the improvement process will utilise the information gathered in the previous simulations to create a control strategy able to minimise the system sensitivity to changes in the load.

### *Control improvement – Dynamic configuration*

The simulation process at this stage will focus into the control of the motorised valves connecting the energy units to the different connection points in the tank. The objective of the improvement process at this stage is to reduce system sensitivity to load changes and reduce overall carbon emission.

The possible control strategies can be divided into two main groups: the first allows only the flow pipe of the heat pump to move up (or down) through the tank (represented at Figure 44). The second option, which proved to be more efficient, moves both connection points (represented at Figure 45).

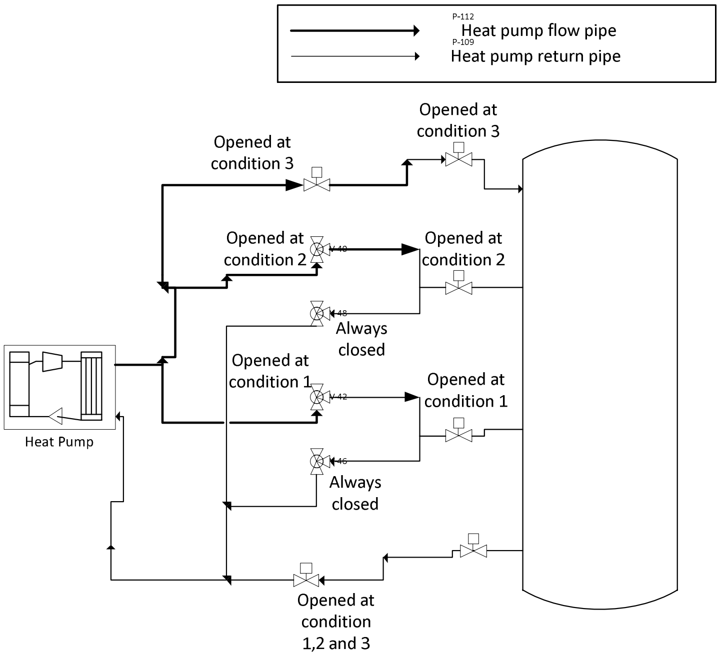


*Figure 44- Dynamic configuration 1*

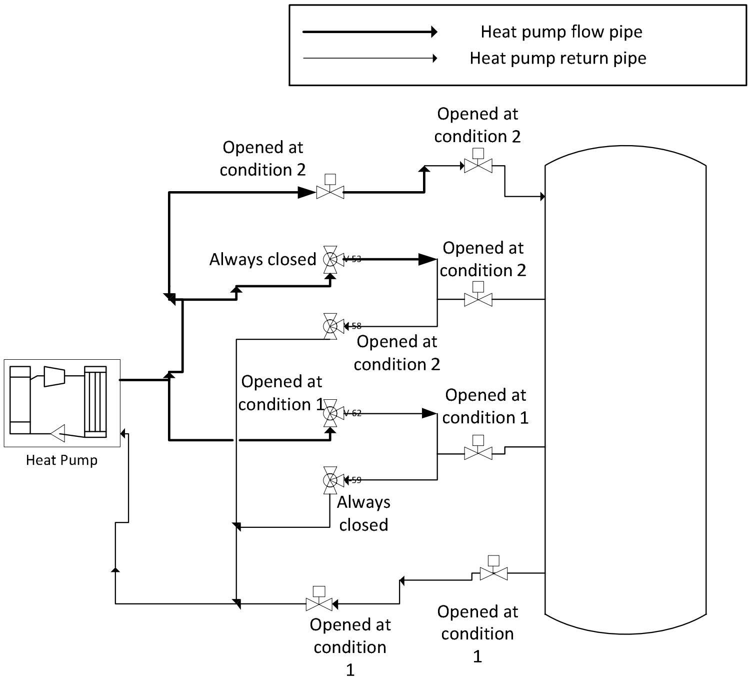


*Figure 45- Dynamic configuration 2*

The best control strategy developed combines the strength from the previous section's configurations 2 and 6. During low demand periods, the energy storage capacity is maximised by moving the heat pump's flow and return pipes towards the bottom of the tank during low demand periods. During high demand periods, the heat pump is moved towards its top, giving the system a better response to sudden temperature drops. The control is described below:

- The solar panel is kept connected at the bottom part of the tank and its pump is activated whenever the differential controller detects a temperature difference above 5°C between the node from where water is drawn and the water in the panel's surface. The system is switched off when this difference drops to 2°C.
- The heat pump is allowed to connect to the tank at two different positions, depending of the "mode" at which it is operating:
    - "Recharge mode": Once at the afternoon and once at evening, periods where lower or no demand is expected, the heat pump connects to the bottom part of the tank, running until the temperature measured at node 7 (middle part of the tank) reaches 55$^{o}$C.
    - "Standby mode": After leaving the recharge mode, the heat pump connects to the top part of the tank, measuring the temperature at node 2. Whenever this point reaches values below 50$^{o}$C, the heat pump is switched on and is kept running until it achieves the temperature of 54°C.

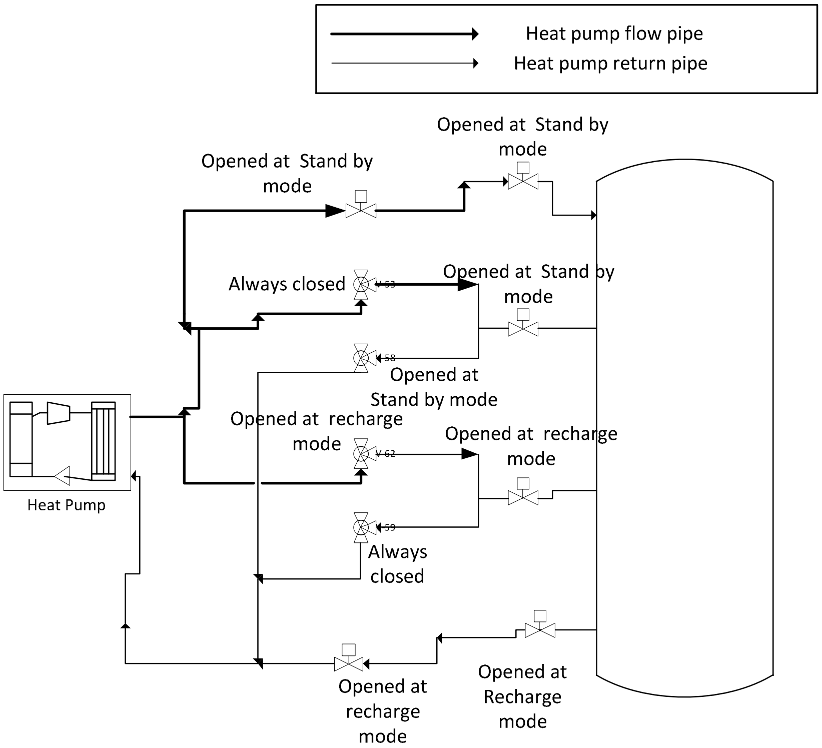


*Figure 46- System configuration during "recharge " and "standby mode"*

Under this configuration the system performance is maintained regardless of changes in the load profile. It was also observed that, although the electric heater participation reduced to virtually zero, the new control had a slight negative impact on how the solar panels perform. The picture below compares the energy supplied by each energy unit at three different system configurations.

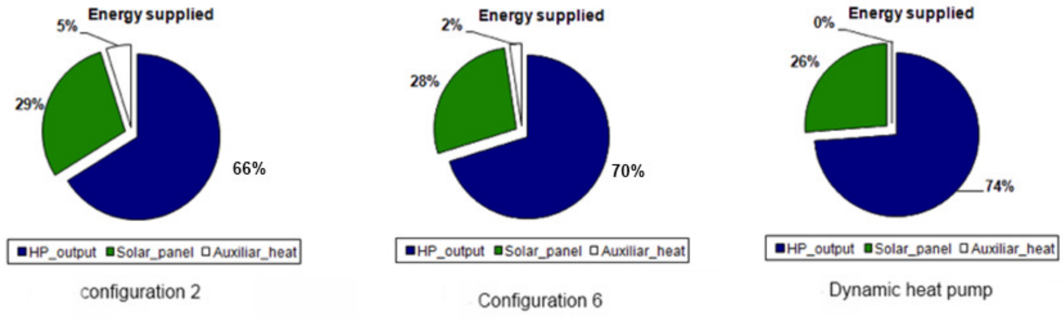


*Figure 47 - Energy units share over the load for each of the simulated design*

The phenomenon observed under the “Dynamic” configuration can be explained by observing the system behaviour at shorter periods of time. In the previous simulations, unless the morning demand happened to be high, the tank would not recharge due the fact that the temperature at higher nodes did not drop enough. The new configuration, on the other hand, maintains the tank average temperature considerably higher due the pre-set recharge times, which ignores the fact that, on a sunny day, one of the recharges may actually not be necessary. This is exactly the issue currently seen in many solar water heating systems within the UK, as described at chapter 3.

The next and last stage will combine the results from the previous one to achieve a final, refined design.

**Design refinement**

Although the design improvement process only considered control strategies that would not change throughout the year, for the studied case it is reasonable to divide the design into two periods: The first, where high level of solar radiation is expected and, therefore, it is sensible to prioritise solar panel performance and a second one, where heat pump performance becomes more important.

Taking this into account, the dynamic control described previously was changed. During the expected high radiation period (Figure 48), the heat pump will be placed into “recharge mode” only once a day, during early evenings.

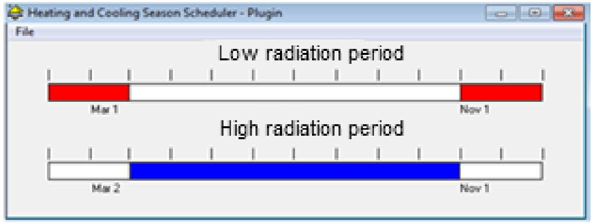


*Figure 48 - Low and high radiation periods*

During the low radiation period, the heat pump behaves as before, recharging the tank twice a day and moving into the “standby” mode during the remaining period.

Because the peaks during this period are considerably lower, having the heat pump mostly at backup mode does not result in a rise on the electric heater unit participation as seen in some of the configurations from previous analysis.

The new system performance can be seen next.

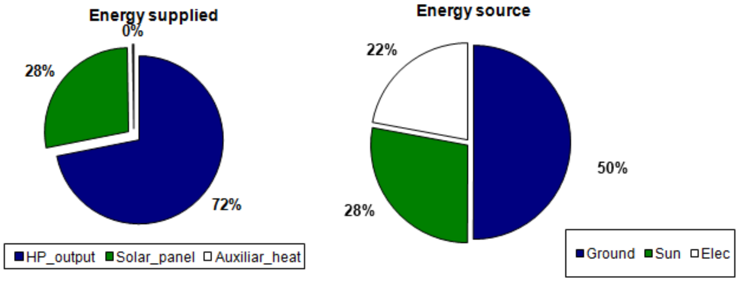


*Figure 49 - New system with seasonal control*

Comparing the results against the configuration without seasonal control it was possible to observe a solar share improvement of about 6% or 700 kWh. Comparing it against the solution presented during the unit sizing stage, the total $CO_2$ reduction is around 13%, as shown in the table below:

| | **CO2 emission** | **HP COP** |
|---|---|---|
| **Dynamic connection and season optimised control** | 5100 kg | 3.3 |
| **Dynamic connection no season optimised control** | 5250 kg | 3.2 |
| **Static connection and no season optimised control** | 5900 kg | 3.2 |

*Table 5- System performance in different configurations*

### 5.3.6 Simulation review

Dynamic simulation proved to be a powerful tool for system improvement. Although the original design, considered here at the feasibility stage, defined the direction the system should follow, the extra flexibility and amount of variables that could be analysed by a software like TRNSYS allowed not just a 13% $CO_2$ emission reduction but also improved system reliability by reducing its sensitivity to load changes.

Although the final configuration may be too complex to be applied at individual residential systems, it does provide valuable information that can still be utilised by manufacturers and installers. One example is the improvement brought by changing the heat pump "recharging" behaviour between summer and winter periods when connected to hybrid systems where solar water panels are present.

# 6. Conclusion

Under the current stringent energy efficiency legislation environment, hybrid energy systems are powerful tools in the challenge of achieving high renewable targets without compromising system reliability and user experience. This dissertation identified a number of common problems in the design of traditional hybrid energy systems which could have been either solved or avoided if appropriate design methodology and tools were utilised in the early stages of the project. A key issue identified was the utilisation of simplified energy system modelling tools to analyse systems where the large amount of renewable energy actually requires the use of detailed simulation tools, as they can cope with volatility of renewable energy supplies and the mixing of different quality (temperature) thermal sources with a thermal buffer, common in many hybrid systems.

It was recognized that one of the main challenges in the adoption of detailed energy system modelling as part of a design process is the amount of time required building such systems. This observation lead to the creation of a design methodology divided into two stages. The first utilises simplified energy system design tools to filter the possible solutions that may be taken to a more time consuming stage, the detailed modelling one. During the detailed modelling stage a detailed model of the energy system is created and taken through the proposed iterative process (figure 49) to improve system performance.

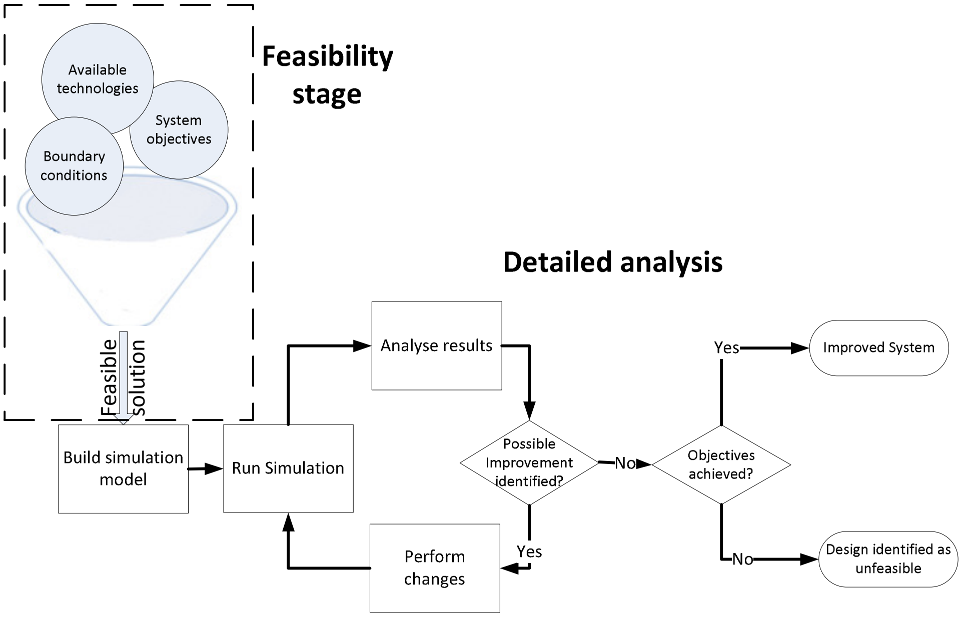
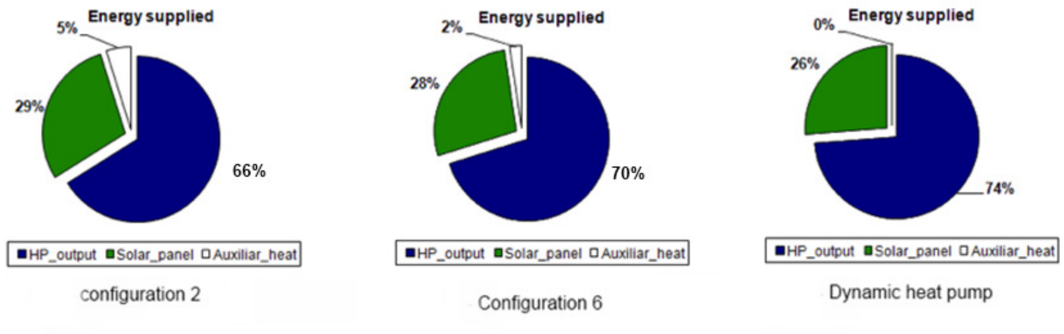


*Figure 50 - Utilised methodology*

To further simplify the design process a performance assessment tool, able to translate the time series generated during detailed simulation into a format that the designer can easily understand, was also created.



configuration 2

Configuration 6

Dynamic heat pump

*Figure 51 - Example of three different designs compared through one of the performance assessment tool output*

The detailed energy system design methodology was applied to three designs originally created through simplified energy system design tools. The findings and benefits brought by application of detailed modelling in such systems are observed next.

## 6.1 Heat pump system sizing and control optimisation

The proposed methodology was utilised in the process of sizing a typical residential heat pump system in the UK.

Through the application of detailed simulation and the proposed methodology, it was observed that current standards, based on steady state analysis, do not consider the impact that the customer behaviour and expectation should have in the system design. The dynamic simulation showed that a mismatch between what is being sized and how the system is used can result into overpriced energy systems and reduced life expectancy.

Additionally, the detailed model suggests that the operation strategy that best matches the design resultant from current standards isn’t the same identified by the Energy Saving Trust’s trial as the one passed to the customers. The detailed analysis highlighted how this mismatch affects both customer experience and system reliability.

## 6.2 The biomass and heat pump system

The detailed analysis of a hybrid biomass boiler and a ground source heat pump system highlighted the fact that the original design, made with a simplified energy system design tool, overlooked the influence that the different energy units' operational temperatures could have into the energy system performance. The dynamic simulation revealed that the original units' size and control parameters did not allow the appropriate utilisation of the heat pump and, therefore, achievement of pre-defined operation targets.

After a series of improvements the final design was able to meet all the pre-defined targets and also made the system flexible to eventual objective changes (such as, for example, lower running costs or $CO_2$ emissions).

## 6.3 The ground source heat pump and solar water heating system

The detailed simulation process also allowed the development of a series of designs able to improve the efficiency and reliability of a hybrid heat pump and solar water heating system. It was observed that by taking advantage of the storage tank stratification and conditioning the control system to the weather conditions, it is possible to achieve $CO_2$ emissions up to 13% below more traditional designs. The iterative process also showed that by changing the position at which the heat pump connects to the storage tank based on expected demand and solar radiation, it is possible to significantly reduce the required heat pump size and system sensitivity to changes into the load. This would be impossible to achieve without appropriate use of detailed simulation.

## 6.4 Detailed simulation importance into the design of hybrid systems

The three case studies confirmed what was presented in the first chapters: the high sensitivity to environmental conditions makes the utilisation of detailed energy system design tools a necessity when improving a hybrid system design. This constitutes a challenge to the current market. New methodologies and tools compatible with the requirements of the new systems must be introduced and made mandatory. Ignoring such fact will have a negative impact in the adoption of hybrid systems with high renewable penetration due bad performance resultant from the limitations imposed by the chosen design methodology and, therefore, bad design.

## 6.5 Future work

It was recognised that developing a detailed dynamic simulations to every single new project may be commercially unfeasible. The development and utilisation of the system performance interface tool was a good step towards minimising this challenge. The next step may be to, once the design process described at chapter three reaches its final stage, convert the resultant design into a template with friendlier user interface and pre-set back ground data. Future designs may then start from this template and apply minimal adjustments as required.

The energy system dynamic design presented at chapter five, combining a heat pump and a solar water heating panel, resulted into a very robust system but with potentially complex implementation. An interesting future work would be to analyse how feasible is the implementation of such system in smaller residential applications where the heat pump could cycle between top and bottom coils in a hot water tank depending of the expected demand. The success of such analysis would be of great value towards the uptake of both technologies in the residential market and could potentially minimise problems such as the ones described at chapter three.

The design developed during case study one should be extended to different property types and weather conditions. The results could have significant impact into how heat pump systems should be sized in the United Kingdom. Current methodology defined by MCS standard (DECC, 2010) utilises steady state values and particularly low external design temperatures. As mentioned in the study, this may be leading to either oversized systems and/or future reliability issues.

Finally, once the energy systems that originated the designs here presented are finalised, a validation process may take place and would be of great value towards the design of similar future hybrid systems.

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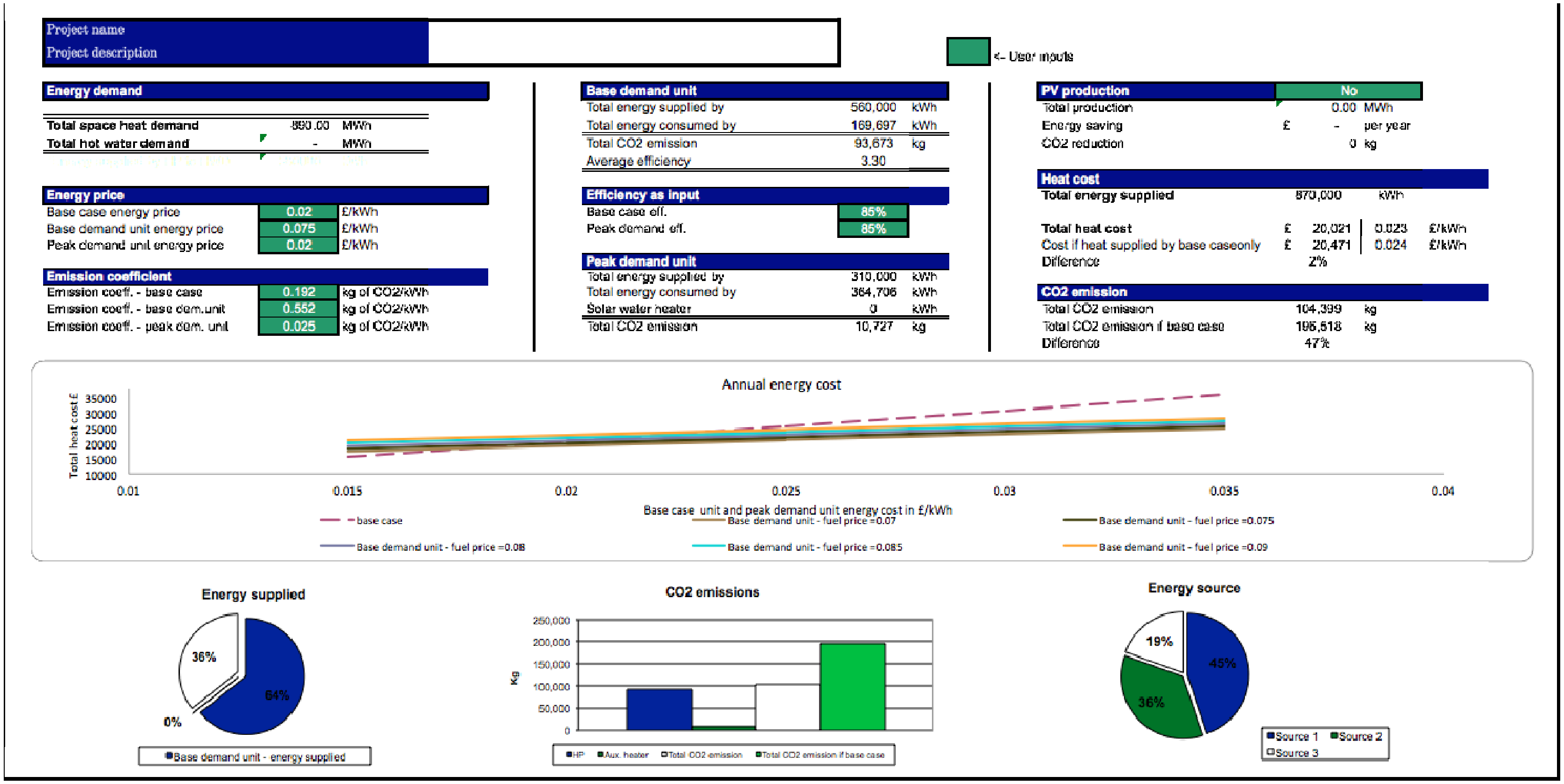
# Annex 1 – System performance interface



Project name

Project description

🟩 <- User inputs

**Energy demand**

| | | |
|---|---|---|
| **Total space heat demand** | 890.00 | MWh |
| **Total hot water demand** | - | MWh |

**Energy price**

| | | |
|---|---|---|
| Base case energy price | 0.02 | £/kWh |
| Base demand unit energy price | 0.075 | £/kWh |
| Peak demand unit energy price | 0.02 | £/kWh |

**Emission coefficient**

| | | |
|---|---|---|
| Emission coeff. - base case | 0.192 | kg of CO2/kWh |
| Emission coeff. - base dem.unit | 0.552 | kg of CO2/kWh |
| Emission coeff. - peak dem. unit | 0.025 | kg of CO2/kWh |

**Base demand unit**

| | | |
|---|---|---|
| Total energy supplied by | 560,000 | kWh |
| Total energy consumed by | 169,697 | kWh |
| Total CO2 emission | 93,673 | kg |
| Average efficiency | 3.30 | |

**Efficiency as input**

| | |
|---|---|
| Base case eff. | 85% |
| Peak demand eff. | 85% |

**Peak demand unit**

| | | |
|---|---|---|
| Total energy supplied by | 310,000 | kWh |
| Total energy consumed by | 364,706 | kWh |
| Solar water heater | 0 | kWh |
| Total CO2 emission | 10,727 | kg |

**PV production** No

| | | | |
|---|---|---|---|
| Total production | | 0.00 | MWh |
| Energy saving | £ | - | per year |
| CO2 reduction | | 0 | kg |

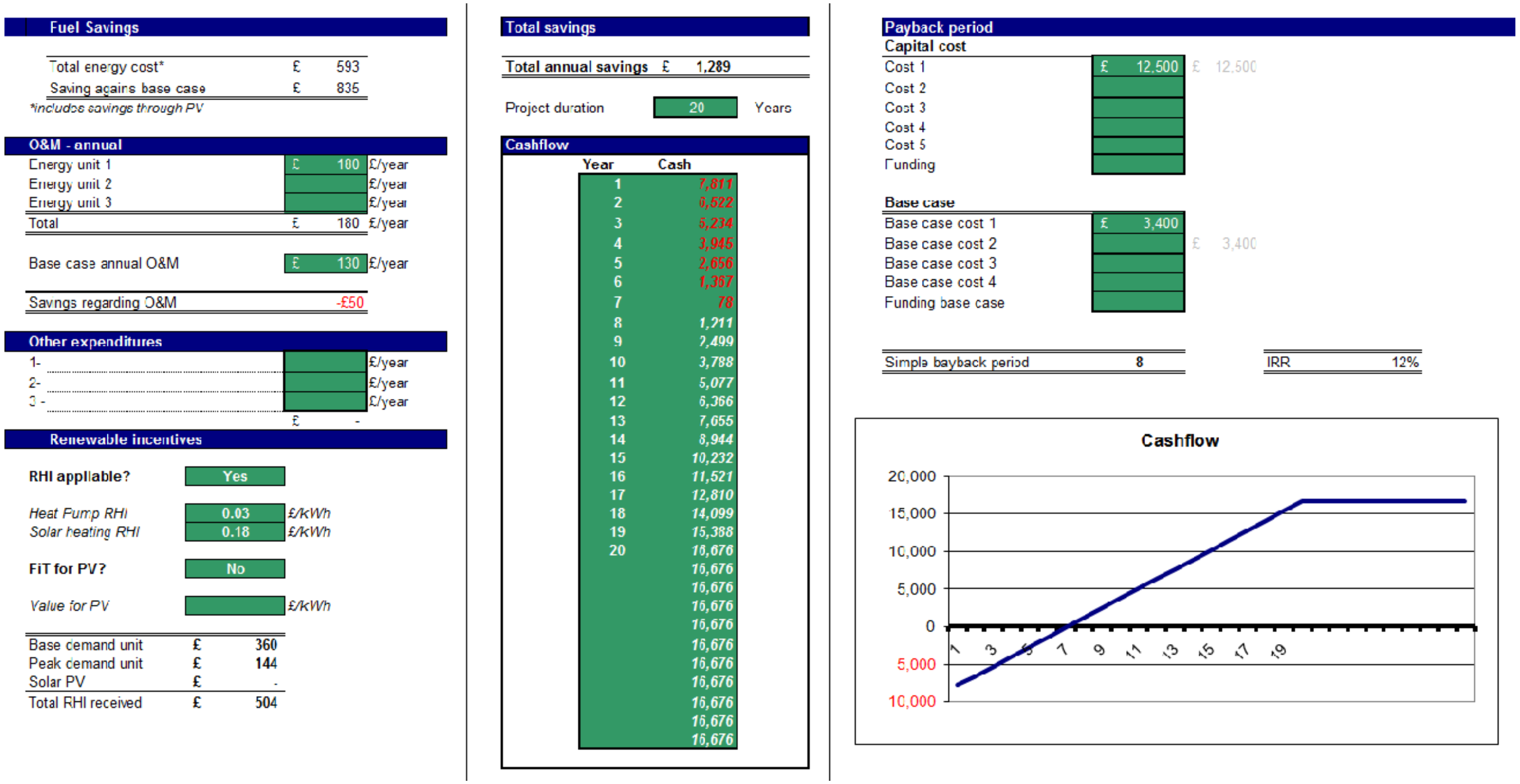
**Heat cost**

| | | | | |
|---|---|---|---|---|
| **Total energy supplied** | | 870,000 | kWh | |
| **Total heat cost** | £ | 20,021 | 0.023 | £/kWh |
| Cost if heat supplied by base caseonly | £ | 20,471 | 0.024 | £/kWh |
| Difference | | 2% | | |

**CO2 emission**

| | | |
|---|---|---|
| Total CO2 emission | 104,399 | kg |
| Total CO2 emission if base case | 195,518 | kg |
| Difference | 47% | |

# Annex 2 – Financial analysis interface



**Fuel Savings**

| | | |
|---|---|---|
| Total energy cost* | £ | 593 |
| Saving agains base case | £ | 835 |

**includes savings through PV*

**O&M - annual**

| | | | |
|---|---|---|---|
| Energy unit 1 | £ | 100 | £/year |
| Energy unit 2 | | | £/year |
| Energy unit 3 | | | £/year |
| Total | £ | 180 | £/year |
| Base case annual O&M | £ | 130 | £/year |
| Savings regarding O&M | | -£50 | |

**Other expenditures**

| | | | |
|---|---|---|---|
| 1- | | | £/year |
| 2- | | | £/year |
| 3 - | | | £/year |
| | £ | - | |

**Renewable incentives**

| | | |
|---|---|---|
| **RHI appllable?** | Yes | |
| *Heat Pump RHI* | 0.03 | £/kWh |
| *Solar heating RHI* | 0.18 | £/kWh |
| **FiT for PV?** | No | |
| *Value for PV* | | £/kWh |

| | | |
|---|---|---|
| Base demand unit | £ | 360 |
| Peak demand unit | £ | 144 |
| Solar PV | £ | - |
| Total RHI received | £ | 504 |

**Total savings**

| | | |
|---|---|---|
| **Total annual savings** | £ | 1,289 |
| Project duration | 20 | Years |

**Cashflow**

| Year | Cash |
|---|---|
| 1 | 7,811 |
| 2 | 6,522 |
| 3 | 5,234 |
| 4 | 3,945 |
| 5 | 2,656 |
| 6 | 1,367 |
| 7 | 78 |
| 8 | 1,211 |
| 9 | 2,499 |
| 10 | 3,788 |
| 11 | 5,077 |
| 12 | 6,366 |
| 13 | 7,655 |
| 14 | 8,944 |
| 15 | 10,232 |
| 16 | 11,521 |
| 17 | 12,810 |
| 18 | 14,099 |
| 19 | 15,388 |
| 20 | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |
| | 16,676 |

**Payback period**

**Capital cost**

| | | | |
|---|---|---|---|
| Cost 1 | £ 12,500 | £ | 12,500 |
| Cost 2 | | | |
| Cost 3 | | | |
| Cost 4 | | | |
| Cost 5 | | | |
| Funding | | | |

**Base case**

| | | | |
|---|---|---|---|
| Base case cost 1 | £ 3,400 | | |
| Base case cost 2 | | £ | 3,400 |
| Base case cost 3 | | | |
| Base case cost 4 | | | |
| Funding base case | | | |

| | | | |
|---|---|---|---|
| Simple payback period | 8 | IRR | 12% |