A guide to specifying biomass heating systems
FOREST stands for “Fostering Efficient long term Supply partnerships”. The project is funded by the European Commission through Intelligent Energy Europe (IEE). For more information about FOREST please see the website at www.forestprogramme.com.
Introduction
Designing a complete biomass heating system requires an in depth knowledge of each of the component systems. Successful biomass installations depend on careful calculations of heat load and must take into account a host of site specific features, so every biomass system is different. In addition, regulatory requirements and incentives can vary nationally and regionally so what works in one case may not work in another.

The aim of this guide is to provide those considering biomass with enough information to help them to ask the right questions, and to persuade those who aren’t to consider the wider range of possibilities that can make biomass an effective and cost efficient source of low carbon heat.
Biomass heating – a system of systems

Implementing a biomass heating solution for a particular site or client is a potentially complex procedure. The simplest conventional ‘wet’ heating systems consist of a boiler (typically oil or gas) and a distribution system (most often radiators). With a biomass heating system there are a choice of boilers and fuels, and although these can often be integrated with an existing distribution system, a number of additional components are required for the system to perform optimally. These will include fuel storage and handling, additional boilers, options for thermal storage and a facility for ash extraction. For this reason we rarely speak of a biomass boiler in isolation and prefer instead to refer to a biomass system.

The majority of the components in a biomass system are interconnected and overall system performance will depend on providing components that are compatible and suited to the heat requirement of the site. It is not uncommon for the responsibility for different systems to lie with more than one provider, and under these circumstances there is a greater risk of problems arising.

Where sufficient expertise is available, one option is to engage a single provider who can provide a ‘turnkey’ solution, taking responsibility for all aspects of design and installation. Additionally Energy Service Companies or ESCOs can undertake the operation and maintenance of the system under a heat supply contract. Such providers are a major feature of advanced biomass markets and provide an effective means of managing the risk associated with large or complex projects. For more information on common partnering arrangements within the biomass sector please the associated FOREST guide ‘Partnerships for Success’.

In a less developed market there may be fewer experts with knowledge of the whole system and ESCOs may be harder to find, so another approach is required which has much in common with ‘Systems Engineering’. This approach treats the installation as a ‘system of systems’ (Figure 1) and is common in large or complex projects. In order to specify a system it is not necessary to have a detailed understanding of each sub-system, it is however important to understand the relationships between each of the components and to ensure that the provider responsible for each sub-system has relevant information on dependent systems.

The FOREST project aims to promote partnership working in the biomass supply chain (Figure 2) as a means to developing more effective and integrated approaches to biomass heating, particularly in the developing markets. The success of many systems is decided during the system design stages and the

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Figure 1, Biomass heating as a system of systems

The importance of a holistic approach cannot be underestimated. Within the scope of this guide it is not possible to cover every detail of system design, however it is expected to:

- Raise awareness of the principles of systems design
- Provide illustrative examples of the technology and design of biomass systems
- Highlight examples of best practice

There is considerable variation across the European regions in the roles of the various professionals who design, install and operate biomass systems. Similarly, regulations governing planning, buildings and the provision of financial incentives and support are far from being standardised, yet the interaction between components and physical processes are the same and much can be learnt from studying successful installations and the process of development.

In this guide an overview of the project life cycle is presented with respect to stages of a biomass installation. This is followed by a description of key components in a biomass system and how they may be suited to operation in different environments and at different scales.

**The project life cycle**

It is useful to consider the stages of a biomass project and to highlight the activities which need to take place during each phase in the cycle. These can be summarised as:

- Project concept
- Project definition
- Implementation
- Handover
- Operation

The following sections highlight the kinds of activity that can be expected to be carried out at each stage. More detail on the nature of biomass combustion and system components can be found in the subsequent sections.

**Project concept phase**

In the context of a biomass system this represents an initial assessment of the feasibility of biomass as a solution for a given site or sites. Where experience of biomass is limited it can be tempting to base design decisions on what has worked elsewhere, but this is not recommended. Each biomass system is different, and to be successful each element needs to be designed to match the characteristics of the site.

The amount of effort undertaken at this stage is a good indication of the likelihood of success; mistakes made in the early stages are likely to have
considerable cost implications later so it is worth taking time to consider the options carefully.

To avoid excessive costs in the early stages this process can be divided into two stages; a pre-feasibility stage where inappropriate sites are filtered out as early as possible, and a more detailed feasibility study which aims to quantify some of the key variables to provide a better test of suitability (Table 1).

If answers to these questions are unclear or unknown, professional guidance should be sought. At the end of this phase the aim should be to make a decision on whether biomass is a viable heating solution for the site.

**Project definition phase**

During the project definition the practical technical and financial details of the system will be further developed. Earlier work undertaken in the feasibility stages should provide the basis for a more informed dialogue with specialist providers.

Key design decisions including the boiler capacity and type of fuel will need to be taken as these affect all other aspects of the system and will need to be made on a clear understanding of the quantity of heat and the pattern of demand on the site.

Identifying issues that could affect the implementation or operation of the system in the early phases can save time and money later and while technical work will often be carried out by expert biomass system designers, it can be hard for an outsider to consider the full range of activities that take place on or near the site. For example if there are dates or times where fuel deliveries cannot be made, or there areas which are sensitive to noise or vehicle movements, these could affect design decisions. It can therefore be useful at this stage to consult with project stakeholders, who can provide useful feedback to specifying clients and system designers. A stakeholder could be anyone affected by the decision to install biomass; this could include site managers, maintenance staff, and building occupants. Individuals and businesses neighbouring the site may also be consulted as they can be affected, for instance by fuel deliveries, which can involve additional vehicle movements or noise.

Good system design is often arrived at through an iterative process, with successive designs being trialled with stakeholders until the requirements of the building, and the people around it, can be met. Competitive tendering can complicate this kind of dialogue, as consulting with providers could be seen as offering an unfair advantage. Only in cases where the system specifier is experienced, should providers be offered a detailed design on which to tender.

However where there is less experience of biomass or the site is complicated, it can be beneficial to tender in stages, based on a detailed description of the requirements at the site. The aim is to allow the technical experts to provide a range of solutions, and selecting the best to go forward to the next stage. This allows for a wider range of solutions to be considered and increases the chance of finding the one that is most suitable for the site.

By the end of this phase the specifying client will have clear picture of the appropriate technical solution and the financial viability of the system proposed.
Examples of pre-feasibility considerations:

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the heat load and pattern of demand at the site suited to a biomass system?</td>
<td>Biomass boilers work most efficiently when they can run at close to their operating capacity for extended periods. Sites with low heat demand or where loads are highly variable will need more careful consideration.</td>
</tr>
<tr>
<td>Is there a suitable fuel supplier in the area?</td>
<td>Access to high quality fuel, preferably from a range of suppliers, is vital. Comprehensive fuel standards exist to ensure that boilers are fed properly. Poor quality or incorrectly specified fuel is a common cause of faults in biomass systems.</td>
</tr>
<tr>
<td>Is there space to accommodate the boiler, thermal store and fuel store?</td>
<td>Biomass boilers are considerably larger than their fossil fuelled counterparts and thermal storage and ancillary equipment will also require space. Wood fuel is less energy dense than oil or coal so there also needs to be sufficient space for storage.</td>
</tr>
<tr>
<td>Is there good access to the site for delivery vehicles and space for them to turn and manoeuvre?</td>
<td>The size and type of vehicle will depend on the fuel that is specified, while the number of deliveries will depend on the energy density of the fuel, the size of the fuel store and the heat demand of the site.</td>
</tr>
</tbody>
</table>

Examples of feasibility considerations requiring more detailed investigation and/or specialist advice:

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>What size boiler will be required?</td>
<td>Boiler sizing is critical and has implications for every other element in the system. Oversized boilers run less efficiently and have higher emissions levels and will add significantly to the project costs.</td>
</tr>
<tr>
<td>How much space is needed for the plant room?</td>
<td>Using existing buildings can help to keep project costs down but allowance needs to be made for thermal storage, additional pipework and, in some cases, an additional boiler for peak lopping. Biomass equipment must also be maintained regularly so enough space must be left for routine tasks such as ash handling and cleaning.</td>
</tr>
<tr>
<td>How much space is needed for fuel storage?</td>
<td>This will depend on the size of the boiler, the type of fuel, capacity of delivery vehicles as well as the heat demand on site. Undersized fuel stores with difficult access can limit the options for fuel supply and will increase the frequency of deliveries to the site.</td>
</tr>
<tr>
<td>What will be the requirements for the flue?</td>
<td>Regulations regarding the position, size and height of flues ensure the free dispersion of flue gases and ensure there is no fire risk.</td>
</tr>
<tr>
<td>Is the boiler in an air quality management area?</td>
<td>Areas where air quality is a concern may place restrictions on the type of equipment that can be installed or on acceptable levels of emissions.</td>
</tr>
<tr>
<td>Can all statutory requirements be met?</td>
<td>Compliance with building regulations and planning regulations may need to be considered as well as environmental permitting.</td>
</tr>
<tr>
<td>Is the system financially viable?</td>
<td>The capital cost of biomass boilers is generally higher than fossil fuel boilers, and project costs can quickly escalate with the additional fuel handling equipment and fuel storage. However boilers can last 20 to 25 years and lower unit prices for wood fuel mean that the full lifecycle cost of a biomass system may be cheaper.</td>
</tr>
<tr>
<td>Are grants or other incentives or available?</td>
<td>Low carbon heating technologies such as biomass can be eligible for a range of financial incentive as well as having environmental and social benefits which can also have an impact on the decision to install.</td>
</tr>
</tbody>
</table>

Table 1: The project concept or feasibility stage
Implementation phase
During this phase contacts are awarded and works are carried out. While the design and specification work may have been done there are a number of roles that a specifying client may continue to fulfil.

It is important to maintain communication between the whole range of supply chain providers who are delivering the project. The interconnection between components in the biomass system means that any changes to the specification can have affects elsewhere. Regular site meetings and close contact with contractors and stakeholders will ensure that any modifications to the system design are considered properly and do not adversely affect the capability of the system or its stakeholders.

This phase ends with the commissioning of the boiler.

Handover phase
Once the system is commissioned the system is handed over to the user or the operator.

Modern biomass systems are clean and efficient, however the learning curve for new owners can be steep where there has been no previous experience of biomass or solid fuels. An important part of the handover process is to ensure that operators receive training in all aspects of operation and basic maintenance such as emptying ash bins, cleaning, and simple fault finding.

Operation phase
Once the system is left to the client there is inevitably a period of familiarisation with the system. Operatives will gain insight into the way the system responds under different loads or to slight variations in fuel quality.

A period of monitoring to ensure that the system is behaving as expected is highly recommended. Ensuring that the new system integrates as expected with existing building management systems and secondary boilers is important and fuel quality and quantity, heat output and ash volumes can all be easily monitored.

Monitoring these performance and cost indicators will also be a good early indicator of any problems within the system.
Biomass combustion systems

Biomass combustion is the main technology route for bioenergy and is responsible for over 90% of the global contribution to bioenergy. The selection and design of a biomass combustion system is determined by a number of factors including:

- The characteristics of the fuel to be used;
- The energy capacity and pattern of demand to be met;
- The costs and performance of the equipment;
- Local legislation relating to buildings and the environment.

A biomass system usually consists of the following components:

- Biomass boiler
- Fuel storage
- Chimney
- Hydronic distribution system for the hot water produced by the boiler
- Hydronic discharge systems (floor heating or radiators)
- A central control device with an outdoor temperature sensor

In biomass heating systems, the fuel is transported from the storage facility to the combustion chamber, where it is combusted. A fan is installed to improve the heat transfer and supply sufficient air for an optimal combustion. The flue gas from the combustion process passes through a heat exchanger and transfers its energy to water. A circulation pump transports the heated water through the distribution system. To reduce heat losses to the boiler room, the boiler and all pipes should be highly insulated.

Some of the features of a modern biomass heating include:

- High fuel efficiency (80-90%)
- Ultra low emissions
- Fully automatic operation (automatic ignition and shutdown, fuel supply, ash removal, heat exchanger cleaning)
- Very high operation and fire safety standards
- Low fuel costs

Modern systems utilize a two stage combustion process in order to combust the fuel as completely as possible. In the primary combustion zone, which is located on the grate, the drying and solid combustion takes place. Volatile gases are released and burned with air in the secondary combustion zone.

The two-stage combustion process results in complete combustion and very low emissions of particulates because of the absence of unburned hydrocarbons in the flue gas. The particulate matter from the system is primarily inorganic, while emissions from lower technology stoves are mostly unburned organics.
There are mainly three types of burner that vary according to the orientation of their fuel feeds (Figure 4):

- **Horizontal feed burners**: the combustion chamber is either fitted with a grate or a burner plate. The fuel is introduced horizontally into the combustion chamber. During the combustion, the fuel is pushed or moved horizontally from the feeding zone to the burner plate or grate. Both woodchips and pellets can be used.
- **Underfeed burners** (under feed stoker or underfeed retort burners): the fuel is fed into the bottom of the combustion chamber or retort. These burners are most suited for fuels with low ash content such as wood chips with low moisture content or wood pellets.
- **Stepped or moving grate**: designed for larger boilers and low quality, high moisture fuel. The wet fuel arrives at the top of an inclined, reciprocating grate and is shuffled toward the combustion zone, getting drier as it makes its way down.

**Horizontal feed burner**
1. Air blower
2. Air chamber
3. Fuel in
4. Fuel feed auger
5. Drying chips
6. Burning chips
7. Ash
8. Ash pan
9. Combustion chamber
10. Flue

**Underfeed burner**
1. Secondary air
2. Burning wood
3. Drying wood
4. Primary air
5. Fuel feed auger

**Stepped grate burner**
1. Water jacket
2. Flue
3. Combustion chamber
4. Ceramic arch
5. Secondary air
6. Fuel feed auger
7. Primary air
8. Reciprocating grate
9. Drying chips
10. Burning chips
11. De-ashing screw
12. Doors
13. Second pass tubes
14. Third pass tubes

*Figure 4, Selected burner types (after R. Landen)*
Top feed burners may also be found in small scale units developed for pellet combustion. The fuel falls through a shaft onto a bed of fire consisting of either a grate or a retort. The feeding system and the fire bed are separated which makes it an effective protection against burn-back into the storage. The ash is removed mechanically by a dumping grate or manually.

**Choosing the right fuel**

The key fuel characteristics of biomass fuels are energy density, moisture content, particle size and ash properties. Fuels are chosen in order to fulfil the technological and ecological requirements of the combustion technology and the most suitable combination of fuels and technologies can vary from case to case.

In general low quality fuels demonstrate inhomogeneous characteristics including high moisture content, variable particle size, and poor ash-melting behaviour. Such fuels tend to be used in large scale systems, while higher quality fuels are necessary for small scale systems. This is due to the complexity and robustness of the fuel feeding systems, the combustion technology and the management of emissions, all of which require economies of scale to be economically viable.

The majority of biomass systems burn wood chips or wood pellets although agricultural residues and energy crops such as miscanthus and short rotation coppice based on willow or poplar are also used. While some boilers are designed to take a range of fuels, others are more particular and regular switching between fuels is not practical as combustion settings have to be adjusted to cope with the different burning characteristics.

Low grade wood chips can have a moisture content of 50% or more and will have a relatively low energy density (630-860 kWh/m³ depending on species) while high grade chips will be expected to be around 30% moisture content (690-930 kWh/m³). High quality wood pellets will be expected to be less than 10% water and will have an energy density of around 3100 kWh/m³.

Key considerations will therefore be how much fuel storage is needed on site and how the fuel will be delivered. A range of vehicles including lorries, tankers and tractors may make fuel deliveries and fuel suppliers should be consulted early on to provide assurance that deliveries to the site will be possible. Sites with lower or intermittent heat loads and limited space may opt for pellets, while non-domestic sites and those with ample space and larger heat loads are likely to find wood chips more economical.

Boiler manufacturers will specify which fuels are suitable for each appliance according to pre-defined standards. European or national Standards may be quoted and will govern all aspects of the fuel characteristics including energy density, moisture content, particle size and distribution. Using incorrect or out of specification fuel can cause the system to operate poorly and will eventually lead to system failure.

A separate FOREST publication, ‘A guide to biomass standards’ is available from the FOREST website. It includes information on standards for fuel and equipment.
**Boiler sizing**

Fossil fuel boilers (particularly gas boilers) have the ability to modulate their output to cope with different levels of demand. For this reason they are often oversized so that the risk of failing to get up to temperature is minimized. Biomass boilers are less responsive and if oversized will tend to turn on and off frequently in a process known as cycling. This is bad for a number of reasons and can lead to:

- Poor quality combustion;
- Lower efficiency;
- Higher emissions;
- Additional wear on components;
- Increased likelihood of failure.

In boiler planning a distinction must therefore be made between the base load and peak load and boilers are often sized to meet only a proportion of the peak load. Specifications differ between manufacturers and boiler types, but in general wood chip boilers should not be run for extended periods at less than 30% of their capacity. This is sometimes referred to as the turndown ratio. For wood pellet boilers, which can be more responsive, this figure may be around 25%.

In the example heat distribution above (Figure 5), it can be seen that a boiler sized at 100% of the required heat load would spend a great many days operating at low load and could be subject to the problems associated with excessive cycling. In this example, the number of hours running at full capacity would be maximized with a boiler sized at 50%-60% of the peak load. This boiler would be much cheaper to buy and would never be required to run at much less than 50% of its capacity.

Where process heat is required, or the demand does not vary significantly across the heating season, the profile will appear much flatter and the boiler may be sized at or near the peak load.

The remaining heat demand can be met with additional boilers, often smaller fossil fuel boilers but also with other biomass boilers, or with thermal storage. It is not unusual for a boiler sized at 50% of the peak load to be able to meet 85% of the total heat demand when combined with thermal storage.

It should be said that accurate boiler sizing and system design depends on many variables relating to the building fabric and the way that the heat is consumed. It is a skilled task and should be carried out by experts. Specifying clients should be prepared to provide detailed data on the actual or anticipated heat requirements of the building.

Where the biomass system is part of a larger refurbishment it is important to account for reduced heat loads resulting from efficiency measures. In the case of new buildings where there is no historical data, detailed calculations of the heat losses will be required.
Thermal storage

Biomass boilers react more slowly than fossil fuel boilers and in most cases biomass heating systems should include thermal storage. Properly designed and integrated thermal storage systems will maximize the number of hours that the boiler will be able to run on full load, and increase the fraction of the load that is met by biomass. This will decrease the total heat generation costs and improve carbon savings.

Thermal stores are highly insulated steel tanks which provide two main functions. As buffer vessels they can protect the system by acting as a heat reservoir when the boiler shuts down, and they help to smooth out peaks in demand (Figure 6).

The term ‘buffer tank’ is often used interchangeably with accumulator tanks which are larger heat stores, providing a more significant reservoir of heat and a greater degree of system control. The accumulator allows the boiler to operate at nominal load for longer periods, avoiding the need for the boiler to be repeatedly shut down and re-ignited when demand is low. By charging the accumulator during periods of low demand, the system is able to provide low levels of heat without cycling and can respond to sudden peaks by providing additional heat when the boiler is unable to meet the full load on its own.

The accumulator tank also has an important role in system control and will be fitted with a number of temperature sensors and a variable speed pump. By maintaining thermal stratification within the tank, temperature sensors at different heights on the tank can trigger the boiler to fire. The hot water from the boiler is introduced at the top of the accumulator and returns at the bottom through inlets that are designed to reduce turbulence so that the temperature stratification is not disturbed.

The simplest systems will have just two sensors, one near the top and one at the bottom. These offer only crude control while more refined systems will have five or more sensors so that progressive control is possible.

The size of the accumulator tank is influenced by factors such as nominal capacity and the size of the boiler as well as the space available in the plant room. Undersized buffer tanks or accumulators will not be able to provide the same degree of flexibility or system protection and serious consideration should be given to compromising on thermal storage. Figures of between 20 and 60 litres per kW of installed capacity can often be presented as ‘rules of thumb’ but these cannot
necessarily be relied upon as every system is different.

**Fuel feeding and handling systems**

Fuel feeding and handling systems are necessary to transport the fuel from the point of delivery to point of storage, and from the storage to the combustion system. Due to its direct influence on the availability and performance of the combustion system, the fuel feeding needs to be designed carefully and has to be adjusted to the combustion technology used.

Examples of fuel handling methods include:

- Belt conveyors
- Augers (screw conveyors)
- Walking floors
- Pneumatic systems

Belt conveyors (Figure 7) are generally used in larger installations and district heating plants to transport large quantities of fuel over longer distances. They are reliable, relatively simple and inexpensive.

Screw conveyors or augers (Figure 8) are often enclosed and allow the conveying of bulk material without dust emissions. They can be used for smaller materials (particle sizes less than 50mm) such as sawdust, pellets and woodchips. While relatively cheap, augers can become blocked or jammed by out of specification fuel; longer particles or bark slivers from woodchips. Other problems can arise from accumulated dust from poor quality pellets with low mechanical durability. These drawbacks can be minimised by using high quality fuels, and ensuring ease of access to closed augers. In general auger runs should also be kept as short as possible.

Hydraulically operated walking floors (Figure 9) are more likely to be found in larger installations and move quantities of fuel over relatively shorter distances. In particular they can be used for traversing fuel within storage areas or built into bulk trailers, and provide an alternative method to tipping which may be preferred at sites where overhead access is limited.

Pneumatic fuel handling is commonly seen in the delivery of pellets which are blown from tankers, although it is possible to blow wood chips as well. Some systems employ pneumatic pipes where the storage facility is somewhat remote from the boiler. The flow characteristics of pellets are far superior to wood chips owing to their uniform size and density, and low moisture content. Despite this apparent advantage pellets will readily degrade if there are sharp bends in the pipework, or if the blowing pressure is too high.
Design decisions will need to be made on the basis of the fuel characteristics, distance and height to which the fuel must be raised, risks from dust (including explosion and fire), the volume and rate at which fuel has to be transported.

Fuel handling mechanisms are common cause of system failure so while capital costs are always a concern, it is worth considering the maintenance and running costs of the system as well as the potential cost of boiler downtime in terms of personnel and additional fossil fuel cost.

**Storing wood fuel**
The key issues in the design of the fuel storage are volume and access. Biomass fuels are less energy dense than fossil fuels so more space is needed, otherwise the frequency of deliveries will become unacceptable, particularly in the coldest winter months. Wood fuel deliveries are usually charged, on the basis of distance travelled so there is a strong economic argument for minimizing the number of deliveries required.

The volume of the storage facility should also take into account of the size of delivery vehicles. The store should be able to accept a whole delivery with allowance for a significant overhead so that fuel can be ordered well in advance of running out. Smaller non-domestic sites should consider a minimum of 1.5 to 2 times the storage capacity of the delivery vehicle and more if the site is a large energy user.

Fuel handling systems are greatly simplified if the distance between the boiler and fuel storage is kept as short as possible. This has benefits in keeping costs lower and can improve the overall reliability of the system. Where sites are not permanently manned, automated systems for filling the store and transporting fuel to the combustion chamber can have higher capital costs but may be cheaper to run over the life of the system.

**Wood chip storage**
Wood chips are less homogenous than wood pellets, have poor flow characteristics and are prone to bridging. For this reason they are often moved using tractors with front shovels, front loaders or other agricultural machinery. Deliveries will usually be made by lorries and tractors with tipping trailers or trailers with walking floors.

Sites using wood chip often make use of local suppliers and it is useful to find out which methods of delivery are employed in the area before settling on the design of the store. The simplest method of delivery is to tip directly into a basement or subterranean bunker. An alternative, similar to underground storage is to make use of natural banks or slopes as ramps so that the costs of excavation are reduced and direct tipping is still possible.

Although the construction costs can be higher than stores which are above ground, deliveries are quick and relatively quiet, and as there is no need for specialist delivery equipment, fuel can be procured from a wider range of suppliers.
Above ground stores will need to be accessible by delivery vehicles. Large installations may have open sheds with direct access and heavy duty walking floors that are designed to take the weight of the delivery vehicle. Alternatively deliveries are tipped outside and pushed onto the walking floor with a front loader. The lighter weight walking floor will be cheaper but requires additional manpower and a front loader to get the fuel into the store itself which will have an associated cost.

Other options for purpose built stores include above ground bunkers, these can relatively cheap to construct but filling can require more effort or the use of specialist machinery (Figure 10). Access can be through the top with hydraulically operated lids in which case a scissor lift tipping trailer may make the delivery. This provides a quick and painless delivery but the trailers are usually towed by tractors and will have limited range which may limit the options for fuel supply.

Blown deliveries are possible with wood chip from adapted tipping lorries and there is also the option of a combined trough-auger unit (Figure 11) which incorporates either a blower or separate auger to deposit fuel into the store. Lorries need to be able to tip (carefully) into the trough which augers the fuel along to a blower. Deliveries like these can be time consuming and very noisy which can render them impractical for some sites. It should be noted that lengthy or difficult deliveries may attract premium delivery rates.

On some sites where large boilers are able to accept wet wood chip, it may be possible to chip directly into the store although this can be similarly noisy and time consuming.

To get fuel into the boiler, many stores employ an auger attached to a large, slowly rotating disc with sprung steel arms known as an agitator (Figure 12).

With successive passes the agitator sweeps the wood chip into an open channel containing the auger. This is a cost effective and widely used solution but care must be taken when calculating the useful capacity of the store because there will be a large amount of ‘dead space’ beneath the
agitator which is usually placed at an angle to the horizontal, and also in the corners of a square or rectangular store. A range of other auger and bunker based solutions can be seen in Figure 14.

For sites with difficult access and restricted space modified hook bins provide another solution (Figure 13). These are self-contained fuel stores, with a capacity of around 30m³, which feature an integral walking floor.

Wood chips can have moisture levels anywhere upwards of 25% and as such need to be considered as biologically active. The natural action of microbes breaks down the organic matter releasing heat in the process and can result in significant loss of mass if stored for extended periods. Very large piles of moist woodchip (>8m high) can generate a significant amount of heat which may have to be monitored. The production of mould and spores is potentially damaging to health so all wood chip stores require ventilation and ‘dead spaces’ within the store (e.g. corners) should be kept to a minimum and turned over periodically to prevent undisturbed fuel from composting. A well ventilated store will also enhance drying and improve the energy value of the fuel.
**Pellet storage**

For many sites, pellet systems provide additional flexibility and enable biomass to be installed where wood chip systems would be difficult. Pellets are energy dense, relatively easy to transport and blown deliveries are possible at many sites. Almost any site that has been serviced by oil tankers can benefit from pellet heating.

There are several options for storing pellets internally and externally (Figure 15), including:

- External hoppers or silos
- Bunkers
- Sack silos
- Underground tanks

The size of the store should be considered carefully to avoid unnecessarily high delivery frequencies. Larger stores will improve economies of scale and reduce the proportionate cost of delivery, and will also avoid problems of having to run low before re-ordering fuel. The exact size will always depend on the heat demand at the site but a minimum of three weeks storage during the coldest period should be considered. One cubic metre of pellets (<10% moisture content) has a net calorific value of 3100 kWh but energy and volume calculations need to take into account the efficiency of the boiler which in a pellet system can easily exceed 90%.

Pellet transport from the storage to the boiler is generally by vacuum extraction, auger extraction or by gravity feed from a hopper or silo. All of these can provide trouble free extraction of pellets from the storage, however there are a number of important considerations most of which relate to the mechanical durability of the pellets and the risks from dust.

At all stages in the transport of wood pellets, handling will result in a degree of degradation. Poor handling will result in excessive quantities of dust which is potentially explosive and hazardous to human health. It can also affect the quality of the combustion and can even cause components like augers and motors to seize. The aim of an effective pellet fuel storage system is therefore to minimize the damage done to the pellets.

Pellet deliveries are done mostly by large pressurized tankers which blow fuel into the store through flexible lengths of hose. The delivery hose is connected to the store through a standardized Storz 110-A fitting which is a two-way airtight connector. A second fitting or vent is also required to equalize the pressure in the store during the delivery, this must be connected back to the tanker or have a dust filter fitted.

The maximum distance that most tankers will reach is 20-30m horizontally and around 12m vertically.

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Figure 15, Selected internal and external pellet storage options
Beyond this the delivery pressure will have to be too high and the pellets will get damaged. Most pellet suppliers will be happy to advise on the access requirements for lorries, including minimum widths, heights and space for turning. While these distances can give a good degree of flexibility when siting the fuel store, every effort should be made to minimize the distance to avoid unnecessary damage to the pellets.

As well as keeping the distance to a minimum, pipework should be kept straight as straight as possible and sharp bends (<0.5m) avoided altogether. Delivery pipes need to be smooth on the inside and should be made of a conducting material such as metal which should be earthed; plastic pipes can build up a static charge which could become a source of ignition in a dusty environment. The system should also be earthed.

It is important that the inlet to the pellet store is at least 2.5 metres from the opposite wall to prevent the blown pellets disintegrating on impact. In smaller stores a baffle or crash mat may be placed a short distance in front of the rear wall to reduce the impact or hoses may be angled to improve and increase the length of the pellet trajectory.

Wood pellets have good flow characteristics and providing the slope of the floor is smooth, and greater than 40-45 degrees, they should flow freely into the auger extraction system to the boiler. A sight glass may be fitted so that levels can be inspected and some suppliers offer ultrasonic and electronic level indicators with internet or mobile connections to allow automatic ordering.

While pellets have much lower moisture content than wood chip and can be stored almost indefinitely in the right environment, they are not biologically inert. Even in small quantities, pellets can release dangerous quantities of carbon monoxide and should be thoroughly ventilated at all times. Other oxygen depleting gases can be also present. Individuals should not put their heads in, or enter confined pellet storage spaces alone or without checking levels of CO and oxygen.

**Ash and emissions**

As well as what goes into the boiler it is important to consider what comes out.

Ash characteristics vary according to fuel type with higher quality fuels generally creating less ash. For top quality wood pellets ash content should be less than 0.7% by weight and can even be as low as 0.3-0.5% depending on the combustion conditions. Good quality wood chip will produce more ash at around 1-1.5%. Lower quality material will produce more ash depending on the amount of bark and foliage that is included. Bark for instance can produce up to 3% ash by weight and foliage up to 6%.

Automatic ash extraction is a standard feature on all modern boilers, usually via an auger into a sealed bin, which greatly reduces maintenance although manual cleaning is also recommended at specified intervals. Ash can accumulate in the grate (bottom ash) or can be removed as particulates from the flue gas (fly ash).
Bottom ash can be used as a fertilizer as it contains large amounts of potassium although high alkalinity means that it should be spread thinly. In Sweden the maximum rate of spreading is 3 tonnes per hectare. Other uses include blending with cement and concrete and the manufacture of lightweight cinder blocks.

Fly ash is produced in much smaller quantities but should not be used as fertilizer as it contains heavy metals. Larger particles can be efficiently removed using a cyclone or multi cyclone, a kind of centrifugal gravity separator through which the flue gas is passed.

Finer particulates (PM\textsubscript{10} and PM\textsubscript{2.5}) are not sufficiently massive to be removed by the cyclone so ceramic filters are used. These are more expensive option but can be retrofitted to existing boilers removing up to 96% of PM\textsubscript{10} and PM\textsubscript{2.5}.

Other emissions from biomass combustion which may be regulated include oxides of nitrogen and sulphur (SO\textsubscript{X} and NO\textsubscript{X}) as well as carbon dioxide (CO\textsubscript{2}). Levels depend to a large extent on the fuels and equipment used and on the mode of operation

Emissions of NO\textsubscript{X} can vary between 60 mg/MJ and 170 mg/MJ which is high compared to gas (5-20 mg/MJ) and oil (50-70 mg/MJ). However biomass installations typically replace oil or solid fuels in low density or rural areas, so impacts can be expected to be relatively low. By comparison diesel cars can be expected to produce 440-530 mg/km (at ground level) or more when cold starting is taken into consideration. Over a year, NO\textsubscript{X} emissions from a 150kW chip boiler could be expected to be equivalent to a single medium sized car doing an average of 24,000km.

Biomass has rather lower emission of SO\textsubscript{X} (20 mg/MJ) than oil or (140 mg/MJ) or coal (900 mg/MJ), but more than natural gas (<1 mg/MJ). Emissions of CO\textsubscript{2} from biomass combustion are relatively high, although sustainably sourced biomass fuel can claim to be almost carbon neutral as a result of a relatively short carbon cycle, based around the fresh growth and replacement of existing forests.

**Containerised systems**

On smaller sites or where there is a requirement to keep disruption to a minimum, containerised biomass solutions or ‘energy cabins’ are seen as a good solution particularly where there is insufficient space in existing plant rooms. A number of boiler manufacturers and installers have developed these systems with a range of boiler capacities and accumulator options, often with integrated fuel storage. The cabins arrive on the site pre-assembled and ready to be connected directly to an existing distribution system. Typical capacities are around 200kW but higher capacities are available, often with additional storage modules.

Although a relatively expensive option, the convenience, lack of down time and savings against building a separate plant room can improve the economic arguments.

Figure 17, Containerised biomass heating cabins
District heating

District heating is often associated with biomass. High and consistent base loads are well suited to the operation of biomass boilers and the opportunity to spread capital costs over a number of properties can make economic returns more attractive. There are other benefits to having centralised plant and fuel storage which can more efficient in space and in energy terms.

Heat networks can be implemented at different scales ranging from a handful of connected sites up to whole towns or cities properties. Urban areas are generally favoured due to the cost of pipe work and density of heat users. Where there is sufficient demand, district cooling can also be provide through absorption cooling technologies.

Key parameters for judging and comparing the feasibility of a district heating system include the areal energy density and the line load. Areal energy density is the ratio of the total energy demand (in MWh or GWh) and the geographical area (in km²) of the proposed system. The line load is the ratio between the total energy demand and the total length of pipes (in km) in the network. Values will vary between regions, in Sweden for example, an annual areal density of 5 MWh/km² (or 5 kWh/m²) and line loads of between 200-300 Kwh/m would be considered acceptable. Areal energy densities can be increased by incorporating larger heat users which can provide a good base load for the system. Low line loads indicate relatively high system losses from pipework which may be remedied by relocating the plant room or re-routing the network.

District heating systems will contain three circuits (Figure 19), one for the boiler, one for the distribution network and one circuit for the consumer. Within the consumer circuit there is separate circuit for domestic hot water. The circuits are thermally connected by two plate heat exchangers, one on the boiler side and one on the consumer side.

**Figure 18, Elements of a district heating system**

**Figure 19, Circuits in a district heating system**
customer side. The circuits are separated to prevent the boiler from being emptied of water in the event of a leak in the distribution system. The size of the distribution system in relation to the boiler means that even a small leak could empty the boiler of water quickly and cause a lot of damage.

The boiler
Boilers designed for district heating up to about 10MWth are usually of the moving grate variety and will produce hot water and/or steam. These boilers are very robust and are often designed to take a range of fuels, especially the lower value, high moisture fuels. These boilers have substantial refractory linings and larger combustion chambers. This means that the boiler takes longer to get up to ignition temperatures but less sensitive to changes that might otherwise result from the introduction of wet fuel. As a result wet wood boilers are generally more expensive than those that are designed to take drier fuels.

To have a high total efficiency it is important to maximise the difference between the flow and return temperature (referred to as a high Delta T or ΔT). With return temperatures (preferably below 50°, this indicates that the largest amount of energy is being extracted from the heated water. At the same time keeping flow temperatures as low as possible (perhaps 65-70°C in the summer) will help to minimise losses in the network.

The distribution network
The quality of the distribution network is of key importance to the economics of a district heating system. It is an important factor in reliability and also in managing system losses. In smaller systems network losses can be in the range of 10-20%, while in larger systems it is possible to have losses as low as 5%, due to advanced combustion control and heat recovery.

To achieve these levels pipes and connectors in the network are usually pre-insulated to a high standard and may take advantage of twin pipes where the flow and return pipes are enclosed by a common insulation with only one outer mantle.

Corrosion can become a major problem in distribution networks over time so pipes also need to be sealed against the diffusion of oxygen into the water. This is done by sealing tube walls or by chemically binding the oxygen with weak concentrations of additives such as hydrazine (N₂H₄). The use of additives may be subject to local and national regulations. Plastic pipes are not subject to corrosion, but metal joints and valves could still be, and while plastic remains inferior to metals with respect to oxygen diffusion, metal pipes and are often considered superior.

The consumer circuit
Replacing individual boilers with compact heat exchangers has a number of advantages for consumers. The heat interface unit (Figure 21) is about the same size as a gas combination boiler and is silent in operation. It provides independent heating and hot water to each dwelling through the existing hydronic distribution system. Where fossil fuels, and particularly oil or coal are replaced, the system is cleaner, virtually maintenance free and reduces the risk of fires.

Older individual appliances can also be very inefficient and therefore expensive to run and few will have the same benefit of sophisticated emissions controls as a large heating plant.
Appendix

Energetic content of fuels

The energy value of wood fuels is largely determined by the moisture content of the fuel. There is little variation between the Net Calorific Value (NCV) of hard and soft woods and the relationship with moisture content is linear. However, due to the difference in density between species, as well as the drying and bulk characteristics, the variation in the volumetric energy density (measured in MWh/m³) is more complicated (Table 2). In general, a cubic metre of hardwood chip will have a higher energy value than a cubic metre of softwood chip.

It is therefore recommended to considering fuel storage facilities in terms of the amount of energy that can be stored rather than just on volume. The figures given here do not take into account the efficiency of the boiler or other system losses which should also be included in storage calculations.

Energy values for typical fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Net Calorific Value kWh/kg</th>
<th>Bulk density kg/m³</th>
<th>Volumetric energy density kWh/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (solid, oven dry, 0% mc)</td>
<td>5.3</td>
<td>400-600</td>
<td>2,100 - 3,200</td>
</tr>
<tr>
<td>Wood pellets (~8% mc)</td>
<td>4.8</td>
<td>650</td>
<td>3,100</td>
</tr>
<tr>
<td>Log wood (stacked, 20% mc)</td>
<td>4.1</td>
<td>350-500</td>
<td>1,400 - 2,000</td>
</tr>
<tr>
<td>Wood chips (30% mc)</td>
<td>3.5</td>
<td>250</td>
<td>870</td>
</tr>
<tr>
<td>Miscanthus (bale, 25% mc)</td>
<td>3.6</td>
<td>140-180</td>
<td>500 - 650</td>
</tr>
<tr>
<td>Heating oil</td>
<td>11.8</td>
<td>845</td>
<td>10,000</td>
</tr>
<tr>
<td>Anthracite</td>
<td>9.2</td>
<td>1,100</td>
<td>10,100</td>
</tr>
<tr>
<td>House coal</td>
<td>7.5-8.6</td>
<td>850</td>
<td>6,400 - 7,300</td>
</tr>
<tr>
<td>Natural gas (NTP)</td>
<td>10.6</td>
<td>0.9</td>
<td>9.8</td>
</tr>
<tr>
<td>LPG</td>
<td>12.9</td>
<td>510</td>
<td>6,600</td>
</tr>
</tbody>
</table>

Table 3, Energy values for typical heating fuels

<table>
<thead>
<tr>
<th>Unit</th>
<th>kWh</th>
<th>MWh</th>
<th>J</th>
<th>MJ</th>
<th>toe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Kilowatt hour (kWh)</td>
<td>1</td>
<td>1000</td>
<td>3,600,000</td>
<td>3.6</td>
<td>8.6×10⁻¹</td>
</tr>
<tr>
<td>1 Megawatt hour (MWh)</td>
<td>0.001</td>
<td>1</td>
<td>3,600,000,000</td>
<td>3.6</td>
<td>8.6×10⁻⁴</td>
</tr>
<tr>
<td>1 Joule (J)</td>
<td>2.78×10⁻⁷</td>
<td>2.78×10⁻⁴</td>
<td>1</td>
<td>0.00000001</td>
<td>2.4×10⁻¹¹</td>
</tr>
<tr>
<td>1 Megajoule (MJ)</td>
<td>2.78×10⁻⁸</td>
<td>0.278</td>
<td>1,000,000</td>
<td>1</td>
<td>2.4×10⁻⁶</td>
</tr>
<tr>
<td>1 tonnes of oil equivalent</td>
<td>11,630</td>
<td>11.63</td>
<td>41,868,000,000</td>
<td>41,868,000</td>
<td>1</td>
</tr>
</tbody>
</table>

Figures from Biomass Energy Centre
Regional Annexe (UK)
Information and links for further reading.

Renewable Heat Incentive
The UK bioheat market has seen significant changes with the introduction of the world’s first tariff for renewable heat. The Renewable Heat incentive (RHI) devised by the Department of Energy and Climate Change, (DECC) is introducing the scheme in two phases, a non-domestic scheme which launched in November 2011 and a domestic scheme due for launch in summer 2013. Both schemes however will be back dated to 2009 when the first announcements were made. In the meantime domestic users can access a one off grant or Renewable Heat Premium Payment (RHPP) to help offset the cost of the install.

The RHI has had a slower than anticipated start but expectations for the biomass industry are high with over 90% of applications to Ofgem (the scheme administrator) being for biomass boilers. The RHI supports installations at all scales but with some strict eligibility criteria regarding metering and useful heat.

Some uncertainty remains over the final shape of RHI as numerous consultations have been released aimed at managing the available budget, introducing sustainability criteria for biomass fuels, and improving the thermal efficiency of buildings. If the proposals are accepted, they are likely to come into force sometime in 2014.

It should be noted that if any public grant finance has been used to help purchase or install biomass heating equipment, then that installation will not be eligible for RHI or RHPP support unless the grant is repaid.

You can find out more about the RHI from the sources below:

DECC
Pages on the Renewable Heat Incentive and its aims
www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/incentive/incentive.aspx

Energy Saving Trust
The current domestic support scheme, RHPP
www.est.org.uk/rhpp

Biomass Energy Centre
RHI calculation tool
www.biomassenergycentre.org.uk/portal/page?_pageid=77,363178&_dad=portal&_schema=PORTAL

Ofgem
Energy regulator, responsible for running the RHI on behalf of DECC and providing regulatory documents which outline the detail of the scheme
www.ofgem.gov.uk/e-serve/RHI/Pages/RHI.aspx

Current UK design guides
CIBSE
In the UK there is currently no single definitive guide to the design of biomass systems, although there are many publications covering different aspects. The Chartered Institute of Building Services Engineers (CIBSE) is developing a detailed biomass design guide which is scheduled for publication early 2013. This is expected to become a valuable resource for system designers and specifiers and it is hoped will accelerate the deployment of UK biomass heating in all of its forms.
www.cibse.org/

The FOREST programme
Intelligent Energy Europe funded project promoting supply chain awareness and partnering as a means of building capacity.
www.forestprogramme.com
Other FOREST guides:

- The FOREST online training tool (developed by Linnæus University) [www.forestprogramme.com/tools-resources/training-tool/](http://www.forestprogramme.com/tools-resources/training-tool/)

Carbon Trust


Biomass Energy Centre (BEC)

- Government sponsored biomass portal covering all aspects of biomass heating including technical, environmental and regulatory matters [www.biomassenergycentre.org.uk](http://www.biomassenergycentre.org.uk)
- Recent BEC guides:
  - *Biomass heating: A guide to medium scale wood chip and wood pellet systems* [www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_TECHNICAL/BEST%20PRACTICE/37821_FOR_BIOMASS_2_LRPDF](http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_TECHNICAL/BEST%20PRACTICE/37821_FOR_BIOMASS_2_LRPDF)
  - *Biomass heating: a guide to feasibility studies* [www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_TECHNICAL/BEST%20PRACTICE/38215_FOR_BIOMASS_3_LRPDF](http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_TECHNICAL/BEST%20PRACTICE/38215_FOR_BIOMASS_3_LRPDF)

Planning permission

Planning guidance for general building improvements can be found at the government online portal. [http://www.planningportal.gov.uk](http://www.planningportal.gov.uk)

Planning permission is not generally required to install a biomass boiler although aspects of the system may fall within planning regulations. Permanent fuel storage or additions to plant buildings, access arrangements and flue positioning are all subject to the same rules as for ordinary buildings. However recent changes to ‘permitted developments’ (changes that can be without planning permission) for example, include biomass boiler flues on a rear elevation as long as they are within one metre of the highest part of the ridge. Listed buildings and those in designated areas may be subject to additional requirements and local planning departments should be consulted. [www.planningportal.gov.uk/permission/commonprojects/biomass](http://www.planningportal.gov.uk/permission/commonprojects/biomass)

Building Regulations

Building regulations for England and Wales should be adhered to for all developments, including the installation of combustion equipment. The building regulations and Approved Documents are free to download and regularly updated. For a biomass installation, a number of sections of the building regulations will apply such as:

- Part L: *Conservation of Fuel and Power* [www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved](http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved)
Part J: Heat producing appliances
http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partj/

Air Quality
The UK government is gradually introducing more stringent carbon dioxide and particulate matter requirements on boilers eligible for financial support (RHI and RHPP). In addition, many built up areas of the UK are deemed Air Quality Management Areas (AQMA) or ‘Smoke Control Areas’. An AQMA can be declared by a Local Authority if air quality falls below required standards. Additionally a Smoke Control Area can be declared which means that only authorised fuels or exempted boilers can be used.

- Local government rules
  www.gov.uk/preventing-air-pollution/local-controls
- AQMA and smoke control pages at Defra
  http://aqma.defra.gov.uk/
  http://smokecontrol.defra.gov.uk/
- Maps of all AQMAs are also available:
  http://aqma.defra.gov.uk/maps.php

Most modern biomass boilers are sufficiently clean to be permitted in smoke control areas, and indeed are already meeting the proposed UK CO₂ and NOₓ and particulate limits. Details on the mechanism for ensuring that RHI financial support is only given to biomass boilers capable of complying with emission limits is now in the Defra Archive:

Grants and support
The Forestry Commission, English Woodland Grant Scheme (EWGS), offers six grants for Woodland Management, including the Woodland Woodfuel Implementation Grant (WWIG). This grant provides specific assistance for woodland owners providing infrastructure support for sustainable wood fuel extraction.
www.forestry.gov.uk/ewgs

In the south west, the Ward Forester project is a Devon based pilot initiative led jointly by Devon County Council and the Forestry Commission. It aims, to bring small undermanaged woodlands back into active management by bringing them together into economically viable, cooperating groups under the stewardship and expertise of a professional forester. Additional income from wood fuel can be a trigger for better management of forest resources.
www.wardforester.co.uk

Standards and assurance
Biomass boiler manufacturers will always specify which grades of fuel the appliance is designed to take. This is essential to the operation of the boiler and users should always use the right fuel for their. Details of fuel and other standards relevant to the biomass industry are available on the FOREST website.
www.forestprogramme.com/tools-resources/guides

The best way to ensure that fuel is within these specifications is to use an accredited supplier.

In the South West region the Woodsure is a not for profit organisation offering a quality assurance standard’ scheme, it provides an accreditation service to wood fuel suppliers based on recognised standards for physical and combustion properties as well as sustainability. Information and advice on fuel quality is provided for end users and a directory of approved suppliers is also provided.
www.woodsure.co.uk

Nationally HETAS is the official body recognised by Government to approve biomass and solid fuel domestic heating appliances, fuels and services including the registration of competent installers and servicing businesses. HETAS provide product approval and installer registration services as well as details of approved
Users of pellet appliances should be aware that national pellet standards were replaced by the European ENplus14961-2 standard in August 2011, and is the key standard that all stakeholders should now follow. [www.enplus-pellets.eu](http://www.enplus-pellets.eu)

**Woodfuel Suppliers group**

The Renewable Energy Association (REA) and Confederation of Forest Industries (ConFor) jointly sponsor the Woodfuel Suppliers Group, a special interest group (SIG) to support and promote businesses on the supply side. It now encompasses all aspects of the supply chain, including installers and consultants. Pivotaly, it has created a charter for membership promoting fuel quality assurance and sustainable practices. [www.confor.org.uk/AboutUs/Default.aspx?pid=331](http://www.confor.org.uk/AboutUs/Default.aspx?pid=331)

**Further guidance**

The FOREST Partners offer local and regional support to business and individuals:

- **RegenSW**
  [www.regensw.co.uk](http://www.regensw.co.uk)
- **Severn Wye Energy Agency**
  [www.swea.co.uk](http://www.swea.co.uk)
- **Forestry Commission (England)**
  [http://www.forestry.gov.uk/southwest](http://www.forestry.gov.uk/southwest)
- **University of Exeter, Centre for Energy and the Environment**
  [www.exeter.ac.uk/cee](http://www.exeter.ac.uk/cee)
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