An Alternative Energy Source for McGill Macdonald Campus Power Plant: Wood Pellets

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EXECUTIVE SUMMARY

Heat energy production can be done several ways in Quebec in order to get through the cold winter climate. Different alternatives such as natural gas, oil, electricity, biomass combustion and geothermal energy are available to provide heat energy for buildings. On McGill Macdonald Campus, four natural gas boilers are installed in the power plant in order to provide heating for all of the university buildings. Since these installations are getting old, McGill University Services is planning to use an alternative environmental system to heat its buildings. Through this project, a wood pellet installation will be considered in order to heat a greenhouse on campus and see its efficiency and profitability. A complete analysis on wood pellet heating systems will be provided through this report in order to understand this process.

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1- Problem Statement

The Macdonald Campus of McGill University currently supplies heat through a centralized power plant where a water treatment facility is also located as well. The power house has two boilers in operation out of the four that are installed, which produce heat for most buildings on the campus using natural gas. All the heat is then distributed through underground pipes located in tunnels under the campus grounds. Since these installations are around 75 years old, heat losses sum up to around 15-20% due to the obsolete insulation on the pipes (André Aylwin, McGill Facilities Operations Director).

McGill University is currently targeting a 7% reduction in energy consumption by 2010. Also, a reduced usage of non-renewable energy sources (oil and gas) and a decrease of its overall greenhouse gas emissions. A decentralized approach for heating is one of the potential solutions being considered by the McGill University Services in order to eliminate losses due to heat transportation. Furthermore, systems working on a renewable energy source to produce heat energy for the buildings on the Macdonald campus are also being considered.

A decentralize approach suggests solutions adapted to the specific needs of a building. On the campus during the winter, the greenhouses become extremely energy intensive. Temperature levels usually need to be maintained higher than standard room temperatures. The greenhouses are currently located at considerable distances from the power plant, contributing to heat losses due to transport. They also have defective carbon dioxide additive systems. Moreover, no back-up system is in place in case of a power plant failure thus risking the integrity of research projects.

2- Objectives and Scope

The main objective of this project is to provide a new heating system relying on renewable energy for the new greenhouse on the Macdonald Campus. A long term goal is to allow this new system to contribute to further research once the initial project has been completed. In order to reduce the environmental footprint of the building, a carbon dioxide recirculation system will be evaluated as well. With this established, the next step is to determine the building's heating requirements. Subsequently, since the goal of this project is to propose a decentralized heating system, a fuel burner size is to be determined using the energy demand of the building. Furthermore, a fuel type for the burner must be selected in terms of energy yield, economical feasibility, sustainability and environmental impact.

The next phase consists of looking at various companies and distributors that meet the needs, requirements and values of this project. The burner company needs to be evaluated upon burner performance, cost, reliability and reputation. The fuel distributor will be evaluated on proximity, quality of product, incentives, in terms of wastes and environmental impacts, as well as price and distribution.

The final phase will be to economically evaluate the equipment and operations necessary for this project to be accomplished in order to determine an approximate budget. With this, the feasibility of the project will be evaluated.

3- Context

The McGill Macdonald Campus was founded in 1905 by Sir William Macdonald who decided to build a major campus to enable people to have access to a quality education in the domain of farm technology. The original campus included several buildings, residences and a power house in order to supply heat to surrounding buildings. (http://cac.mcgill.ca/campus/buildings/Macdonald_Campus.html)

Since the infrastructures are getting old, they are also beginning to be energy inefficient. In the context of sustainable development, it becomes environmentally and economically imperative to improve these installations. McGill University has started an environmental campaign called Rethink McGill. Since then, a lot of initiatives have been taken from both students and staff members. For example, there is the Green Building Work Group which has set a primary objective of energy consumption reduction of 7% for 2010. During a meeting, this group came to a conclusion that the power house of the Macdonald Campus would need to be modified and that renewable energies were going to be considered (Dennis Fortune, Sustainability Director of McGill University Services).

The Macdonald Campus power plant has four steam boilers that were previously working on oil but are now powered by natural gas. Only two boilers are currently in use during peak demands and supply heating to the campus as well as part of John Abbott College. The facility also provides treated water and distilled water to the various buildings. While it is considered a central power plant it is actually located closer to the edge of the campus. Replacing natural gas use by a renewable source would decrease the campus's greenhouse gas emissions while a decentralizing approach could reduce energy losses. (Mac Sustainability Project)

As a renewable source of energy, biomass could be a very interesting candidate since it is available locally. The province of Quebec is a predominant actor in the forestry industry. Sawmills can provide biomass by recycling their waste in the form of pellets. However, while the wood pellet industry is expanding in British-Columbia, it seems to be stagnant in Quebec. The demand is lower and most of the pellets are exported in Europe where the market is very strong. According to John Swaan from the

Wood Pellet Association, there are even some wood pellet factories in Quebec that have their production on halt. Therefore, a university pilot project using this type of biomass could serve as an ideal demonstration of the technology and a support to the local industry.

4- Literature Review

4.1 Characterization of Biomass for Energy Use

Moisture content

The moisture content of biomass is often a very predominant factor when determining what kind of energy conversion process to use. When considering biomass with high moisture content, bio-conversion technology will more likely be used, where when dealing with low moisture content, usually less than 50%, a thermal conversion process is recommended. In the analysis of moisture content, there are two forms to consider. There is intrinsic moisture content, which only reflects the moisture content of the biomass excluding the influence of the weather and its environment where the other is extrinsic, which includes the influence of weather and gives the actual moisture content of the biomass after it has been harvested.

Heating Value

In relation to moisture content under thermo-chemical conversions is the calorific value (CV) of biomass, which is usually represented in (MJ/kg). Where the gross heating value (GHV) represents the total heat energy obtained by burning a particular biomass, it includes the energy required to vaporize the water, but since this energy cannot necessarily be recovered, in order to get the actual heat energy output of burning biomass, the lower heating value (LHV) can be used which represents the net heating energy excluding the latent heat of water. This heating value is a more convenient unit from an engineering point of view. In this case, moisture content will reduce the potential calorific value of burning biomass which is why it is an important aspect to consider when determining the type of energy conversion process that will be used.

Volatile Matter, Fixed Carbon and Ash

Solid biomass has energy stored in two forms namely volatile matter (VM) and fixed carbon (FC). Volatile matter is the portion released in gaseous form during combustion and fixed carbon is the portion remaining after the release of the gases but excluding the ash and moisture content. The ash in terms of a biochemical conversion resembles more of a solid residue and represents the non-biodegradable carbon that cannot be further broken down. In thermo-chemical reactions, the portion of ash obtained will be less than that from a bio-chemical reaction since only the inorganic content remains, everything else can be burnt. Ash is very important to consider since the magnitude of ash content suggests a reduced amount of available energy at a proportional rate. Also, ash must be managed and handled properly since it may account for operational costs, especially in thermo-chemical reactions.

Table 1 - Properties of biomass materials

Table 3
Properties of selected biomass materials (wt%)

Material	Moisture content (% H_2O)	HHV[a] (MJ/kg)	FC content (%)	VM content (%)	Ash content (%)	Alkali metal content (as Na and K oxides) (%)
Fir	6.5	21	17.2	82.0	0.8	
Danish pine	8.0	21.2	19.0	71.6	1.6	4.8
Willow	60	20.0			1.6	15.8
Poplar	45	18.5			2.1	16
Cereal straw	6	17.3	10.7	79.0	4.3	11.8
Miscanthus	11.5	18.5	15.9	66.8	2.8	
Bagasse	45–50	19.4			3.5	4.4
Switchgrass	13–15	17.4			4.5	14
Bituminous coal	8–12	26.2	57	35	8	

[a] Dry basis, unless stated otherwise.

Alkali Metal Content

Alkali metal content is very important when considering thermo-chemical reactions since the reaction between alkali metals present in the biomass and silica present in the ash can form a sticky substance that can accumulate on the lining of air ways inside a thermal conversion unit and can eventually lead to problems and further operating costs.

Bulk Density

The bulk density of biomass that is to be used in a conversion process plays a major role in the transportation, storage requirements, handling and will influence the efficiency of combustion or biodegradability. The best scenario is to have a low volume per mass ratio hence a high mass per unit volume ratio. A common practice to obtain these conditions is to process bulky biomass into pellets. Notice the pellet properties on the following table.

Table 2 - Bulk volume and density of biomass sources

Table 5
Bulk volume and density of selected biomass sources

Biomass	Bulk volume (m^3/t, daf)[a]	Bulk density (t/m^3, daf)
Wood		
Hardwood chips	4.4	0.23
Softwood chips	5.2–5.6	0.18–0.19
Pellets	1.6–1.8	0.56–0.63
Sawdust	6.2	0.12
Planer shavings	10.3	0.10
Straw		
Loose	24.7–49.5	0.02–0.04
Chopped	12.0–49.5	0.02–0.08
Baled	4.9–9.0	0.11–0.20
Moduled	0.8–10.3	0.10–1.25
Hammermilled	9.9–49.5	0.02–0.11
Cubed	1.5–3.1	0.32–0.67
Pelleted	1.4–1.8	0.56–0.71

[a] Dry, ash-free tonnes.

Cellulose/lignin ratio

The cellulose to lignin ratio is only important from a biochemical conversion point of view. Since cellulose has a high biodegradability factor compared to lignin it is a key factor that is used when determining which type of biomass to use to get the highest ethanol yield through a biochemical process. Since wood material is known to have a higher lignin content, it is not often used through biochemical processes compared to grass crop biomass which have high cellulose content.

Table 3 - Cellulose/lignin content of biomass

Table 4
Cellulose/lignin content of selected biomass (wt%)

Biomass	Lignin (%)	Cellulose (%)	Hemi-cellulose (%)
Softwood	27–30	35–40	25–30
Hardwood	20–25	45–50	20–25
Wheat straw	15–20	33–40	20–25
Switchgrass	5–20	30–50	10–40

Harvesting

The greatest energy costs when considering biomass are those associated with the harvesting machinery and pre-drying before further processing. Another important aspect to take into consideration in harvesting is soil contamination. It is important to avoid having any soil enter a biomass fuel burner since it can cause problems and lead to operating costs. In this case, recycling and converting industrial wood waste, forest residues or wood mill sawdust into usable forms of combustible biomass becomes interesting because although there are energy demands for these processes they coincide with that of harvesting. In this case using recycled biomass as a primary combustible can be a plausible alternative to growing and harvesting biomass depending on the circumstances. (McKendry 2002)

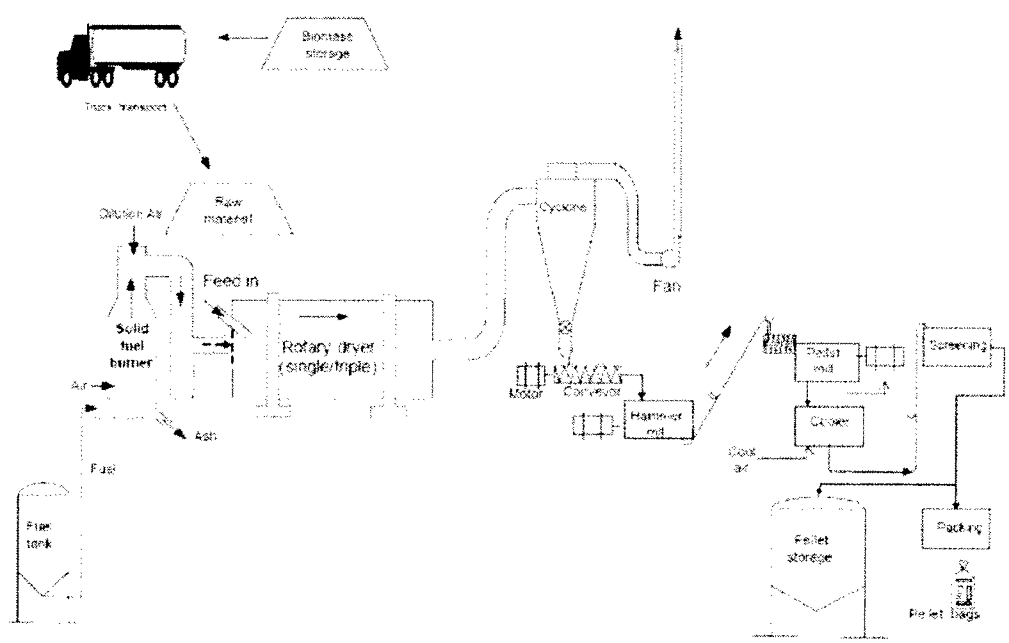
Pellets (wood pellets, grass pellets)

Typical biomass is known to have particularly low bulk density and relatively high moisture content (in the range of 10% to 70%) which is one of its major disadvantages when considering it as a bio-fuel. The moisture content can considerably reduce its potential energy output and the low bulk density makes the handling, storage and transportation inconvenient and costly. In this case, the formation of pellets has been developed such that it increases the bulk density of the biomass and reduces its moisture content. In other words, it condenses biomass into small cylindrical 6-8 mm diameter and 10-12 mm long pellets which can be handled much better by the producer as well as by the consumer. Note that these are average dimension values and can vary depending on the type of biomass from which they are formed as well as the manufacturing company that produced them. The pellets can be made from biomass originating from woody forest biomass, to saw mill residue all the way to agricultural crops and grasses. Not all pellets will have the same calorific values and internal properties such as ash, emissions etc, but they will have the same physical properties such that a pellet burner should be able to burn pellets produced from various types of biomass. (Mani, Sokhansanj et al. 2006)

Pellet Production

In the production of pellets, there are three major stages that the biomass incorporated will go through, that namely being drying, grinding and densification. First the biomass is dried to a moisture content of about 10% in a compartment called a rotary drum. In Canada, drying is done using the heat dissipated through the combustion of natural gas although there are various other systems used in Europe. There is also some incentive to use biomass fuel in the drying process for pelleting. Next is the hammer mill where a screen reduces the size of the dried biomass to one suitable for pelleting. Finally, the biomass mash is compacted in the press mill and the pellets are formed. As the pellets come out at temperatures between 70 and 90˚C, they are cooled and hardened within a cooler to roughly 5˚C and conveyed to a storage area. There may also be a final screening system which gets rid of any fine particles. The final individual density of the wood pellets ranges between 1000-1200 kg/m^3 and the bulk density sits between 550 and 700 kg/m^3. (Mani, Sokhansanj et al. 2006)

Figure 1 - Pellet production diagram



Standards

When determining the standards for fuel pellets, the two main components to take into consideration are the chemical and the physical characteristics. The following table shows the parameters of each component and why they should be considered.

Table 4 - Chemical and physical parameters for pellet standards

Parameter	Effects
Chemical and compositional characteristics	
Water content	storability, calorific value, losses, self-ignition
Calorific value	fuel utilisation, plant design
Element content	
Cl	HCl, dioxin/furane emissions, corrosion in superheaters
N	NO_x, HCN and N_2O emissions
S	SO_x emissions
K	corrosion in superheaters, reduction of ash melting point
Mg, Ca, P	raising of ash melting point, effect on pollutant retention in ashes and use of ashes
Heavy metals	pollutant emissions, use or disposal of ashes
Ash content	particle emissions, costs for use or disposal of ashes
Ash softening behaviour	operational safety, level of pollutant emissions
Fungi spores	health risks during fuel handling
Physical characteristics	
Storage or bulk density	transport and storage expenditures, logistical planning
Unit density	combustion properties (specific heat conductivity, rate of gasification)
Particle size distribution	pourability, bridge-building tendency, operational safety during fuel conveying, drying properties, dust formation
Share of fines	bulk density, transportation losses, dust formation
Durability (for pellets, briquettes)	quality changes during transhipment, disintegration, fuel losses

During the fabrication of pellets, it is mostly the physical properties that are altered since the use of any chemical or natural additive during the production in most cases is prohibited. Of the chemical components, it is mostly the moisture content that is modified.

The heating system in which the pellets will be combusted is a key factor to determine the quality and specs of the pellets that are to be used. Large combustion operations do not need to worry about durability and the presence of fine particles as much as small stove burner operations do. Small stoves have more chances of experiencing clogging problems; therefore their pellet standards will not be the same. In Europe, the first national standard on pellet quality was developed in Sweden in 1998, and other countries followed afterward. In this case, their national standard will be used as reference (Table 5).

Table 5 - Europe standard on pellet quality

Property	Test Method	Unit	Group 1	Group 2	Group 3
Dimensions: diameter and length in producer's store	By measuring at least 10 randomly selected fuel pellets	mm	To be stated as max 4 times ∅	To be stated as max 5 times ∅	To be stated as max 5 times ∅
Bulk density	SS 18 71 78	kg/m³	≥ 600	≥ 500	≥ 500
Durability in producer's store	SS 18 71 80	Weight of fines < 3 mm, %	≤ 0.8	≤ 1.5	> 1.5
Net calorific value (as delivered)	SS-ISO 1928	MJ/kg	≥ 16.9	≥ 16.9	≥ 15.1
		kWh/kg	≥ 4.7	≥ 4.7	≥ 4.2
Ash content	SS 18 71 71	% w/w of DM	≤ 0.7	≤ 1.5	> 1.5
Total moisture content (as delivered)	SS 18 71 70	% w/w	≤ 10	≤ 10	≤ 12
Total sulphur content	SS 18 71 77	% w/w of DM	≤ 0.08	≤ 0.08	To be stated.
Content of additives		% w/w of DM	Content and type to be stated		
Chlorides	SS 18 71 85	% w/w of DM	≤ 0.03	≤ 0.03	To be stated.
Ash dissolution	SS 18 71 65 / ISO 540	°C	Initial temperature (IT) to be stated.		

There are no set standards for fuel pellets in Canada but European standards are well developed and can be used as guidelines. Each country has their own specific standards but they do not vary exceptionally from place to place. (B. Hahn, 2004)

Ash content, disposal and reuse

During combustion of oxygen with a biomass fuel, a solid residue called "ash" is formed. Over time, it accumulates and needs to be disposed of. Sending the ash in landfills is said to cause negative environmental impacts on a local scale. Fortunately, the alkaline metal content of the pellets can become useful. Considering that most of the ash is inorganic nutrients and metals that the biomass had accumulated, it is possible to return it to the land area where it came from. It can become a substantial nutritive supplement for forests and agricultural land which can promote long-term sustainable forest management. However, it does not provide any nitrogen support since it volatilizes completely during combustion. Another advantage is that the ash itself has a high pH which makes a counterbalance with the acidification of soils caused by human activities.

Nonetheless, ash cannot be applied directly from the stove to the soil. Combined with nitrogen fertilizers, ash could increase formation of ammonia (NH_3). In this case, it needs to be stabilized through pelleting, crushing and self-hardening. This former method suggests the addition of water to solidify the ash. Then again, special care needs to be taken in the case of leaching of sodium and potassium since these salts are not desired. Swedish researches suggest that the maximum application of ash should be in the range of 3 Mg/ha. (McKendry 2002) and (Ring, Jacobson et al. 2006)

Storage

Wood pellets can be purchased either in bags or in bulk quantity. Under large operations, when the pellets are delivered in bulk, they need to be stored somewhere where they will be able to conserve their moisture content. The storage area should protect the pellets from rain, snow, dampness and moisture condensation. The moisture content of the pellets is an important factor for storage sustainability. A general study observed biodegradation when the moisture content rose higher than 18%. Under these conditions temperature could rise, fermentation could occur and the combustion quality of the pellets would diminish. (Hardtle, Marek et al. 1987) The pellets should also never come in contact with sand or dirt particles. In this case, the area in which the pellets will be stored in, whether in a silo or a concrete structure, must be cleaned thoroughly before filling. The storage room or compartment must also be equipped with an air suction outlet to let air escape while being filled. This outlet must be larger than the inlet from the delivery trucks compressor since a pressure accumulation inside the storage facility is undesirable. (B. Hahn, 2004)

There are also some innovative companies that have developed very versatile silos, which provide all of the storage requirements for pellets, and are composed of high-tech polyester fabric that is supported by a set of steel beams. They are able to accommodate indoor and outdoor storage for both large and small operations. (ASB)

Transportation/Delivery

In terms of delivery, the transport trucks must ensure that the pellets are well protected from moisture and that they undergo the least amount of mechanical stress. Since the concentration of fine particles can increase during handling, it is important to limit the accumulation as much as possible. The delivery truck must be equipped with a weighing system to precisely measure the amount of pellets being fed. This is important for the delivery company in order to size the bill, as well as for the client whose storage area can only permit a certain volume of pellets. Finally, the delivery truck must be equipped with a minimum length hose of 30 m in order to make sure that it will be able to reach almost any storage area, even if it is difficult to attain. These criteria are based on Austrian standards which were developed soon after Sweden established theirs. (B. Hahn, 2004)

4.2 Types of Energy production

Selecting an Energy Conversion Process

Since there are several ways of converting biomass into energy, there are a set of factors that will determine which process to choose. In most cases, the key factors are the type and quantity of biomass feedstock that will be required, the desired form of energy whether it be heat, mechanical power or electricity and there are also the incentives and requirements of the energy conversion; for example, environmental standards, economic and financial conditions and project specifications. For the purpose of this project, since the main objective is to provide energy to a building in terms of a heat source, only the thermo-chemical processes will be explored.

Combustion

Combustion is an exothermic reaction meaning that it produces energy in the form of heat. The chemical reaction of combustion consists of a fuel undergoing oxidation where a large amount of energy is released and the internal temperature can reach up to 800-1000 °C. To have combustion, three elements are needed, fuel, air and heat. In order to start the combustion process, the fuel needs to be brought to its ignition temperature. The general equation of combustion can be written as follows (Çencel Y.A, Boles M.A, 2006):

$$\text{Fuel} + \text{Air} \xrightarrow{\text{Heat}} \text{Water} + \text{Carbon dioxide} + \text{Nitrogen}$$

Complete combustion occurs when all the carbon in the fuel is burnt and transformed into CO_2, while all the hydrogen is burnt and transformed to H_2O. Incomplete combustion will occur when insufficient amounts oxygen is supplied to the fuel. This process will then produce components such as C, H_2, CH_4 and CO. Incomplete combustion contributes to the emissions of greenhouse gases, for example:

Methane produced as a product of incomplete wood combustion is a greenhouse gas and it has a Greenhouse Warming potential 21 times larger than carbon dioxide.[1]

Biomass Combustion

Biomass combustion is an alternative way to produce heat which is considered more environmentally friendly than burning fossil fuels. The main advantage of biomass combustion is that it is carbon neutral, meaning that while it burns, it releases the carbon that was captured during the plant's growth. Wood fuel is the main source of biomass for heating and is still commonly used around the world. It can be burnt in different forms such as logs, charcoals, chips, pellets and sawdust. Combustion is applicable to any form of biomass but in terms of energy efficiency it is best to use bio-material with relatively low moisture content since the latent heat energy required to vaporize the water is energy that will be lost and not converted into thermal energy.

Wood combustion creates by-products that can have negative environmental effects. The main by-product of wood combustion is the production of ash which in this case can potentially be used as fertilizer. The second most important by-product of wood combustion is smoke. The smoke is composed of water vapour, carbon dioxide and chemical particulates, mainly nitrogen and sulphur oxides. Smoke can have an effect on air pollution but depending on the combustion technique and the type of wood fuel being used, the negative effects of wood combustion can be reduced. For example :

> La combustion des sous-produits de sciage dans des installations modernes et efficaces permettrait de solutionner le problème des émissions gazeuses et particulaires, en plus de produire une quantité appréciable d'énergie utilisable par la scierie et la communauté. [2]

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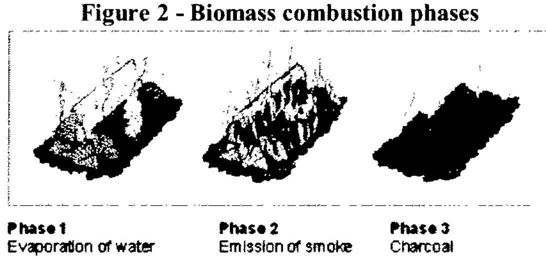
[1] Houck J, Tiegs P. 2007

[2] Dupuis J, Vallée V. 2007

The process of wood combustion can be separated into three steps. The first step is boiling off the water. In this process, all the water contained in the wood absorbs heat energy where it is transformed into water vapour. The second step is the emission of smoke. It occurs when the temperature is higher than the boiling point of water. At this step, the solid wood begins to decompose and the smoke represents of the combustible gases that are being vaporized. The third step is the charcoal phase. When most of the gases have vaporized, only the charcoal remains. Where its main constituent is carbon, charcoal is a good fuel that can easily be burnt but emits substantial amounts of carbon monoxide. During wood combustion, all three phases can occur at the same time.

Figure 2 - Biomass combustion phases



(Natural Resources Canada. 2002)

Wood Pellet Combustion

Wood pellet combustion is considered as a low CO_2 emission solution for heating. This is explained by the neutral ratio of carbon dioxide in the process, meaning that all the CO_2 emitted is equal to the CO_2 previously absorbed by the plant during its growth. Compared to traditional wood combustion, wood pellet combustion is a more environmentally friendly approach for heating since the emissions and residue such as volatile organic compounds and ashes are low due to the high efficiency of today's burners. The energy content of wood pellets is approximately 19.8 GJ/Ton and can be converted to heat with an efficiency of up to 82%. (Samson R). To obtain a low emission output, a specific combustion methodology can be use:

In order to ensure complete pellet combustion with low emissions and low slagging, the quantity and method of supplying the combustion air is of extreme importance. To optimize the combustion it is necessary to divide the combustion chamber into a primary and a secondary combustion zone, where each zone has its own air supply.[3]

The method of having two different zones with different air supplies allows the reduction of some by-products. It reduces the amount of carbon monoxide and unburnt hydrocarbons in the flue gas, which is the conveying exhaust gas of a furnace. On the other hand, the amount nitrogen oxides emitted will be higher than a conventional burner:

The amount of excess air in the secondary zone is not only of importance for carbon monoxide (CO) and unbumt hydrocarbons (OGC). There is a trade-off of between these emissions and the emission of nitrogen oxides (NOx). Too little air will result in increased emissions of CO and OGC, but will keep the amount of NOx in the flue gas small. With greater excess air, more NOx will be released from the bumer. Measurements have shown that pellet bumers often emit two to four times more NOx compared to oil bumers.[4]

Looking at studies previously done, different results were obtained when comparing the combustion of wood pellets and wood.

Table 6 - Combustion comparison between wood pellets and wood

	Total efficiency, %	Efficiency to water, %	Exhaust gas temperature, °C	CO, ppm@13%O_2	NO_X, ppm@13%O_2	PM_{10}, mg/Nm^3
Wood	78	47	250	3500	85	250
Pellet	87	72	150	500	130	70

http://www.combustioninstitute.it/download/proc%202007/data/papers/06%20-20Combustion%20of%20Waste%20and%20Solid%20Fuels/06-06-Allouis-038-paper.pdf

[3] Fiedler F. 2003

[4] Fiedler F. 2003

In order to avoid the problem of too high emission of nitrogen oxides, two parameters can be used to optimize this situation. These parameters are the retention time of the flue gas and the temperature in the combustion chamber. A longer retention time and a higher temperature in the combustion chamber will help reducing the amount of by-product produced through wood pellet combustion.

Wood Pellet Boilers

For wood pellet combustion the main type of system to consider is a central heating boiler. The wood pellet boiler functions like a traditional oil boiler but instead of receiving oil through a pipe, it uses pellets which can be fed in automatically. The stored wood pellets can be brought to the boiler using a conveyor screw or a suction system. These wood pellets are then burnt using the optimal air ratio to reduce emission of CO and nitrogen oxides. The flue gas is then distributed to the heat exchanger where the hot air is transmitted to a fluid, usually water or vapour, which is then pumped through the heating system of a building. These boilers are designed with a fan to optimize the heat transfer in the combustion chamber and in the heat exchanger. Also, to reduce heat loss to the surroundings, insulation is included in the boiler design. The cleaning of the system and the ash removal can be done manually or automatically depending of the type of system used. A chimney is also needed in the design of the system. A humidity-resistant chimney is usually required since condensing can occur while gas is exiting the exhaust. (Fiedler F. 2003). Here are a few pictures of a KOB boiler and a conveyor screw distribution system (Figure 3 & Figure 4):

Figure 3 - KOB boiler

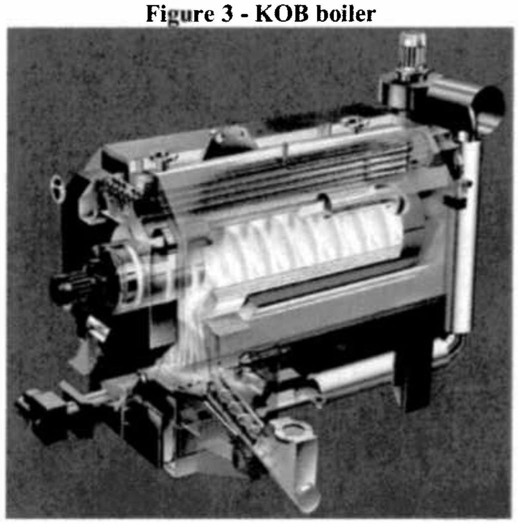
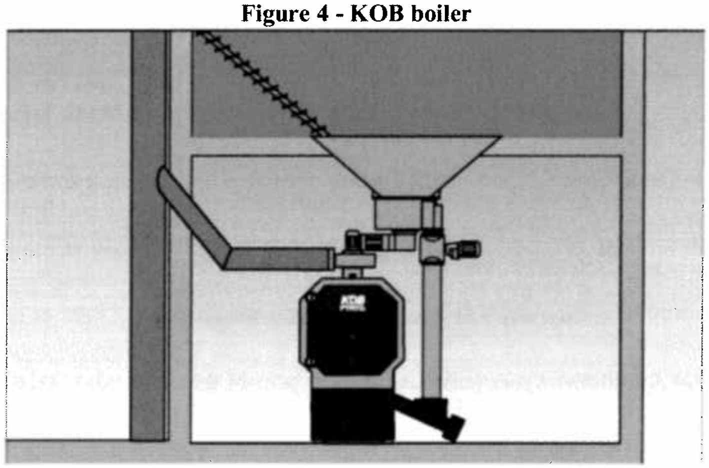


Figure 4 - KOB boiler



http://www.koeb-holzfeuerungen.com/kus_tree//powerslave,id,1,nodeid,1,lang,EN.htm

Here are pictures of a Swedish pellet boiler Effecta-Pannan and an Autrian pellet boiler OkoFen:

Figure 5 - Swedish and Austrian pellet boiler

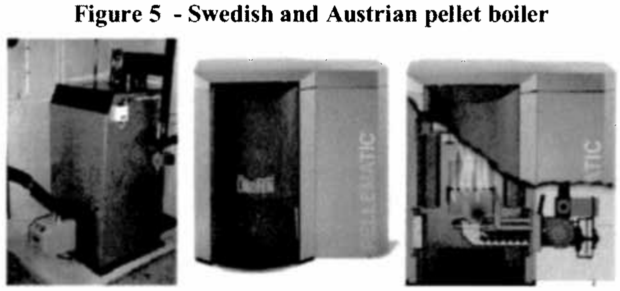


Fig. 4. Left: Swedish pellet boiler Effecta-Pannan [13]. Middle, right: Austrian pellet boiler ÖkoFen [24].

Fiedler F. 2003

One important characteristic of pellet fuelled boilers is their dependency on electricity. Indeed, electricity is needed to run primarily the pellet feeder, the different blowers and the potential ash remover. Consequently, a backup system becomes essential in case of a power failure. However, it seems that a lot of commercial wood pellet stove suppliers provide battery back-up systems. (Custom Fireplaces & More, 2008) Additionally, most buildings of the Macdonald campus have their own power generators which run on oil. In the further design process, the use solar captors, to charge up the emergency batteries during the day, will be evaluated depending on the size and power requirement of the expected boiler.

Gasification

This process is the conversion of chemical energy stored in biomass into a combustible gas mixture through two stages which include both thermo-chemical and biochemical reactions. The output gas is more versatile and can be used to power gas engines or gas turbines which can then be used to produce electrical energy. A new system being developed using gas turbines is known as a biomass integrated gasification combined cycle (BIG/CC) where one of its main advantages is that the gas is cleaned before being burned inside the turbine which reduces a lot of the costs associated with the cleaning and maintenance of equipment. Gasification is renowned for its high energy conversion efficiency and versatility. (McKendry 2002)

Cogeneration

Cogeneration consists of producing electrical or mechanical energy and useful heat simultaneously. This dual process has the advantage of reducing heat loss, therefore increasing overall efficiency of energy conversion to around 80%. (Onovwiona and Ugursal 2006)

With a wood pellet stove, combustion is still controlled by the air flow rate, the fuel flow rate or both. In the boiler, water flows in tubes and captures the heat resulting from the combustion. Consequently, steam is generated and sent to a steam engine. The hot steam will produce mechanical energy by provoking the rotary motion of a shaft. An alternator will assure that the mechanical movement is converted into electricity. Then, the exhaust steam can serve for different purposes. It can be sent in a heat exchanger to obtain hot air which can be useful for drying applications. Also, the heat can be stored for later use. By using its energy, the steam is finally condensed and recycled back into the boiler. (Prasad 1995)

The major energy losses from this system depend a lot on the manufacturer's equipment design. Therefore, the boiler can be optimised to reduce energy losses from the change of phase of water, radiation, convection on the boiler and from incomplete combustion. Although it is minimal, some energy is also lost to the ash. The low moisture content of the biomass is, once again, an important factor to diminish wasted heat. However, the main loss goes into the exhaust of the boiler. With a low quality design, this particular loss can reach to as much as 40% of the energy present in the fuel where in an optimised and well designed boiler waste can represent only 10%.(Prasad 1995)

Depending on the energy demand of the building, there is most likely some surplus whether it is heat or electricity. In Quebec particularly, if the electricity production is over 50kWh, it can be sold to the local grid. Another alternative is to store the electricity in batteries or capacitors. On the other hand, the extra heat can be stored in an insulated hot water reservoir which can be use for heating. (Onovwiona and Ugursal 2006)

Obviously, when compared to the alternative of having to produce electricity and heat separately, cogeneration makes much more economical sense. However, the situation is different when applied to one specific building, such as a greenhouse located in the province of Québec. Due to the competition with hydroelectricity, a small scale production is not economically advantageous. Moreover, most of the energy used in the greenhouse is for heating during cold periods. In practice, if a power failure would occur, research projects in the greenhouse would be mostly compromise because of the lack of heat rather than the lack of electricity. (Onovwiona and Ugursal 2006)

As a result, it might be more economically efficient, as well as more optimal in terms of energy consumption, to use biomass for the production of heat only. The next chapter discusses the means of transportation of energy for heating the greenhouse.

4.3 Greenhouse Heating

Fuel type

Different fuels can be used in order to produce heat for a greenhouse. Natural gas, oil, coal, electricity, wood or geothermal energy are all possible fuels for greenhouse energy production. Dual systems, combining two types of fuel are also possible in order to have a backup system and more flexibility depending on fuel costs. Alternate fuel such as wood is now considered an important alternative for heating with the rise in price of fossil fuels that we are experiencing today. There are some greenhouses in Canada that currently utilize woody biomass for heating. Amongst others, the greenhouses "Jardins Nature" in the province of Quebec use wood pellets produced by Lauzon LTD. Their pellets are taken from sawdust residues of the company's quality hardwood flooring products. Additionally, Beverly Greenhouses in Ontario uses wood chips to provide heating to its seven acres of cucumber production while natural gas is used to provide carbon dioxide.

Energy Transport and Distribution

Space heating is the most energy demanding requirement of a building and particularly for a greenhouse under Canadian weather conditions. Many distribution technologies exist. Choosing an adequate system depends on many aspects of the local environment: temperature, soil, building material, building purpose, actual system, etc.

Currently, heat generated in the power house is distributed by steam throughout the radiators of the campus' buildings. Therefore, a piping system is already installed in the greenhouse. Replacing this system completely might not be the optimal solution. For instance, electric resistance heating might be cheap to install but it is considered as an inefficient solution and expensive to maintain. Alternatively, geothermal technology can be very expensive to install on existing buildings. Therefore, an alternative mean of transportation, which could use the actual piping network of the greenhouse, would be a high-temperature hot water distribution system. (US Department of Energy, 2008)

A hot water system is already known to be more efficient than the old steam system. However, a better look at the actual piping network of the greenhouse has to be done in order to make sure that the conversion to hot water is possible and make an appropriate design decision. Moreover, the whole length of the distribution pipe has to be insulated in a hot water system in order to minimize heat losses. In comparison, the returning pipe of the steam system does not have to be insulated to assure that the condensate returns. Pressure in a hot water system is elevated between one and two atmospheres in order to prevent boiling and to have temperatures over 100°C. The returning water usually has temperatures between 35 and 65°C. This energy is then conserved by having well insulated end pipes. Compared to steam, water can store 15 to 25 times more heat per cubic foot meaning that it can distribute and store much larger quantities of heat. More precisely, if the specific heat is compared at 100°C, water vapour has 2.060kJ/kg.°C while saturated hot water has about the double with 4.222kJ/kg.°C. (Holman 2002) Additionally, corrosion and scaling is reduced with hot water in generators, valves, piping and fittings. There is also about 10 to 20 percent loss of steam in the older systems because of flash tanks, flanges, valves stems, reducing valves, traps, etc. Hot water pipes do not need to have any specific slope as they are pressurised and the head loss is compensated since it is a looped network. Therefore, this piping system is advantageous for not requiring different pipe diameters such as for steam heating. Then again, further analysis has to be done to know if the current pipes can be used or not. (Liegois 2003)

During warmer seasons when heat is not needed, energy can still be produced by the stove and can be stored in a water tank. It was suggested by the Ministère de l'Énergie et des Ressources du Québec to use a 60 m^3 tank, for a building of 108m^2 of area and 435 m^3 of volume, with at least two fibreglass walls and a thermal insulation of polyurethane or an equivalent material. Therefore, CO_2 can still be produced and distributed during the day while the energy is stored in the tank. The hot water stored will be used for standard water needs or until heating is necessary.

Energy Requirements: Heat production

The amount of fuel required for a greenhouse can be estimated with the following equation (Aldrich R. A, Bartok J. W. 1990):

$$F = \frac{HDD(24) \times h_t}{C \times E \times t}$$

Where:

F= Fuel in trade units

HDD= Mean annual heating degree days for the location

h_t= Heat loss for the greenhouse, Btu/hr

t= Temperature difference for ht, ^{o}F

C= Heat content of fuel, Btu/trade unit for fuel

E= Efficiency of heating system in decimal form

To calculate the heat energy needs for a greenhouse, the heat loss must be determined. The heat loss is calculated based on the construction system of the greenhouse, the minimum inside temperature and an average outside temperature. The following equations are used to evaluate the heat loss of a greenhouse where the total heat loss is the sum of the four equations (Aldrich R. A, Bartok J. W. 1990):

Heat Loss Equations

$h_{clgl} = A_{gl}U_{gl} (t_i\text{-}t_o)$,

$h_{clcon} = A_{con}U_{con} (t_i\text{-}t_o)$,

$h_{clp} = PU_p (t_i\text{-}t_o)$

$h_{sa} = 0.02 M (t_i\text{-}t_o)$

Where:

h_{clgl} = Heat loss through glass, Btu/hr.

h_{clcon} = Heat loss through concrete, Btu/hr.

h_{clp} = Heat loss through the perimeter, Btu/hr.

h_{sa} = Heat loss by air exchange (infiltration), Btu/hr.

A_{gl} = Glass area, ft^2.

U_{gl} = Heat transmission through glass, Btu/hr.-^oF-ft^2.

A_{con} = Glass area, ft^2.

U_{con} = Heat transmission through concrete, Btu/hr.-^oF-ft^2.
P= Perimeter, ft.

U_p = Heat transmission through perimeter, Btu/hr.-^oF-ft^2.

M = Air exchange rate, ft^3/hr.

Annual reduction in fuel use with an increase in heating system efficiency can be estimated with the following equation (Aldrich R. A, Bartok J. W. 1990):

$$F = \frac{(E_n - E_o) \times 100_t}{E_n}$$

Where:

Fr=Reduction in fuel used, %

En= New heating system efficiency

Eo= Original heating efficiency

Carbon Dioxide Consumption in a Greenhouse

Carbon dioxide is the raw material needed for photosynthesis along with water. The rate of absorption of CO_2 by plants is determined by several factors being concentration, temperature, light intensity and stage of growth of the plants. Being able to control the amount of carbon dioxide between 1000 parts per million (ppm) and 1500 ppm in a greenhouse can have many advantages on plant quality, yield and development (Table 7). For instance, Laval University has observed a 30% production increase for their tomato cultures where CO_2 was artificially supplied. This effect has even been observed during winter when sunlight intensity and duration is at the lowest. Different sources of carbon dioxide are available for greenhouse supply since the atmosphere contains about 300 ppm. The easiest way to provide CO_2 to plant is using manufactured CO_2 since it is easy to store and offers a high purity but it is usually the most expensive option. A less expensive technique is using carbon dioxide from combustion. The main problem with this technique is if incomplete combustion occurs it can provide toxic quantities of ethylene gas and sulphur dioxide to the plants. To calculate the amount of CO_2 required for plants and the sizing of the equipment needed, the plant demand of CO_2 and the losses due to the infiltration of air through the greenhouse surface must be considered. The following formulas are used for these calculations (Aldrich R. A, Bartok J. W. 1990 & Conseil des productions végétales du Québec 1988):

1. Make-up CO_2 = Plant use + Infiltration Loss
2. Plant use = Greenhouse Floor Area X Plant Usage Rate
3. Infiltration Loss = Greenhouse Volume X Air Exchanges per Hour X 0.000001 X (Desired CO_2 level – 300)

Table 7 - Recommended CO2 concentration per plant species

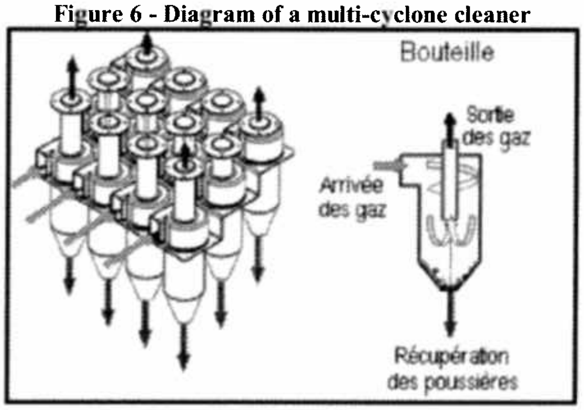
Specie	Recommended CO2 Concentration
Rose	1000-1200 ppm
Rhododendron	700-1000 ppm
Chrysanthemum	700-900 ppm
Poinsettia	600-800 ppm
Tagetes erecta	700-800 ppm
Petunia	700-800 ppm
Campanula	700-800 ppm
Begonia	700-800 ppm
Codiaeum	600-800 ppm
Dieffenbachia	600-800 ppm
Calathea	600-800 ppm
Tomato	1000 ppm
Cucumber	1200 ppm
Pepper	1000 ppm
Lettuce	1000-1500 ppm

(Conseil des productions végétales du Québec, 1988)

CO_2 Distribution

Since combustion from wood pellets does not provide pure carbon dioxide, the resulting gas has to be treated before being distributed. There are many different technologies to purify exhaust gases. For instance, multi-cyclone cleaners are useful since they can separate dust depending on the density of the particles, hence getting rid of the bigger ones (Figure 6).

Figure 6 - Diagram of a multi-cyclone cleaner



Dépoussiéreur multi-cyclones
Source : Compte. R. , CRIQ

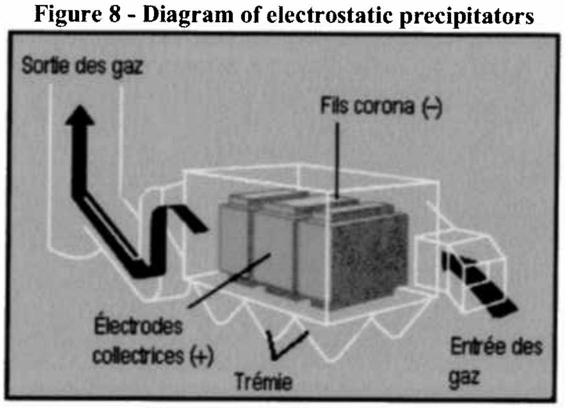
Alternatively or in parallel with the previous technique, wet scrubbers which operate by washing the smoke of the combustion can also be used (Figure 7).

Figure 7 - Diagram of a wet scrubber

Laveur de gaz
Source: www.forbesgroup.co.uk, CRIQ

Electrostatic precipitators are also very efficient. Dust particles are ionised by a series of negatively charged emitting electrodes and are then collected by positively charged electrodes. These are shaken by vibration to let the precipitate fall into a hopper (Figure 8). (Ministère des Ressources Naturelles et de la Faune 2006)

Figure 8 - Diagram of electrostatic precipitators



Précipitateur électrostatique
Source: www.epa.gov, CRIQ

The treated exhaust gas could be distributed throughout the actual tube system which is already in place at the greenhouse. The plastic tubes are perforated along the length and are considered as an efficient and economical means of distribution. Some CO_2 sensors could monitor the concentration of gas depending on what is being produced in each chamber. In case of excess, the gas should be redirected outside or compressed back in a storage tank since it is known that a high concentration can become a nuisance for the plant. The reports also stressed that carbon dioxide addition is even more justified when the building is well insulated. However, the current greenhouse of Macdonald Campus had a lot of open ceiling windows during the winter. Consequently, it was suggested by the greenhouse senior technician, Richard Smith, that the CO_2 additive be injected at a lower elevation. (Conseil des productions végétales du Québec, 1988)

5- Methodology

5.1 Design approach

First of all, to design the appropriate system for the new greenhouse on the campus, meetings with specialists in the domain of greenhouse management and wood pellet heating systems will be arranged. A meeting with the greenhouse technician on Macdonald campus will help to evaluate the current system and its main problems in order to design a system which is accurate and user friendly. To plan the heating system, we will meet a wood pellet specialist to take a look at different projects currently in place. Furthermore, a specialist in plant science and greenhouse management will be contacted to get information on CO_2 utilization for plants, using the carbon dioxide from wood pellet combustion.

After the relevant information has been gathered, data will be collected on the selected building. To establish the amount of energy required to heat this greenhouse, its dimensions will be measured using the plans provided by the greenhouse technician. The perimeter of the greenhouse will be determined along with the surface area of glass and concrete covering the building. Besides, the construction materials used will be identified to calculate the heat transmission coefficient needed to calculate the heat loss on the building.

To establish the amount of carbon dioxide required for optimal plant growth, an analysis of the actual system will be performed. Looking at the current devices installed in the greenhouse will help to design for a new CO_2 distribution system. A discussion with the greenhouse technician will also take place to find out his requirements and advice in order to have a system which is efficient.

Then, from data collected different calculations will be performed. The heat requirement will be established using the appropriate formulas. From this point, the amount of fuel required will be determined, which will lead to the amount of fuel that can be saved with this new design. With this, it will possible to compare the difference between using wood pellet fuel rather than natural gas. Another important calculation will be to determine the amount of CO_2 required for this type of greenhouse operation. Since it is a research unit, the help of the greenhouse technician will be needed to ensure that the design meets his requirements.

The next step will consist of designing the new heating system. Through this operation, the fuel type will be decided depending on the availability of Quebec suppliers. Another aspect that will be included in the choice of the fuel suppliers will be its location, in order to minimize the costs of transportation. Then the burner manufacturer will be chosen such that it accommodates the fuel type selected but also to provide the most efficient system, the best control on emissions and the lowest environmental impacts possible. Another decision that will be made at this point of the project will be the type of heat distribution system between hot water and vapour to have the lowest cost possible and best efficiency. When all these parameters will be determined, a storage area will be designed and the location of the burner will be established. The chimney will also be planned to accommodate the CO_2 redistribution system. The choice of filters to control the emissions and the ash disposal system will be planned. Finally the CO_2 distribution system will be designed to reach all rooms in the greenhouse and provide the necessary amount of gas needed.

Finally, a cost analysis of the whole system will be performed in order to choose the most reliable, efficient and environmentally friendly system.

5.2 Expected results

The expected result of this project is to design an innovative heating system for the new greenhouse on Macdonald Campus that will use renewable energy as a source of fuel. Different biomass will be considered in the design process in order to choose the most sustainable approach in providing heat to this building. A comparison of biomass supply will be done to see the difference between wood waste and grown biomass as a fuel.

Since the university must reduce its energy consumption by 7% by 2010, another important result that needs to be met with this project is to design a system that will bring to an important reduction in energy consumption for the same amount of heating requirements. In order to monitor the energy consumption of the greenhouse, meters will be included in the design and will serve as an example for Macdonald Campus which does not have any meters on any of its buildings.

Another important part of this design project is to observe if it is possible to use the CO_2 from combustion for plant growth enhancement. A new CO_2 distribution system will be designed to replace the actual one that is currently not in use. This part of the design could also serve as a possibility of further research being developed alongside a wood pellet system on the campus.

Because this heating system will be designed for a single building, compared to the actual power plant that provides heat for all buildings on campus via underground distribution, the advantages and disadvantages of a decentralized system will be evaluated in order to choose the most viable technique for future modifications on the campus.

5.3 Budget

The budget will include the annual cost of the selected type of pellets, including transportation and delivery fees. Next will be the cost of the boiler, storage facility and the installation fees. There will also be a substantial cost associated with the connection of the boiler to the distribution pipes as well as adjustments made to the energy distribution system. In terms of CO_2 distribution within the greenhouse, a filtering system for the boiler emissions and a storage tank for the accumulated gas will need to be considered as well as the CO_2 distribution system itself. In association with this, certain costs for installation and maintenance will be evaluated. Details on the exact prices and pellet quantities will be precisely determined in the second phase of this project since we need to perform specific calculations in order to determine what is required. Also, specialized suppliers will be contacted in order to have a clear vision of the possible costs that can be associated with this type of installation.

6- Anticipated Schedule

Table 8 - Anticipated Schedule

MONTH	TASK	TIME (hr)
September 2008	• Meeting with McGill University Services	5
	• Meeting with Greenhouse Technician	5
	• Meeting with Dr. Lefsrud	5
	• Meeting with biomass heating system specialist	5
October 2008	• Data collection on the new greenhouse	15
	• System calculation	10
	• Choose the fuel type for the burner	10
	• Determine the fuel burner system	10
November 2008	• Determine the burner company	10
	• Determine the fuel distributor	10
	• Perform the cost analysis	5
	• Design of system	15
December 2008	• Final Design Report development	40
	• Final Presentation development	15
	• Final Presentation	0.5
	TOTAL	160.5

7- Conclusion

In respect to this project proposal, there has been enlightenment about Macdonald campus and an appreciation of its distinctive attributes which make it unique. Under the circumstances that the campus is renowned to practice environmental sciences, the prominence of our project becomes that much more significant. Emphasizing the small scale of the campus, projects can easily be evaluated in the case of their respective potential and dynamics since information is readily available and contact personnel are easily accessible. Also, the campus's continuous evolution opens the door to new ideas, changes and opportunities for both staff members and students. Pertaining to the governing concepts of this proposal, there is a great feeling of pride and fulfilment in respect to the suggested support of the local industry through the use of our province's predominant natural resource and using this as a means of progressing towards environmental sustainability on the campus. Not only do we wish to support a local market but also an evolving technology that has not yet been exploited in this sector of the globe. An environmental campus setting the example in this case could be the ignition spark of further development of the wood pellet industry in Quebec.

In terms of design approach, real assumptions and calculations will be performed such that the outcome portrays to an actual design that could be used as reference if the project were to be seriously considered and financially supported. On that note, a true financial analysis will be evaluated where the actual cost of the project would substantially resemble the pre-calculated required investment. Although the design will not actually be constructed, there is hope that this project proposal will stimulate further sustainable development incentives on the campus.

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Bibliography

Aldrich R. A, Bartok J. W. 1990: Greenhouse Engineering. Northeast Regional Agricultural Engineering Service (NRAES). Ithaka (NY). 203 pages

(*ABS. Flexible Storage of bulk goods. Osterburken, Germany. http://mehlsilo.com/englisch/woodpelletsilo.htm*)

B. Hahn. Existing Guidelines and Quality Assurance for Fuel Pellets. 2004. UMBERA;Existing Guidelines on Quality of *Fuel Pellets: PELLETS FOR EUROPE PROJECT*

Çencel Y.A, Boles M.A, 2006: Thermodynamics – An Engineering Approach. McGraw-Hill. Pp 751-783

Conseil des productions végétales du Québec. (1988) “L'apport de CO2 dans les serres.” Gouvernement du Québec. Ministère de l'Agriculture, des Pêcheries et de l'Alimentation. 29 pages

Custom Fireplaces & More. (2008). “Pros and Cons of Burning Wood vs. Pellets to Beat High Heat Bills”. Retrieved on March 23rd, from http://www.customfireplacesandmore.com/hearth-articles/wood-pellet-heat.html

Dupuis J, Vallée V. 2007: Profil des produits forestiers - Étude de cas d'utilisation de la biomasse provenant de la forêt dans les chaudière à résidus pour la production d'énergie. Ministère des Ressources naturelles et de la Faune. Québec. 20 pages

Fiedler F. 2003: The state of the art of small-scale pellet-based heating systems and relevant regulations in Sweden, Austria and Germany. Solar Energy Research Center SERC, Department of Mathematics, Natural Sciences and Technology, Dalarna University College, Sweden. 21 pages

Holman, J. P. (2002). “Heat Transfer”. McGrawHill. Ninth Edition. 665 pages.

Houck J, Tiegs P. 2007: Global Warming Reduction Benefits from the Use of Pellet Fuel for Residential Heating. OMNI Environmental Services. 16 pages

Koeb-holzfeuerungen.15th March 2008 <http://www.koeb-holzfeuerungen.com/kus_tree//powerslave,id,1,nodeid,1,lang,EN.html>

Liegois, W. A. (2003). "Campus heating with high-temperature hot water." HPAC Heating, Piping, AirConditioning Engineering **75**(5): 56-59.

Mac Sustainable Project. 2006. “Ecosystem Sustainability Assessment”. MacDonal Campus. McGill University.

Mani, S., S. Sokhansanj, et al. (2006). "Economics of producing fuel pellets from biomass." Applied Engineering in Agriculture **22**(3): 421-426.

McKendry, P. (2002). "Energy production from biomass (part 1): overview of biomass." Bioresource Technology **83**(1): 37-46.

McKendry, P. (2002). "Energy production from biomass (part 2): conversion technologies." Bioresource Technology **83**(1): 47-54.

Ministère de l'Énergie et des Ressources du Québec. (1983). "Chauffage Solaire et Stockage Intersaisonier." Gouvernement du Québec. 57 pages

Ministère des Ressources Naturelles et de la Faune (2006). Biomasse Forestière Résiduelle. Direction du développement de l'industrie des produits forestiers. Gouvernement du Québec: 1-123

Natural Resources Canada. 2002: Burning Wood Efficiently. 10th March 2008 <http://www.canren.gc.ca/prod_serv/index.asp?CaId=103&PgId=613>

Onovwiona, H. I. and V. I. Ugursal (2006). "Residential cogeneration systems: review of the current technology." Renewable and Sustainable Energy Reviews **10**(5): 389-431.

Prasad, S. B. (1995). "Biomass-fired steam power cogeneration system: A theoretical study." Energy Conversion and Management **36**(1): 65-77.

Ring, E., S. Jacobson, et al. (2006). "Soil-solution chemistry in a coniferous stand after adding wood ash and nitrogen." Canadian Journal of Forest Research **36**(1): 153-163.

Samson R: Opportunities for Growing, Utilizing & Marketing Bio-Fuel Pellets. Resource Efficient Agricultural Production-Canada. Ste-Anne-de-Bellevue. 32 pages

US Department of Energy. (2008) "Energy Efficiency and Renewable Energy - A consumer's guide – Heat distribution systems." Retrieved on March 15th 2008, from http://www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/mytopic=12580