elementenergy

ARCOLA THEATRE

Energy feasibility study

Final Report

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Project No: 575

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1 EXECUTIVE SUMMARY

Arcola Theatre has commissioned Element Energy to conduct a study into the feasibility of the theatre eliminating its net emissions of carbon dioxide. The theatre is planning to undertake a renovation and expansion which will include measures to reduce electricity and heating consumption, and to wholly satisfy the remaining demand with renewable energy; the vision is to become the world's first *carbon neutral* theatre, giving wide public exposure to climate change and its potential solutions.

The study concludes that carbon-neutrality is indeed feasible. It would cost £250k – £350k in capital expenditure to avoid the 54 tonnes of CO_2 emissions *p.a.* which would otherwise be emitted. Savings of £4k *p.a.* would be made thereafter. Government funding is available which, if granted, would reduce the capital cost to the £140k – £180k range. These budget costs reflect today's prices, which are expected to fall over time.

A range of options have been considered. The following approach has been decided upon as the most feasible path toward carbon-neutrality.

- **Stage 0. Ensure baseline refurbishment takes place as planned.** It is crucial that all currently planned refurbishments do in fact take place. This includes double-glazing all windows, draught proofing the building, and fitting it with a controlled ventilation system. These measures (compared with using the building in its existing state of disrepair) will reduce CO_2 emissions from a total of 72 tonnes to 54 tonnes *p.a.*

- **Stage 1. Reduce consumption.** Demand for heat and electricity will be reduced by 43% and 32% respectively, through sensible use of energy. This will save 30 tonnes of CO_2 *p.a.* and cost £50k above the baseline refurbishment costs.

  Measures to be adopted are: the fitting of motion sensors on lights; individual thermostatic valves on radiators; internal roof insulation; CO_2-detector-controlled ventilation with heat recovery; maximal use of daytime lighting; use of energy efficient 'HIR' stage lights or possibly LEDs; energy-efficient appliances in general; and cultivation of a responsible attitude toward energy use.

- **Stage 2. Renewable heating – biomass boiler and active solar heating.** A boiler which runs on wood pellets and 3m^2 of solar thermal panels will supply nearly all of the building's remaining space heating and hot water demands[1]. These will cost £18 – £26k and £2.5k – £3k respectively, and save a combined 8 tonnes of CO_2 *p.a.* Government funding is available, which would reduce the cost by nearly 35%..

  Wood pellets will be delivered by lorry every two months (in winter) and pneumatically blown through a chute built into the side of the theatre. A new boiler room and separate fuel storage room will be required, and fire-safety and maintenance issues must be considered. At current prices, wood pellets will cost an extra £500 *p.a* over gas heating, and a maintenance and support contract with the supplier would cost £300 *p.a.*

- **Stage 3. Renewable electricity – photovoltaic cells.** A large array of solar cells will cover the building's roof, supplying all of the theatre's electricity needs and exporting excess to the national grid. This will be the most expensive part of the project, costing up to £210k for basic modules, and saving the remaining 16 tonnes of CO_2 *p.a.* Government funding is available, which would reduce the cost by 50%. It may be prudent to wait some time before installing this technology, as costs are expected to come down significantly in the next 2 – 5 years.

[1] A gas stove is still required for cooking, and a gas boiler will most likely be kept as a back-up. Their CO_2 emissions will be offset by extra electricity from PV arrays.

One exciting possibility is to turn the building's roof into a rehearsal space, shaded by a 'canopy' of semi-transparent PV modules, maximising exposure to the technology. Assuming 120m^2 of semi-transparent PV, this would cost an additional £40k for the modules, plus the price of the special frame (*ca.* £25k) and structure.

- **Stage 4. Promote energy issues.** The theatre will embark on a program of education and exposure from its firm foundation of carbon-neutrality. The aim will to lead others by example and if it is successful, the ultimate consequence of the project will be to save far more carbon dioxide than that saved at the site of the theatre alone.

  The technologies used (above) will be made as visible as possible, incorporated into the building's aesthetic. For example, internal insulation in the café area may consist of dyed sheep's wool covered with glass and illuminated from behind.

  The theatre may also adopt technologies primarily for the sake of demonstration. A fuel cell UPS (uninterruptible power supply) could be used to provide back-up electricity to the auditoria and Arcola's servers in the case of a grid failure.

  An integral aspect of the theatre's philosophy revolves around the 'foyer' concept. The theatre is intended to be a mingling place for minds and ideas. Energy issues are expected to work their way into people's conversations and on into the world.

- **Stage 5. ' Incubator' and energy services.** With its experience in attaining carbon-neutrality, Arcola Theatre will be in a position to be actively involved in energy-related technology.

  The building's second floor will be used as a workshop ('incubator') for developing energy-related technologies such as LED stage lights. The theatre will then act as a testing ground for these emerging technologies.

  Arcola may also help other theatres to reduce their CO_2 emissions. It would set up an 'Arcola Energy' team to assess other theatres' energy consumption, give them a set of proposed measures, then physically implement those measures.

Measures ruled out on the grounds of cost and feasibility include:
- External wall insulation (cost)
- Internal wall insulation on all internal walls (cost, space, though some exemplar walls may be insulated)
- Ultra-insulating glazing (cost)
- Wind turbine (structural issues, lack of wind due to surrounding buildings)
- Ground source heat pump (insufficient roof space to supply its electricity with photovoltaics. Heat pumps would be an alternative to biomass if substantial cooling is required)

The following graph shows how successive measures from stages 1 to 3 taken to eliminate the building's CO_2 emissions. These stages are dealt with in some detail in this report.

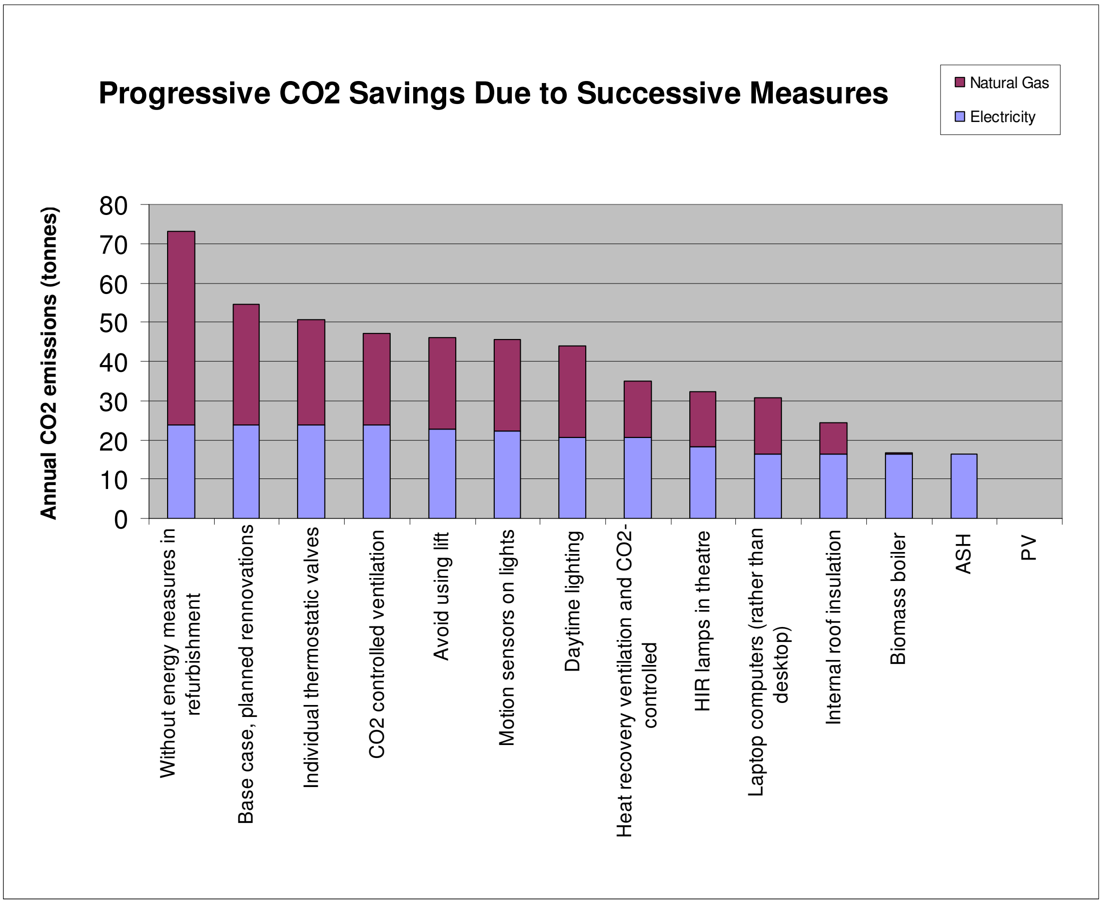

Figure 1 – Illustration of path to CO_2 neutrality

2 INTRODUCTION

In the light of increasing concern about anthropogenic climate change, and the traditional position of the arts at the vanguard of social change, the Arcola Theatre has a vision to eliminate all its building's CO_2 emissions.

Arcola is currently developing a new project to purchase and refurbish its existing theatre's building, a four storey industrial building in London's East End. As a part of this project, Arcola hopes to include energy-saving measures and renewable energy technologies, in order to become a net CO_2 neutral establishment and an inspiration for its forty thousand annual visitors.

This report has been commissioned by Arcola, to investigate and assess a wide range of measures which could be taken to realise the vision of carbon-neutrality. The report has concluded that carbon-neutrality is achievable, and sets out a plan to reach it.

2.1 Existing Refurbishment Plans

The planned refurbishment will expand the theatre from its existing two floors, into all four floors of the building it occupies[2]. In addition to theatre performances, the building will accommodate a range of cultural and community activities such as dance, film, music, technical training, writing, seminars, innovation and many others. The main spaces in the building are planned to be used as follows.

Basement floor
- Studio 1 – A 250-seat auditorium

Ground floor
- Bar/café – A space for working, relaxing and discussing ideas
- Office – Includes an IT training centre

First floor
- Studio 2 – An 80-seat auditorium
- Studio 3 – A 70-seat auditorium
- Studio 4 – A seminar room and general studio

Second floor
- Creative unit – Workshop and office space for development of technological concepts

The refurbishment will also involve double-glazing all windows, and installing a mechanical ventilation system.

2.2 Vision of Carbon-Neutrality

Currently, the Arcola Theatre produces 32 tonnes of CO_2 each year, due to consumption of 23MWh/year of grid electricity and 102MWh/year of mined natural gas. Under the baseline refurbishment scenario, it is expected to emit 54 tonnes of CO_2 *p.a.*

Emissions can be eliminated by using energy more efficiently, and exploiting renewable sources for the remaining energy demand.

[2] Currently, the building's first floor contains light industry, while the second floor is unused.

3 HEATING DEMAND REDUCTION

The yearly heat demand in the existing theatre is 105 MWh. Heating comprises 82% of the theatre's total energy use, and 60% of its CO2 emissions. Heat is lost mostly through walls, windows, the roof, and air changes.

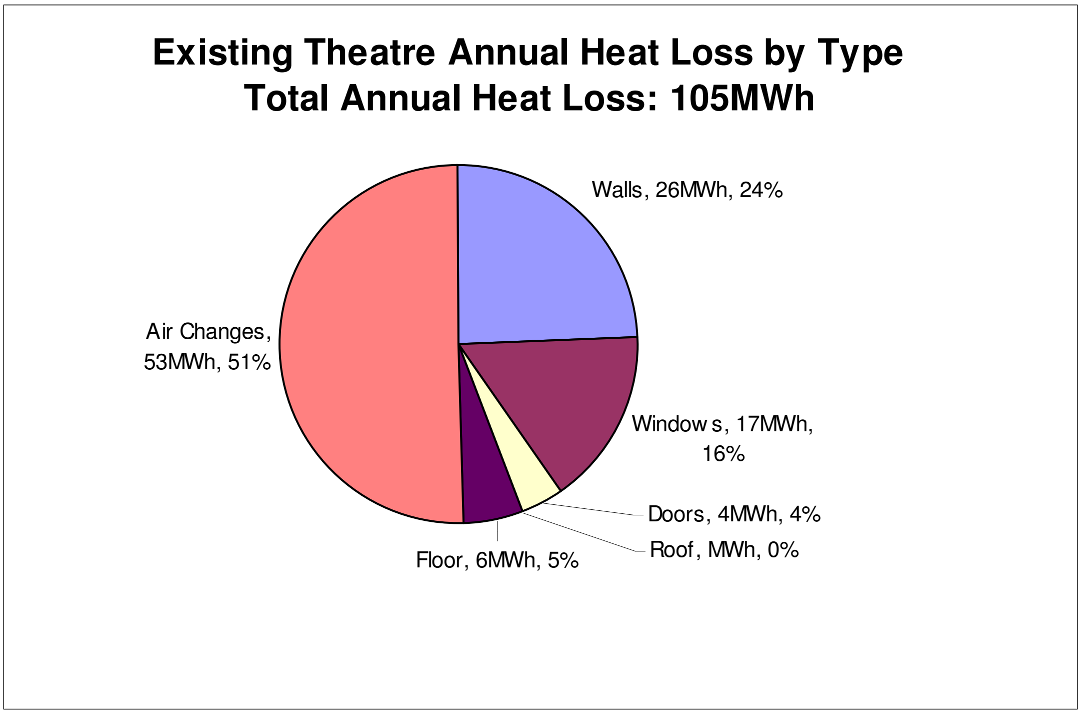

Figure 2 – Graph showing breakdown of heat loss in existing ground floor and basement

A model for the building's heat loss was constructed, taking into account conduction and radiative loss through building fabric and loss due to air infiltration as influenced by London's weather patterns. Analysis showed that the heat demand for all four floors of the building in its existing state would be 249MWh/year if it were heated throughout. The theatre's expansion is expected to be associated with refurbishment, including double-glazing of all windows and Installing controlled ventilation. Under these measures, the projected baseline heat demand for the theatre is 172MWh/year.

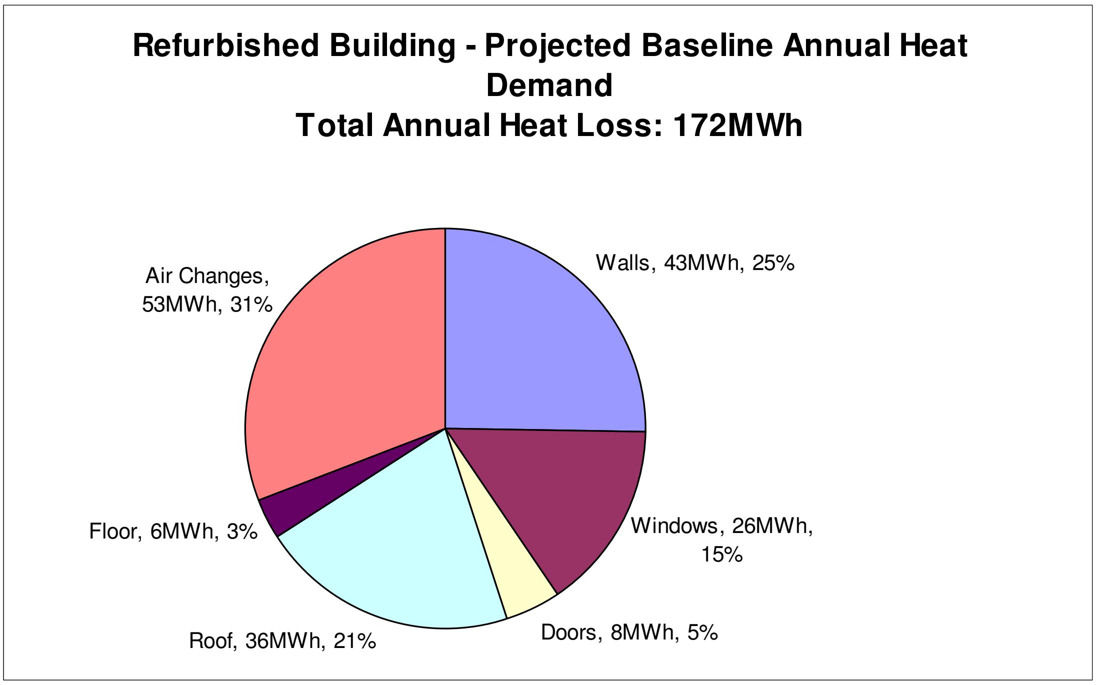

Figure 3 – Graph showing projected breakdown of heat loss in baseline refurbished building

Losses through walls and roof can be reduced with extra insulation. Losses through windows can be reduced through further glazing measures. Losses due to ventilation can be reduced to a point through more accurately controlled ventilation, and reduced further using heat recovery technologies.

3.1 Heat Loss Through Windows – Insulating glazing

Windows lose heat through conduction (heat transferred between adjacent bodies) and radiation (infrared rays passing through the glass). Double glazing reduces conduction losses since the air gap acts as an insulator. Filling the gap with a partial vacuum, or a heavier gas such as argon, further reduces conduction losses. Radiation losses can be reduced by coating the glass with a 'low-emissivity' material which reflects infrared radiation back into the building while allowing visible light to enter from the outside (identical to the 'greenhouse effect').

Windows' frames and sashes can also result in heat losses, particularly if made out of metal (usually aluminium). These losses can be reduced by including a 'thermal break' in the frame. This is a layer of rubber in the frame/sash, splitting it into an outside half and an inside half, with no metal bridge joining the two.

Curtains or blinds can have an insulating effect. These can only be used when daylight is not required. In addition, good habits are needed to ensure that the curtains are pulled every night. Alternatively, this can be automated.

3.1.1 Specific Relevance for Arcola

The existing building has mostly very old windows with metal sashes and frames, contributing to significant heat losses (50 MWh/year). Many of these are boarded or bricked up since the theatres need to be dark. The planned renovations involve replacing all old windows with double-glazed ones. This will save 24MWh/year of heat. The remaining heat loss through the windows will be26MWh/year. For further heat savings, the theatre could consider highly insulating windows (low-emissivity coating and argon-filled) saving a further 11MWh for a price of £20,000.

3.1.2 Implementation

The decision regarding the degree of energy-efficiency of the windows will need to be taken before the renovations occur, so that the building's windows only need to be replaced once. The decision is a straightforward one, based on cost and CO_2 saving. No extra planning is required.

3.2 Heat loss through walls and roof.

Figure 4 – Application of internal insulation

Buildings lose heat through their walls and roofs by conduction. The loss can be reduced by using extra insulation material. The properties of the walls and roof are characterised by a 'U-value' which states the rate of heat flow (in W) per square metre per unit temperature difference (℃). A well-insulated building will have a low U-value. The 2006 Building Regulations Part L requires that new buildings have walls with U-values less than 0.3W/Km^2.

The Arcola Theatre building has 972m^2 of external solid brick walls (60cm thick) and a 536m^2 concrete roof, 30cm thick, with U-values of around1.0 W/Km^2 and 1.6 W/Km^2 respectively. When the building is heated throughout, they will conduct 79MWh a year of heat away from the building. This figure could be nearly quartered with adequate insulation. Since the walls have no cavity, and the roof has no loft, insulation must be placed either internally or externally.

3.2.1 Internal Insulation

Internal insulation is typically achieved by laying slabs of polystyrene or mineral wool in a frame against a wall and fitting a plasterboard covering. It is relatively cheap and does not require professional installation. The main downside of internal insulation is that it takes up space. Insulation 10cm thick on all levels for all external walls would use up 33 m^2 of floor space. Valuing floor space at £200/m^{2}year, this carries an effective cost of £6,700 per year. The relevant cost/benefit figures for internal insulation are shown in the following table.

	Insulation type	Cost/m^2 (material)	Cost/m^2 (labour)	Yearly cost in lost space	Total Cost	Final U-value	MWh saved/year

Walls	6cm rock wool	£20	£20	£4.7k	£39k	0.29	32
Roof	6cm rock wool	£20	£30	–	£27k	0.31	29

Internal insulation carries the disadvantage that it insulates the building from the wall's thermal mass, lowering the walls' thermal store cooling advantage in Summer.

3.2.2 External Insulation

This involves gluing 120mm thick polystyrene slabs to the external wall, with 5mm of rough cement render. Since weatherproofing is necessary, details such as windows and pipes add significantly to the cost. Most of Arcola's services run on the outside, and there remain unused vents and pieces of pipe left in the wall from the building's time as a factory. Finally, scaffolding needs to be built around the entire building. The cost of the whole undertaking is estimated to be £85,000, and the energy savings 35Mwh/year. This report does not recommend external insulation for Arcola.

3.2.3 Implementation

Internal insulation should be fitted before serious work is undertaken on the interior finish. However, in the studios, where the interior is finished with a coat of black paint, insulation could be installed at any time.

In the bar/café area, aesthetics need to be strongly considered. Plasterboard can lend a sterile atmosphere, compared with the earthiness of the existing warehouse brick décor. Coverings other than plasterboard are available (chipboard for example has a more interesting texture).

One possibility would be to use organic (possibly dyed) sheep wool insulation, covered with glass. Insulation is usually hidden from view and its benefits are rarely thought about. Making an aesthetic feature of it instead would be a way of bringing it into people's minds and conversations – an aim which is central to Arcola's energy project.

3.3 Ventilation and Cooling[3]

Whenever cold air enters from the outside, it needs to be warmed by the building's heating system. To heat The building's 1,500m^3 of air from 5°C to 22°C, takes 9 kWh of energy. The heating demand due to cold air can be reduced by eliminating draughts. However, in order to keep people comfortable and avoid mould, a certain rate of fresh air is required[4]. The heat loss from this minimum ventilation can be reduced through heat recovery ventilation systems.

Summer cooling needs will also be considered in this section.

3.3.1 Draught Proofing

Draught proofing[5] is usually the most cost-effective way of reducing heating demand, quickly paying back its capital cost. The Arcola building has draughts due to old windows, broken windows, old doors, and gaps where pipes (water, gas, vents) penetrate the wall. The windows will be replaced, and the rest of the building draught proofed as a matter of course during the renovation. The draught proofing procedure involves attaching rubber strips to the

[3]The behaviour of moving air is very difficult to model, and the only way of achieving accurate figures regarding the air flow through the building would be to do field tests. The numbers in this section must therefore be treated with caution.
[4] Recommended 10L/s per person
[5] The procedure involves attaching rubber strips to the perimeter of doors and windows, and sealing small gaps with sealants.

perimeter of doors and windows (costing *ca.* £4 per metre) and sealing small gaps with sealants.

As a large building with a low ratio of wall space to volume, draught proofing alone would make the Arcola building insufficiently ventilated yet installing passive fixed vents to compensate would negate the benefits. The advantage of draught proofing therefore, is that it allows an effective controlled ventilation system to be installed.

3.3.2 Ventilating and cooling the main auditoria

The current theatre has a problem with over-heating in summer. There is no ventilation and no active cooling during performances. As a result, the internal gains can lead to very high internal temperatures and uncomfortable conditions for both actors and audience.

One aspect of the proposed renovation is to address the over-heating problems in the summer. The performances in the theatre require the elimination of noise and this limits the availability of natural ventilation during the performance. Whilst there are well designed louvre devices which minimise noise from openings in a façade (see below), it is unlikely that these will provide sufficient ventilation for cooling during performances. As a result, some form of ducted ventilation system is likely to be required. To minimise energy requirements for ventilation, consideration should be given to including in the ventilation system a natural system based on openable areas in the façade (either windows or louvres), in this type of 'hybrid' system, the mechanical ventilation is minimised, only used when either cooling or fresh air requirements dictate the need to turn it on. This type of operation is most applicable in the spring and autumn, where external temperatures are appropriate to allow air into the theatre, without creating additional heating or cooling demands.

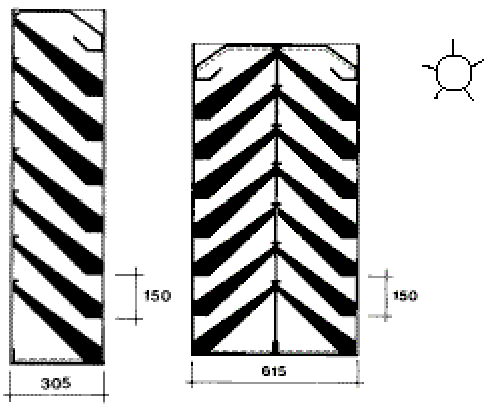

Figure 5 – Illustration of noise reduction louvers, which can be used as a part of a natural ventilation strategy

To improve summer time comfort still further, it is possible to add active cooling to the mechanical ventilation system to reduce the temperature of the air dispersed throughout the theatre. Where possible, the theatre should be designed to minimise the need for active cooling as this imposes a substantial additional energy demand on the theatre and will affect the overall zero CO_2 strategy - essentially more on-site generation would be required to offset the active cooling.

Measures to avoid active cooling include:

- Specification of theatre internal temperatures – in order to avoid active cooling being specified in the renovation, it is important to specify the internal temperatures so that the M&E designers do not feel obliged to install an active cooling system. A specification that internal radiant temperatures should not exceed 25ºC for more the 5% of occupied hours and 28ºC for 1% of occupied hours is a recommended specification which would suit a natural or limited mechanical ventilation strategy.

- Night time ventilation (passive) – by opening the theatre windows and any other openings at night, it is possible to create a flow of cool night time air into the theatre. This flow of cool air cools the massive stone walls inside the theatre and provides cooling during the day (similar to a church). A night time cooling strategy requires a) sufficient open openable area at night – this can create a security hazard and appropriate grilles or well designed louvers are required to avoid unwanted entry, b) the mass of the theatre must be exposed (i.e. not covered by false ceilings and plasterboard walls), to ensure that it is available to reduce the temperatures during the day.
- Installation of cooling, with strict criteria governing its use – if cooling is to be provided, then is necessary to be very strict about its use. From an energy perspective, one week of active cooling a year will not jeopardise the zero carbon strategy of the building. The danger of active cooling is when it is used regularly throughout the year. Any active cooling should be carefully rationed and used as part of a cooling strategy which maximise night time cooling and accepts higher temperatures in summer.
- Use of ground source heat pumps to provide cooling – if the M&E engineers for the theatre regeneration conclude that the theatre will require substantial active cooling, then it is possible to substantially improve the efficiency of the cooling by using ground source heat pumps (see below).
- It should be noted that all electrical appliances produce heat. For example, stage lighting strongly contributes to overheating of auditoria, particularly for the performers working under the glare. The more energy-efficient these appliances are, the less heat they produce. This makes a further argument for using energy-efficient appliances (see section 3).

Without a detailed design of the theatre layout it is difficult to assess the need for active cooling – the renovation design work should include an assessment of the most appropriate cooling strategy by the M&E engineers, as informed by the specification considerations above. In addition, aspects of layout of vents and ducts are important to the efficacy of any cooling strategy and should be carefully considered by the theatre M&E engineers.

The diagram below illustrates a displacement ventilation strategy, which is often successful in low energy theatre designs

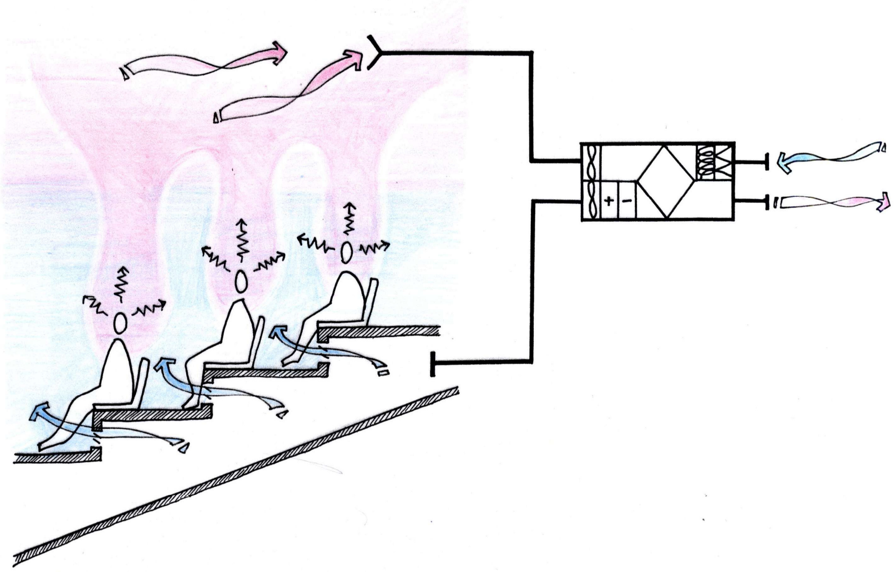

Figure 6 - image of a displacement ventilation strategy for cooling in a theatre. Cold air is introduced at low level, to cool theatre occupants. As the air is heated, it rises to high level where it is removed.

3.3.3 Non-auditoria spaces

Small spaces which are unlikely to be subject to large occupancy (dance studios, office etc.) can be cooled using a single sided natural ventilation strategy. Maximising openable areas allows windows to be opened to achieve ventilation and cooling during the day. This implies specifying windows with a large openable area, the most appropriate sash type is illustrated below. If these windows can be opened at night (with some form of security), the cooling effect from the building's thermal mass can be maximised.

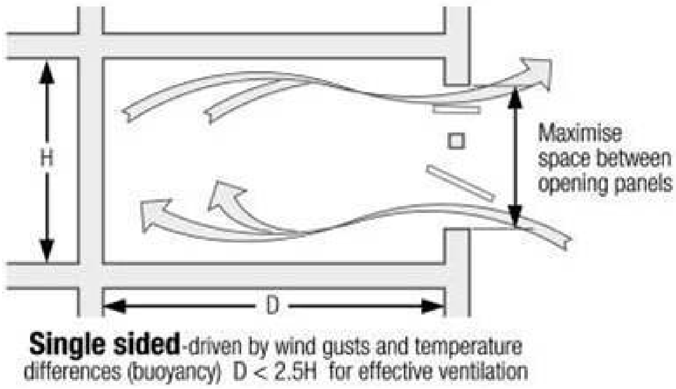

Figure 7 –illustration of a single sided ventilation strategy, appropriate for smaller rooms in the renovation near to openable areas.

3.3.4 Shading

In addition to maximising openable area, consideration should be given to shading, to prevent excess gains through the windows. In practice, as the main window area of the building is to the east, and the building is surrounded to the south and east by other buildings, the shading requirements are minimised. However, on the higher south facing floors and east facing floors (particularly if a new level is added, shading options should be considered, including external louvres (ideally) on the upper floors or reflective internal blinds (which are not as effective as they allow some heat into the space and also minimise daylighting).

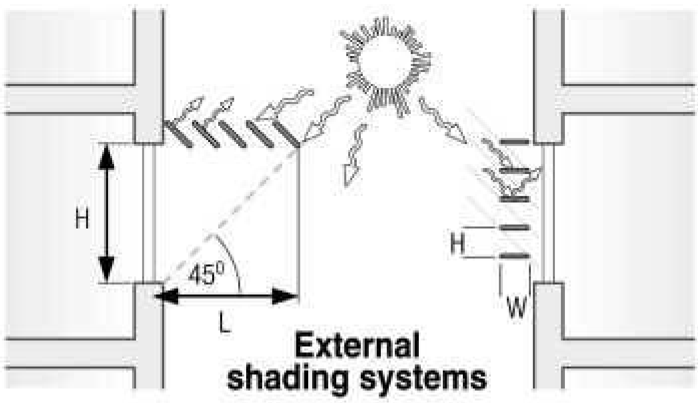

Figure 8 – external shading devices offer the most effective shading, as they keep all incident heat out of the building and minimise glare whilst still allowing a substantial portion of available daylight into the building.

3.3.5 Controlled Ventilation

Once draught proofed, the building will need to have a system to maintain adequate ventilation. This is expected to be a centrally controlled mechanical ventilation system involving ducts and fans, particularly to ventilate the café and auditoria. The advantage of controlled ventilation is that the rate of air flow can follow the occupancy of the building – when the building is near empty, little ventilation is required.

It needs to be ensured that the mechanical ventilation system in the Arcola building does in fact adjust its flow according to occupancy. This can be automated with carbon dioxide sensors, or the system can simply work on a timer, given that the occupancy follows a similar pattern each day.

The planned baseline controlled ventilation (using a timer) will save 54MWh/year over the current situation of 'accidental ventilation'. Controlling ventilation via a CO_2 sensor timer would save an additional 16MWh/year. There would also be an associated electricity saving.

3.3.6 Heat Recovery Ventilation

Heat recovery ventilation systems pass the outgoing warm air close to incoming cold air so that the streams exchange heat but don't mix. Thus the incoming air is warmed by the outgoing air before entering the building. As much as 70% of the heat of the outgoing air can be recovered.

To include a heat exchanger in the system would save 35 MWh per year of heat, and cost £15k, above the base case of time-controlled ventilation.

The CO_2 advantage of such a system is weakened by the fact that it consumes electricity. If the outside temperature is 8°C cooler than inside, saving 1kWh of heat would require 0.34kWh of electricity. This does constitute a net CO_2 saving, but if electricity is expected to come from PV arrays, it increases the effective monetary cost of using a heat recovery system.

3.3.7 Implementation

The ventilation system needs to be tailored to Arcola's circumstances. The peak occupancy of 500 people will only occur in the evenings, and when so occupied, the 50kW of heating produced by 500 bodies significantly reduces heat demand. It would be sensible to have a heat exchanging ventilator which can provide enough ventilation to accommodate a daytime occupancy of max. 100 people. In the evenings, the heat exchange unit would be bypassed, and the system would act as traditional mechanical ventilation. This would also be done during summer nights, when it is desirable to thermally equilibrate with the outside air (see next section).

3.4 Summary of Heating Demand Reduction Measures

Measure	Capital cost	Yearly monetary savings (assuming gas heating)	Yearly CO_2 savings (tonnes)	Recommended?	Notes
Double-glazing	(baseline)	£935	6.3		Baseline refurbishment measures. CO2 savings are compared with fully heated building in current state.
Controlled Ventilation and draught proofing	(baseline)	£2066	14		
Low-emissivity coated, argon filled glazing	£21,200.00	£349	2.3	NO	
Internal wall insulation	£38,908.00	-£3663[6]	6.8	NO	Reduces thermal mass cooling during Summer. Requires floor space
External wall insulation	£85,002.40	£1118	7.5	NO	
Internal roof insulation	£26,790.50	£922	6.2	YES	
CO2 detector-controlled ventilation	£1,050	£507	3.4	YES	
CO2 detector-controlled and heat recovery ventilation	£16,050	£1336	9.0	YES	
Individual thermostatic valves	£208	£607	4.1	YES	Requires people's engagement for effectiveness

[6] Cost is due to rent price of lost floor space

4 ELECTRICITY DEMAND REDUCTION

Current electricity demand for the theatre's two existing floors is 22.8 MWh/year. After the renovations, the baseline demand is projected to be 41 MWh/year. Low-power fluorescent lights will be used for space lighting, traditional incandescent (usually halogen) lamps will be used to light the theatre. It is assumed that under this baseline scenario, the theatre and studio spaces will make no use of natural lighting. The other main sources of electricity demand will be ventilation fans, a three-storey lift, computers and bar appliances (fridges, coffee machines).

A model has been constructed to predict electricity demand after the refurbishment (see appendix for assumptions). The biggest consumer of electricity will be space lighting. This demand can be reduced significantly by taking advantage of sunlight. LED lamps for stage lighting, motion sensors on all lights, and general energy-efficient appliances are technological solutions to demand reduction. Procedural changes will also be necessary.

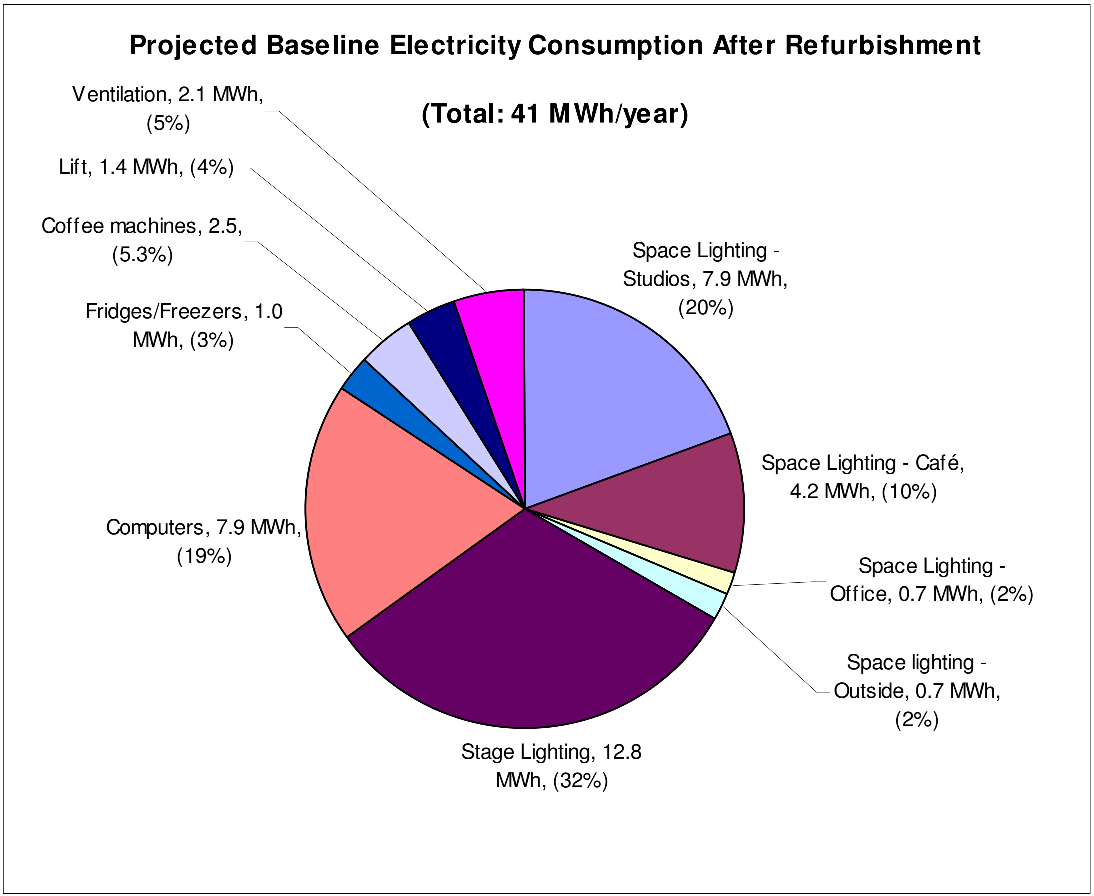

Figure 9 – Graph displaying baseline electricity consumption after refurbishment and expansion

4.1 Natural Lighting

The sun's light is free and carbon-neutral as well as psychologically and physiologically beneficial. Properly utilising sunlight for daytime lighting could save 35% of the overall space lighting demand over the baseline scenario, or 3.3MWh of electricity per year.

The building as stands requires daytime electric lighting because the basement and ground floor spaces have had their windows bricked or boarded. Theatre spaces do need the capacity to block out all external light, but this can be achieved by fitting all windows with heavy blackout blinds rather than permanent barriers, allowing daylight to be used whenever simple space lighting is required. A conventional approach in rehearsal studios is to use thick heavy black curtains which run across an entire wall. Some existing brickwork will need to be removed.

To further maximise natural lighting, spaces other than auditoria should be painted light colours, and include wall mirrors (desirable for a dance studio in any case). Circuitry should be such that the lights in areas shaded from sunlight are on circuits separate to other lights, so that they can be turned on independently.

'Light shelves' are a technological aid to natural lighting. They are essentially horizontal mirrors (or white surfaces) positioned to maximise natural lighting. Placed at window level (two-thirds up) they can divert sunlight evenly around the room rather than having it pooled next to windows. Alternatively they can be external and beneath the windows, exploiting sunlight which would otherwise fall uselessly on bricks.

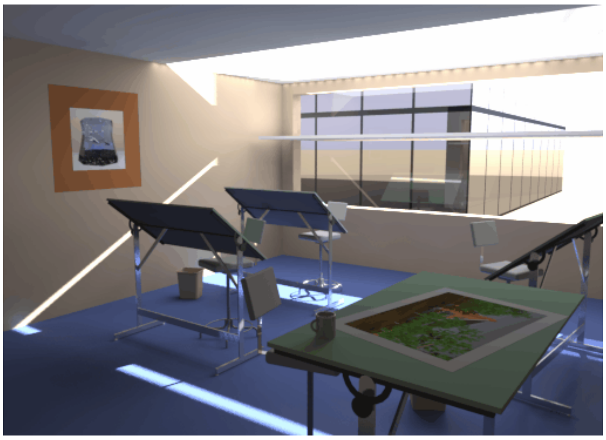
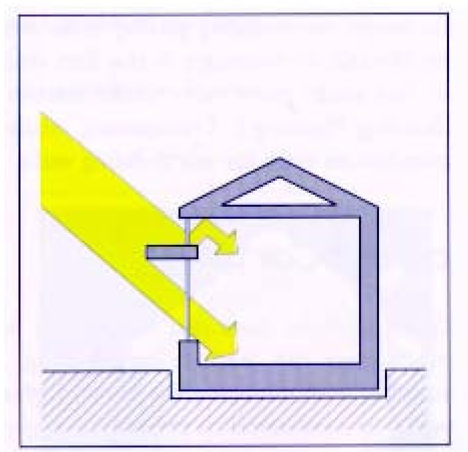

Figure 10 – Illustrations of light shelf principle

4.2 Stage Lighting

Figure 11 – An existing stage light

Stage lights are projected to account for nearly a third of all electricity use. However, it is difficult to make them more energy-efficient. Currently, very bright halogen lamps are used. Fluorescent lighting cannot be used because of its warm-up time and inability to be dimmed. Low-energy LEDs are predicted to dominate stage lighting in years to come, but are currently undeveloped and unworkable. Special energy-efficient 'HIR' halogen lamps are available and should be used.

4.2.1 LED lighting

In principle, light-emitting diodes (LEDs) would make ideal stage lights. They are low-energy (so less likely to overheat the actors) and in arrays can be controlled to give a range of lighting effects involving timing and colour[7].

The barrier to using LEDs in stage lighting is the problem of overheating. For efficiency and longevity, LEDs must operate at low temperatures. To collect LEDs in the concentrations required to produce light equivalent to a 1kW halogen lamp generates a prohibitively high concentration of heat. Researchers are attempting to tackle this problem by developing LEDs to work at higher temperatures, as well as more effective heat dissipation systems. Increasing political will for energy efficiency, notably the recent EU pledge to phase out incandescent lights, will provide further drive for such efforts.

LED lighting should be kept in mind as a long-term option. Current LEDs are around twice as efficient as halogen lamps, allowing a potential electricity saving of at least 6MWh/year. Efficiencies and costs are improving at a surprising speed.

One option for the theatre would be to engage in a partnership with a company undertaking research into LED stage lighting. In return for cheap cutting-edge lighting, the theatre would provide a testing ground and publicity platform for the researchers.

4.2.2 Halogen Infra-Red (HIR) lamps

It is possible to obtain halogen lamps which are coated with a optical layer which reflects infra-red, allowing visible light to pass through. The reflected infra-red further heats the

[7] A common claim that 'LEDs cannot be dimmed' is now redundant. Modern electronics can dim LEDs either by carefully controlling current, or by pulsing at high frequences.

filament, reducing the required electric current. The efficiency of these lamps is 35% higher than standard halogen lamps, while their cost is approximately triple. These lamps are not easily obtainable. The theatre should make an attempt to establish a source of HIR lamps, and use them whenever replacing conventional lamps. Up to 4MWh/year of electricity could be saved.

4.3 Automatic Controls

Lights commonly remain switched on after people leave the room. Indeed, the basement's electricity consumption is significantly higher than that of the (much larger) first floor. Anecdotal evidence suggests this may be due primarily to wasted lighting. Motion sensing switches can be installed in each room, to switch off lights after a period of no movement. These are inexpensive at around £50 per unit, and could save a large amount of electricity (depending on current habits, probably around 15% of space lighting electricity).

Timed switches are another effective way of reducing electricity consumption for devices which do not require continuous use, but which people tend to forget to switch off. The bar fridges for cooling drinks do not need to be left on at night. Similarly, the outside lights could benefit from timed control (currently some are on manual switches, and are often left on).

4.4 General Energy-Efficient Appliances

General appliances, projected to consume 14MWh/year of the building's electricity, commonly have energy-efficient alternatives. All appliances should be assessed on their energy-efficiency before being purchased. Particularly, laptop computers should be purchased in preference to desktop computers wherever possible; this alone would save 3Mwh of electricity per year.

4.5 Procedural Changes

Encouraging people to use less electricity will reduce electricity demand, and provide an educational opportunity. People should be encouraged to avoid using the lift (saving ca. 1.3 MWh/year) switch off stage lights when not in use, and leave computers off or on hibernate where appropriate. Laptop chargers can consume electricity even when not in use, so people should be encouraged to switch off power at the wall. This would be easier if all chargers were fed by a single wall socket which could be switched off every night. A culture of energy-awareness should be fostered.

4.6 Summary of Electricity Demand Reduction Measures

Measure	Capital cost	Yearly monetary savings (assuming grid electricity)	Yearly CO_2 savings (tonnes)	Recommended?	Notes
Natural Lighting	£3,000	£253	1.9	YES	Installing curtains and removing brickwork
HIR stage lighting	£0	- £370	2.3	YES	If obtainable
LED stage lighting	Unknown		3.3	YES	Experimental technology
Motion sensors	£678	£68	0.5	YES	
Laptop computers	£0	-£368	2.0	YES	Compared with desktop computers

5 HEAT SUPPLY

The theatre's existing space heating and hot water demand of 107 MWh/year is supplied mostly[8] by three gas-powered combination-boilers (non-condensing), running at approximately 80% efficiency. The fuel is natural gas, supplied by the gas grid at an effective rate of 2.8p/kWh.

Alternative heating technologies should sensibly be considered only after demand-reduction measures have been taken. If, on top of the baseline scenario, CO_2 ventilation controls and internal roof (not wall) insulation is fitted, a dedicated heater will need to supply only 45MWh/year of heat, with an average midwinter daily heat demand of 500kWh, and a peak daily heat demand of 700kWh. A non-seasonal demand of 3MWh/year of hot water must also be satisfied.

The renewable or low-carbon heating technologies which will be considered are ground source heat pumps, biomass boilers, and 'combined heat and power' fuel cells[9,10]. The heating systems in this section are specified for ratings of 60kW (satisfactory for heating demands stated above). Prices for these systems scale roughly linearly with power rating.

Low-carbon heating technologies tend to have large capital costs per kW of output. It may be sensible to size these for a 'base' heating load, and have a gas combination-boiler on standby to meet unexpected peaks. Retaining a connection to the gas grid will be necessary regardless, as the theatre plans to have a kitchen with gas stoves.

The actual heating demand will depend on the extent to which the measures recommended in section 2 are adopted. Given this uncertainty, there are three approaches to deciding on a low-carbon heating system:

- Oversize the low-carbon system to ensure demand can be met
- Size the system to an anticipated 'base' demand or under. Use a gas boiler to meet spikes in demand. This is the most likely option.
- Keep the existing heating system until a post-refurbishment winter has been experienced. Heating demand can then be measured directly from gas bills.

Once scheme details are confirmed, sizes should be checked by a services engineer.

[8] The boilers supply 82MWh/year. The rest is waste heat from appliances (11MWh/year of useful heat) and occupants' metabolism (14MWh/year of useful heat). For the rest of this section, 'heat demand' will refer only to the amount of heat which must be supplied by dedicated heating systems.
[9] The new bar/café will have kitchen using a gas stove. This will have to remain gas, as electric heating is much harder to cook on, and worse from a CO_2 perspective. To achieve carbon neutrality, this (very small) gas use will need to offset by, for example, a net export of electricity from PV cells.

[10] CHP is dealt with under the 'Electricity Supply' section, 5.3

5.1 Biomass Boiler

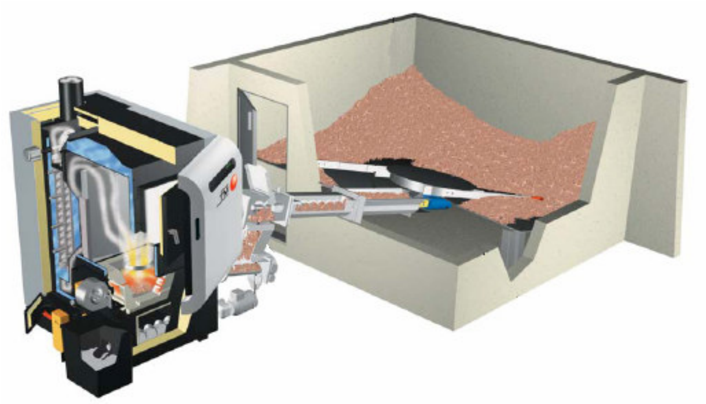

Figure 12 – Biomass boiler and store room; wood pellets

Burning crops is a carbon-neutral heating method, since all carbon released during combustion originates in the atmosphere, having been absorbed during crop growth[11]. Wood-based fuels are the current leader, in the form of chips or pellets made from waste wood. Wood pellets are formed from sawmill waste which would otherwise go to landfill.

Fully-automatic chip or pellet-fuelled boilers are available. Fuel is delivered in large loads (several tonnes) by lorries. Storage space is an issue to be considered. A prospective owner of a biomass boiler would also need to consider reliability of supply, fire safety, and the best way to integrate a boiler into a heating system.

5.1.1 Space and Placement Demands

A typical 60kW pellet boiler needs a space of 2.2m x 3.2m of floor space, and a height of 2.1m for adequate access and function. The space needed for fuel storage depends on the arrangement set up with the supplier. Suppliers prefer to deliver several tonnes of pellets at a time and deliveries are priced accordingly. A 10m^3 storage space would allow deliveries of 6.5 tonnes. In winter, deliveries of this size would have to happen every two months to satisfy the projected heat demand. This volume would require 3-4m^2 of floor space. Structural integrity must be considered when planning the storage space as the walls would need to withstand the significant pressures caused by the fuel's weight.

Fuel is transported from the storage room to the boiler via an electric worm conveyor, whose power consumption can be as high as 2.5kW. Due to gravity, the power needed to move the fuel depends on the height of the storage room relative to the boiler. In order to use as little electricity as possible, the storage space should be close to, and higher than, the boiler.

Fuel is pneumatically delivered to the storage room (see Fuel Supply below). The storage room would therefore ideally be located at the edge of the building, with a feeding chute accessible from the outside of the building. Having the chute at a low level would allow delivery to be gravity-assisted, making fuel delivery easier and less energy-intensive.

5.1.2 Integration with services system

Boilers produce high-temperature (65 – 90℃) water, which could be used in the existing radiator system without modification.

Biomass boilers require more ventilation than gas boilers. A flue would need to extend from the boiler to 1.5m above the building. Existing flues could be utilised for this purpose.

[11]Currently, there are some CO_2 emissions due to the growing, processing and transportation of biomass fuel. The energy used in these processes however, is estimated to be less than 2% of the energy provided by the fuel.

Hot water demand could be met by a biomass boiler. Unlike gas boilers, which can increase output suddenly to heat flowing water, biomass boilers have large 'thermal inertia'. A hot water tank would need to be installed in order to use a biomass boiler for hot water heating. A biomass boiler could also dovetail nicely with active solar heating to supply year-round hot water (see next section).

5.1.3 Safety Concerns

Without careful measures a biomass boiler, and its associated mass of dry wood, could pose a fire hazard. Arcola would need to update its assessment for the Regulatory Reform (fire safety) Order in consultation with the fire brigade.

Specific safety measures recommended by boiler manufacturers include:

- Fireproof wall between boiler and store
- Fire resistant walls for boiler room and store room
- No electrical equipment in store room
- Light and labelled emergency stop switch outside boiler room
- Portable fire extinguisher, 6kg filling weight

5.1.4 Fuel Supply

A number of companies offer fuel delivery. Fuel would be delivered by lorries on a regular basis, and blown through a hose into the storage room, up to 30m away. A chute anywhere on the walls of the South, East or North sides would therefore be easily accessible.

Contracts would need to be negotiated with fuel supply companies. Companies offer varying levels of price, security of supply, and guarantee of environmental merit. Prices will also depend on frequency of delivery, and whether the buyer is prepared to engage in a long-term contract. Details would need to be negotiated.

5.1.5 Feasible Implementation Scenario

The boiler could be sensibly placed anywhere along the east edge of the Basement, with the store room in the floor above, or in an elevated structure in the basement. This is close to existing wet heating connections, and oriented to allow gravity-assisted fuel transport.

Once particular scenario would be to place the boiler in the south-east corner of what is now Studio 2 (to become a tech room). The store room could be built above the basement's WC, below the basement's ceiling, avoiding use of floor space. Leaving the new WC ceiling at a height of 2.3m, the store room could have 1.6m height, giving a more than adequate 13.5m^3 volume.

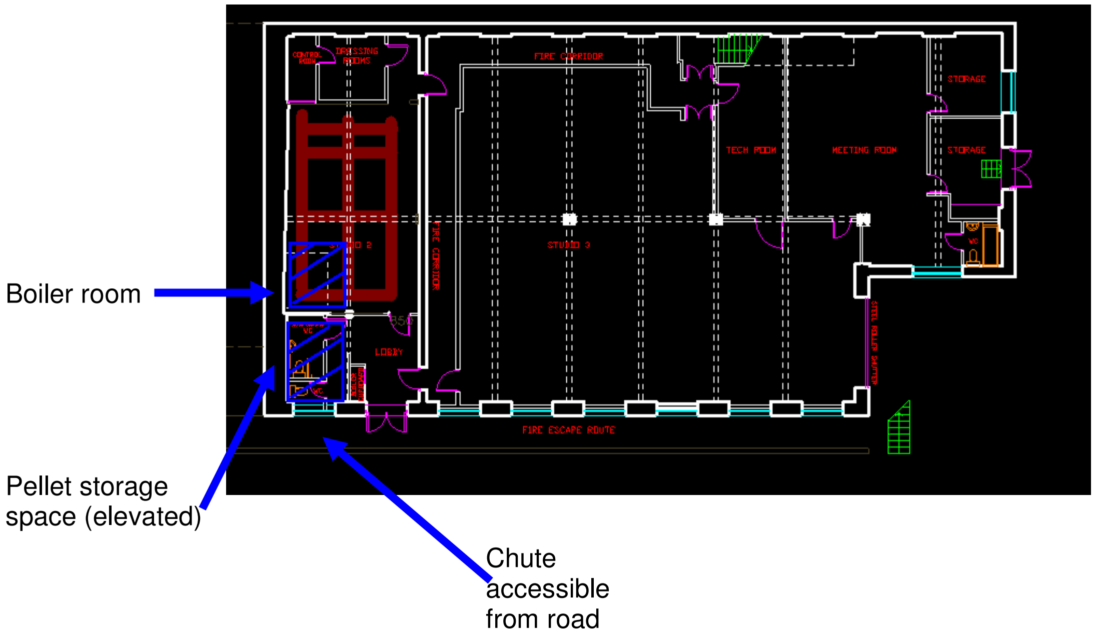

Figure 13 – Diagram of basement showing possible placement of boiler and store room

The two basement boilers would be removed. Hot water during Summer could be supplied either by the remaining gas boiler, an electric immersion heater, or by the boiler itself if it is able to operate efficiently at loads as low as 0.5kW.

5.1.6 Costs

Boiler prices vary according to manufacturer and are in the region of £16k - £24k for a 60kW boiler, covering all parts and installation. In addition, the cost of preparing or building appropriate boiler and storage rooms would needs to be considered. This is likely to involve straightforward brickwork, at a cost of £50 – £57 per square metre (single brick thickness).

Prices of wood fuel are more stable than gas prices, and are expected to fall considerably over coming years unlike rising gas prices. Currently, delivered wood pellets cost 3-4p/kWh (compared with gas, at 2.8p/kWh). The additional annual fuel cost will therefore be *ca.* £500/year at today's prices.

Boiler suppliers offer an ongoing maintenance and support service, at *ca.* £300/year. Maintenance could be carried out by those using the boiler much more cheaply.

Taking into account the additional floor space required for a biomass boiler and storage facility, an extra £1,500 could be added to the effective annual cost, based on a rent price of £200/m^2.

5.1.7 Implementation

A biomass boiler system should be implemented after detailed discussions with fuel suppliers, boiler suppliers and builders. The size of storage space will depend on the contract agreed to with fuel suppliers. Fire-protection and structural integrity also need to be ensured.

5.1.8 Summary

Biomass Boiler Summary		Notes
Required size of boiler room Required storage space	2.2m x 3.2m x 2.1m $10m^3$	
Frequency of fuel delivery (winter)	Every 2 months	
Cost of Boiler (installed) Cost of building storage and boiler rooms	£16k - £24k £1,700	Assuming $34m^2$ of wall needed
Price of wood pellets per kWh Annual marginal cost of wood pellets at 58MWh/year consumption Energy density of wood pellets Bulk density of wood pellets	3-4p/kWh £500 5kWh/kg 650kg/ m^2	Compared with gas
Annual effective cost of lost space Suppliers' quoted annual maintenance and support cost	£2,000 £300	
Annual CO_2 savings	14 tonnes	
Other issues	Fire Safety, security of supply.	
Conclusion	**A biomass boiler is a sensible option for meeting heating demands**	

5.2 Hot Water Supply

2MWh/year of hot water is required for washing, the same as for a typical household. During summer, this could be supplied by active solar heating (ASH) panels. These are roof-mounted panels which use the Sun's radiation to heat a fluid to temperatures close to 100℃, The fluid is passed through coils in a hot water tank, transferring its heat. Usually there is a secondary heating coil in the tank (from the wet heating system) to provide heat when there is o output from the solar panel.

If a biomass boiler was installed (see above) it could supply hot water during Winter.

In order to use ASH or a biomass boiler for hot water, a new two-coil hot water tank would be required (*ca.* £500). This should be as highly insulated as possible to reduce heat loss. A gas boiler would still be kept to bridge unexpected supply gaps.

Around 3m^2 of 'evacuated tube' panels would be required, costing £2,000 - £3,000.

The ASH works well with a biomass boiler, as it can be sized to meet summer hot water demands, avoiding operating the biomass boiler at very low utilisation levels with frequent cycling (which tend to damage the boiler).

Figure 14 – Active solar thermal panels

5.3 Ground Source Heat Pump

Ground source heat pumps (GSHPs) use the ground as a heat source. Cold antifreeze (4℃) is pumped through underground loops of pipe, where it absorbs heat from the ground (which is at an even temperature of around 10℃). Heat from this fluid is then 'pumped' into the water of a wet heating system, using the same principle as a fridge – electricity is used to pass refrigerant through a compression and expansion cycle, effectively transferring heat from one place to another.

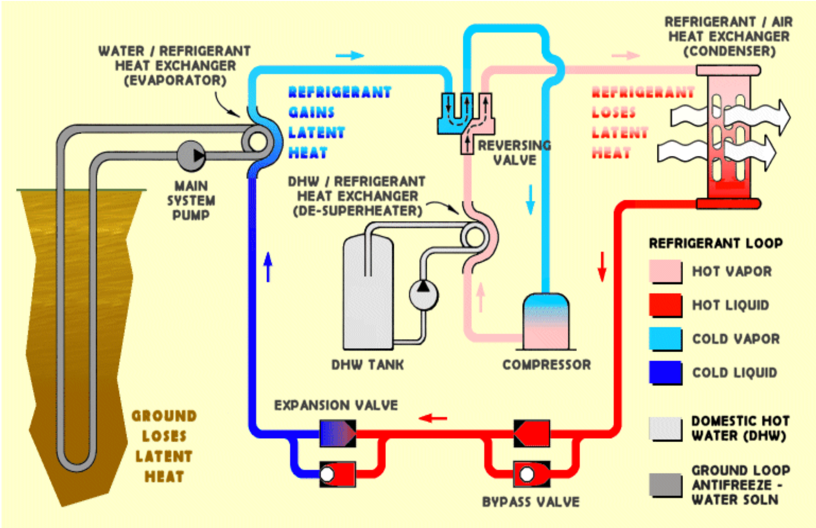

Figure 15 – Schematic diagram illustrating GSHP principle

The GSHP holds considerable appeal, because it exploits genuinely local and renewable energy. Unfortunately, it has substantial electricity consumption[12], which weakens its CO_2-saving merit. Using a grid electricity-powered GSHP instead of gas boilers would reduce emissions due to heating by only 33%.

Another concern is that the final water temperature is around 45°C (radiators usually operate at ~85°C) which means that a large heat distribution area, compared with heating demand, is required. For this reason, GSHPs are suited to well-insulated buildings with underfloor heating.

There are also GSHPs available which can be switched to reverse cycle to provide cooling in summer.

5.3.1 Installation

The main installation issue is the underground pipes. Horizontal trenches are a common approach, but impractical in the case of Arcola due to a lack of space. The alternative is to drill deep bores 75-100m containing loops of pipe. These bores need to be well spaced (5-7m separation) and there needs to be a bore for every 3-5kW of the GSHP's rated thermal output. Arcola owns some land on the East side of the building, including a car parking space to the northeast . The following diagram speculates how 17 bores could be placed, allowing for 60kW of GSHP peak thermal output. Actual placement will depend on accessibility, and geological issues. Indeed, in some areas of London, drilling becomes very difficult beyond 50m. A geological survey would need to be carried out before drilling bores.

[12] Each kWh of heat from a GSHP requires 0.25 – 0.33 kWh of electricity, producing 0.14 - 0.18 kg CO2 if the electricity comes from the British grid. For comparison, gas heating produces 0.21kg CO2 per kWh, and electric heating produces 0.57.

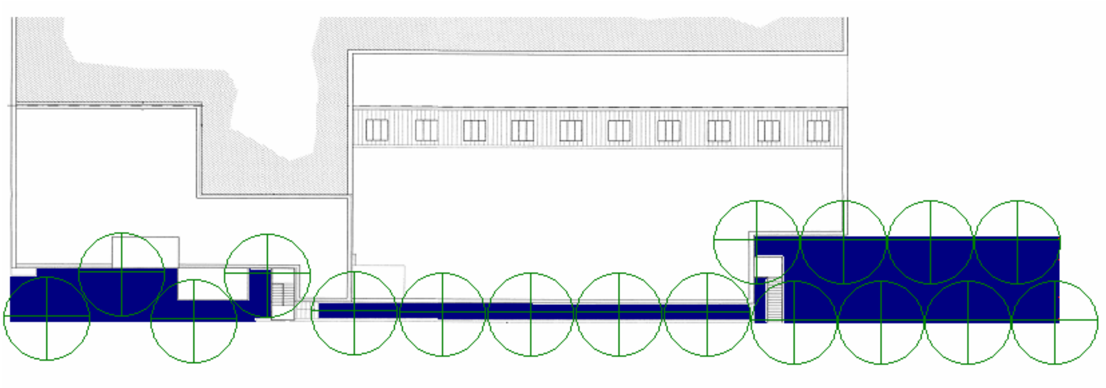

Figure 16 – Diagram showing possible placement of bores

5.3.2 Integration

Even if a heat pump can in principle produce enough heat to replace a building's heat loss, the rate at which heat can be delivered is limited by the heat distribution system. An underfloor heating system would be ideal for a GSHP, but it would be costly and difficult to install.

The radiators which Arcola currently uses can transfer heat sufficiently quickly for the current heating demand, given water temperatures of ~85°C. After energy-conscious refurbishment, the heating demand relative to the number of radiators may be halved. Assuming that the heat transfer is proportional to the temperature differential between radiator water and room air, a radiator temperature of 45°C could satisfy the future heating demands if the number of radiators was increased by 50%. In reality, radiator effectiveness depends strongly on convection currents whose effects are non-linear, so we couldn't expect such a system to be effective. Very lightweight 'low water radiators' are also available which are designed to work at temperatures as low as 40°C.

Figure 17 – Low water radiator

5.3.3 Costs

The cost of installing a GSHP is dominated by the cost of drilling boreholes, at a rate of at least £20 per metre. Price and effectiveness will depend on the geological properties of the Arcola's ground, but a system of bores adequate for a 60kWth GSHP would be expected to cost £50,000– £100,000.

The heat pump itself would cost £20,000 – £30,000. The cost of installing further radiators or underfloor heating must also be considered.

Maintenance costs for a GSHP would be small.

Electricity costs need to be considered, especially if electricity is expected to eventually come from PV panels. At current electricity and gas prices, the theatre would save £1,000 annually.

5.3.4 Summary

Ground Source Heat Pump Summary		Notes
Required number of bores	12 - 20	
Bore spacing	$10m^3$	
Coefficient of performance	3 - 4	Ratio of heat out to electricity in.
Water temperature	45℃	
Cost of bores for 60kWth GSHP	£50k - £100k	
Cost of heat pump (installed)	3-4p/kWh	
Annual net savings	£1,000	Assuming current grid electricity and gas prices
Annual CO_2 savings	3 tonnes	(33% of emissions due to gas boilers)
Other issues	Requires greater heat distribution area. Ground may not be suitable. Running costs will be very high if electricity is to come from PV	
Conclusion	**GSHP is not recommended for Arcola Theatre**	

6 ELECTRICITY SUPPLY

All electricity in the existing theatre comes from the national electricity grid, through EDF Energy, branded as 'Green Electricity'[13]. Each kWh of electricity produces 0.57kg of CO_2 and costs 7p. The available technologies for supplying electricity on-site are photovoltaics, wind turbines, and 'combined heat and power' fuel cells. These are technologies which can supply electricity to the theatre building and, when there is insufficient demand, automatically sell the electricity to the national grid. Each technology is considered separately.

For carbon-neutrality, a renewable electricity system must supply 28MWh of electricity annually, assuming the recommended energy-saving measures have been adopted (see section 2).

6.1 Photovoltaics (solar cells)

Figure 18 – Photovoltaic array

Photovoltaic (PV) cells convert sunlight into electricity. Since they have no moving parts, they boast very low maintenance and a long lifetime. Their capital cost is their biggest detractor. Typically, a 3mx3m PV array will cost £5,000, generate 1kW of electricity in peak sunlight, produce around 800kWh of electricity in a typical year (in the UK) and have a 20 to 25-year warranty. PV technology can work wherever there is direct sunlight, and it is often the only way of using on-site natural resources to produce electricity.

When planning to install an array, there are a number of practical issues to consider.

- Location. Any shade severely impairs PV performance. If a single cell within an array is shaded, the performance of all other cells in the array is also reduced. Cells should be placed such that there are no obstacles at 30° or higher to the south, east or west.
- Orientation. The panels need to be oriented to maximise sunlight. In the UK, the ideal is south-facing, at an angle of 30° to the horizontal.
- Circuitry. Individual PV cells produce low-voltage, direct current (DC) power. Usually, many cells are linked in series to produce arrays of 400V to 600V. If the array needs to be connected to the electricity grid, or used with appliances designed for grid electricity, the output needs to be converted to the standard 230V 50Hz alternating current (AC) power produced by the grid. This is done with a device called an inverter, which typically comprises about 10% of the whole system cost. Inverters need to be replaced periodically, with average lifetimes of 8 – 15 years.

[13] This does not mean that it is carbon-neutral. Under the renewables obligation, EDF is legally obliged to source a minimum proportion of its electricity from renewable sources, and it does not surpass this obligation. Purchasing this 'Green Electricity' therefore does not result in a reduction of CO_2 emissions, as the electricity would have been sold regardless.

- Fixing. Attaching PV cells to a structure is not usually difficult, since there are no large or awkward loads involved. However, when attaching PV to a roof, care must be taken to maintain the roof's integrity, particularly regarding waterproofing.

6.1.1 PV potential for Arcola Theatre

Arcola Theatre has a large unshaded roof, which makes photovoltaics a viable option. Indeed, there is enough roof space to meet more than twice the theatre's current electricity demand.

The roof has almost no external shading (the highest shading angle comes from the building to the East, which is at *ca.*11° elevation). There are features of the roof itself which do produce some shading. As seen in the picture above, the roof has two levels. The lower level, on the North side, is partially shaded by the upper level. Other sources of shade are the five vents and a shed on the lower level, the lift shaft, and the parapet. The following diagram shows the sufficiently shade-free areas of the roof, under successive scenarios.

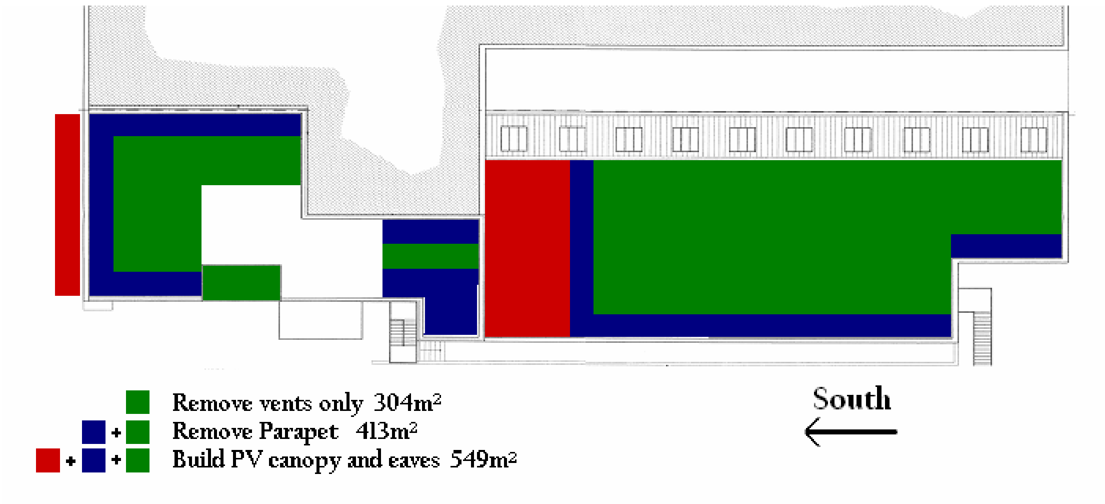

Figure 19 – Roof area able to be used for PV

6.1.2 Technical Issues

There is a compromise between cost and efficient use of space. To maximise total output one would tile the entire roof with modules laid horizontally. To maximise efficient use of funds one would lay modules at 30°, facing south, and space modules far apart from one another and from any other potential sources of shade.

Considering circuitry, the only difficulty is in taking wires inside the building while keeping the roof waterproof. There are a number of access points on the roof which can be used. The details will need further investigation.

There are two standard options for attaching modules to the roof. The modules can be clipped to a standard aluminium frame, which is attached to the roof – either by drilling into the roof itself with appropriate waterproofing measures, or attaching to elements such as the parapet. Alternatively, the modules can rest on the roof without penetrating it, weighted down by ballast (concrete slabs or sandbags).

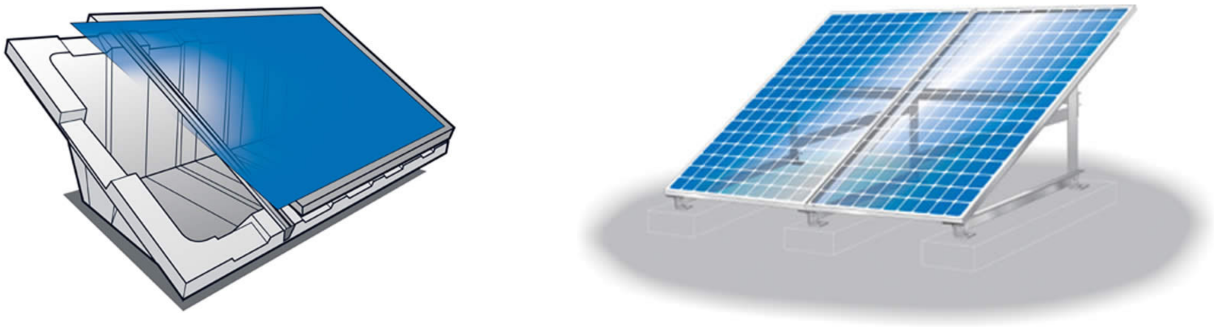

Figure 20 – Pictures of ballast and metal frame systems

6.1.3 Multi-use Structures

One exciting option particularly suited to Arcola, is to integrate PV into a rooftop canopy. Thus the lower roof could be converted into a rehearsal space for Summer, where shade is provided by a canopy of PV cells. The canopy, if big enough, would be able to maximise the space's PV potential, while staging a striking and potentially quite beautiful demonstration of solar power.

In the same vein, another idea which could be explored is to have PV cells projecting from the top of the south façade like eaves, visible from the theatre's entrance. Again, this would have the benefit of making the technology more visible, promoting awareness. It would also have the traditional advantage of eaves – providing shade from the high sun in Summer, while permitting Winter's low rays.

There are two practical ways of implementing these ideas. One is to build a structural frame (eg. aluminium) and clip standard PV modules to it. Unfortunately this only allows people to see the uninteresting plastic underside of the modules. The second option is to use glass-backed modules, and to integrate these into the structure (see below). This gives a semi-transparent sheet, creating a dappled light effect and making the PV cells an aesthetic feature.

Figure 21 – Double-glass PV installation

Glass-backed modules are significantly more expensive (around 40% more) since they need to be made bespoke, whereas the plastic-backed modules are standardised and mass-produced.

6.1.4 Costs

Currently, the fully-installed cost of PV is £5k – £6k per kW (peak). To meet the theatre's projected net electricity demand of 27MWh/year, a 40kW system would be needed, costing around £210k and consisting of 300m^2 of panels. To fit, most panels would be laid at 5° to the horizontal, taking up 430m^2 of roof space. With careful tailoring, this would be able to fit on the existing roof without need for extra structures.

If the plan were to include eaves and a canopy, the cost of the modules would increase by around £40k. Then the cost of the frame (*ca.* £200/m2, and the structural support must be added).

Arcola is currently paying 7.6p/kWh for electricity, and would be paid 4p/kWh for selling electricity to the grid. Assuming 50% of electricity is exported, an array of this magnitude would save £1,800 each year. This won't pay back the capital cost over the system's lifetime, but discounted at 6% (mortgage rate) the lifetime electricity savings amount to a present value of £23k.

NB. PV is still an immature technology, and its price is expected to drop in the coming years. In addition, the current prices in the UK of £5k – £6k per kW are heavily inflated. In Germany for example, PV costs £4k per kW. One option to consider would be for the theatre to import German PV and install it itself.

6.1.5 Implementation

Due to its high cost, PV should be the final phase in the Arcola's carbon-neutral project. There are no cost benefits in installing PV during the refurbishment and the price of PV should drop during this time.

6.1.6 Summary

Photovoltaics Summary		Notes
kWh/year per kW rated	800	In the UK, at optimum angle of 30°
PV area (m^2) per kW rated	8	
Fraction of ideal output obtained if panels are horizontal	0.85	
Total kW/year potential: remove vents	25843	
Total kW/year potential: also remove parapet	35105	
Total kW/year potential: also build extensive canopy and eaves	46623	Assuming Panels laid flat
Price per kW (standard modules)	£5	Fully installed, including inverter.
Price per kW (double-glass modules)	£7k	Price expected to come down.
Cost of PV for 28MWh/year	£210k	Laid flat on roof
Cost of PV for 28MWh/year, including 12m^2 of eaves, and 120m^2 of canopy	£250k	Not including cost of structures
Possible cost of canopy frame	£24k	(200£/m^2)
Yearly savings	£1,800	Assuming PV produces 33MWh/year
Yearly CO2 savings	16 tonnes	

6.2 Micro-Wind Power

Figure 22 – Picture of 'swift' wind turbine

Small-scale wind turbines (0.5 to 15kW) can be an effective way of generating electricity from local resources. The wind's kinetic energy is converted to electrical energy via the turbine's blades and generator. Fully installed systems cost £3k– £4k per kW (peak), generating 2,000 kWh/year per kW peak.

Wind speeds of at least 5m/s are recommended by manufacturers, and can be difficult to find in urban landscapes. Wind passing over a city is slowed by the unevenness of the built-up surface. In addition many locations are directly sheltered by neighbouring buildings. Urban wind also tends to 'gust', changing direction frequently. Often a turbine can't turn to face the wind direction quickly enough, preventing it from exploiting the available energy.

Anchoring the turbine is the other major concern. Strong wind forces (several kN) on the turbine generate large moments and vibrations at the base. The fixing details of the turbine need to be carefully considered in order to maintain the building's structural integrity, and to obtain planning permission.

6.2.1 Micro-wind potential for Arcola Theatre

The Arcola Theatre building is sheltered on three sides by buildings 1.5 storeys taller, making it a poor place for wind power. In order to penetrate the wind's boundary layer, a turbine would have to be extended at least 10m above the height of the building. Suppliers are loath to attempt this. The cost and planning barriers to building an effective turbine are prohibitive.

Element Energy advises that the theatre is not a suitable site for micro-wind technology.

6.3 Fuel Cells

Fuel cells are devices which convert a fuel into electricity using an electrochemical process. The electrochemical process does not suffer from the thermodynamic losses inherent in conventional electricity generators which make use of combustion processes. As a result, fuel cells offer greatly improved efficiency for electricity generation and hence significant CO_2 savings if they are adopted widely.

Fuel cell technologies are in the pre-commercial stage of their development. A wide variety of fuel cell technologies and fuel cell applications are being trialled and the costs of fuel cells are falling rapidly[14]. As part of the aspirations for using the Arcola theatre's renovation to demonstrate new energy technologies, the possibility of deploying a pre-commercial fuel cell has been suggested.

There are two practical applications for fuel cell deployment at Arcola, a fuel cell based UPS system or a small fuel cell CHP demonstrator Neither of these would save more CO_2 than achieved by the measures above and would be more useful as demonstrations of the technology than for cutting the overall CO_2 of the theatre.

6.3.1 Fuel cell UPS

Fuel cells have found an early niche application in Uninterruptible Power Supplies (UPS) in buildings. The rapid response time of a Proton Exchange Membrane (PEM) fuel cell when powered by hydrogen means that PEM fuel cells can provide a backup source of electricity in a system designed to protect important electrical loads in a building. Because the conventional technology for UPS systems (lead acid batteries) tend to be expensive and bulky and because the fuel cell life in a UPS application is very short, the PEM fuel cell is able to compete today in UPS applications

Typically a UPS system would be connected to sensitive loads linked to data storage in a building. Arcola theatre does not currently make use of a UPS system, relying instead on the grid stability. It is therefore difficult to justify a hydrogen based UPS system. However, Arcola's entire IT system is based on servers at the site, including processing of payments from the internet and it may be practical to consider a UPS system inked to hydrogen fuel cells.

UPS systems are available from a range of suppliers:

Supplier	Size	Estimated installed cost
Plug power (most widely used)	5 kWe	£20,000
Relion	1 kWe (modular)	£3-8,000
P21	1 kWe	£3-8,000
UPS (Hydrogenics)	10 kWe	£50,000

These systems can be procured from a range of UK suppliers including SIgen, FDT and Logan Energy. Each of these systems require a supply of hydrogen, which would be sourced from an industrial gas supplier such as BOC or Air Products (indicative cost £500-£1,000/year, including cylinder rental cost and delivery). Hydrogen would ideally be situated outside the building in a secure (fenced) compound.

6.3.2 Fuel Cell Combined Heat and Power (CHP)

The possibility of combining a fuel cell and a boiler to produce a combined heat and power system (CHP) on a similar scale to domestic boilers is attractive. The high electrical efficiency of a fuel cell means that a significant amount of electricity can be generated for every unit of heat consumed in the building. Because the waste heat from electricity generation is used on-site, the process is substantially more efficient than the conventional electricity supply which wastes the majority of the input energy in the cooling towers at power stations.

[14] For an introduction to fuel cell technology, see www.fuelcelltoday.com

Two fuel cell technologies are relevant to small scale CHP, neither of which are yet commercially available. In either case the fuel supply would be natural gas. The table below summarises the technologies closest to commercialisation in the UK market.

Company	**Size**	**Technology type**
Ceres power + British Gas	1 kWe	SOFC (intermediate temp)
Plug power	5 kWe	PEM
Baxi	1 kWe	PEM (Europe)
Ceramic Fuel Cells (+ various European boiler manufacturers)	1 kWe (approx)	SOFC (high temp)
Sulzer Hexis (in some financial difficulties)	1 kWe	SOFC (high temp)

These systems have been developed primarily for the domestic boiler market and as such could replace one of the existing domestic boilers currently in use at Arcola. Perhaps the most appropriate system for Arcola would be the Ceres Power system which is being developed with British Gas, as a wall hung unit. This has the advantage of being developed by a UK company, making the company more likely to support a Arcola based demonstration.

It is possible to buy into pre-commercial demonstrations of the technology. For example demonstration units of the BAXI system have been made available at a cost of £100,000 each. This is not a practical use of funds for Arcola. It may be possible to encourage a fuel cell supplier to use Arcola as a demonstration site for their fuel cell systems, as part of the overall low carbon strategy for the theatre, though it should be noted that there are a number of willing demonstrators for FC technology in the UK.

Failing becoming involved in an early CHP demonstrations, the alternative is to design the building heating systems to allow retrofit of fuel cells once the first fuel cell CHP systems become available on the market.

6.3.3 Implementation

In taking forward either of these projects, Arcola would be demonstrating a valid use of a fuel cells in a building and would be one of the first users of fuel cell technology in the UK. As a result, Arcola would contribute to the development of the emerging fuel cell industries. However, either fuel cell would be unlikely to achieve a major CO_2 reduction for the theatre and fuel cells should not be considered core to the low carbon energy strategy for the theatre.

7 FUNDING

7.1 The Low Carbon Building Program

The DTI is running the Low Carbon Building Programme is aimed at stimulating the uptake of a range of low carbon building technologies, including Photovoltaics, Ground source Heat Pumps, Biomass boilers and Active Solar heating. The programme is specifically aimed at buildings which demonstrate an integrated approach to the deployment of low carbon building technology as has been recommended for Arcola. The possibility of linking two technologies (biomass and PV) as suggested here would increase the chances of funding under the programme.

The programme is divided into two phases:

Phase 1 (administered by the Energy Saving Trust – EST) £30 million to spend by 2008 – aimed at any adopter of the technology. In this case an application could be made to support the entire energy refit, with an expectation of 40-50% of the costs of the active generation technologies. The Phase 1 process is open to all buildings in the UK and as such any application would compete with applications from businesses and private individuals.

Phase 2 (administered by the Building research Establishment - BRE) aimed specifically at Public and charitable bodies has £50million to spend by 2009 – Arcola will need to confirm if they can achieve a public body status to gain access to this funding. As phase 2 is a newer scheme, it is likely that this will be the easier to source funding from (though the emphasis on whole systems for zero carbon buildings is reduced).

A well structured grant application to either of these programs has a high chance of success. ***Because the funding pot is bigger and the number of applicants is smaller, application to the Phase 2 scheme is most appropriate, provided Arcola can demonstrate its charitable status.***

The funding programs are best understood by examining the funding web-site (www.lcbp.org.uk), but it is likely that the energy systems at Arcola could be funded as follows:

Technology	Total support available (to 2009)	Percentage of capital costs available
Solar PV	£17.5m	50%
Solar thermal hot water	£7m	30%
Wind turbines	£12m	30%
Ground source heat pumps	£7.5m	35%
Biomass	£4m	35%

Details of funding levels under the Phase 2 program (Phase 1 applications would be similar)

One of the conditions of funding for the Low Carbon Building Programme s that the installers under the programme must be accredited by the programme administrators. The complete list of potential suppliers is available at the links below.

Phase 1 - http://www.clear-skies.org/households/RecognisedProducts.aspx
Phase 2- http://www.lowcarbonbuildingsphase2.org.uk/filelibrary/LCBP2_Product_list_v1.0.xls

The peculiarities of the funding administration mean that the different programs support different products.

7.2 Other sources of funding

7.2.1 DEFRA biomass capital grants scheme

This DEFRA scheme will support the installation of biomass-fuelled heat and combined heat and power (CHP) projects in the industrial, commercial and community sectors. Available grants will cover up to a maximum of 40% of the difference between the biomass capital cost and the fossil fuel alternative. The minimum grant starts at £25,000 with a maximum single award of £1million. The scheme does not target any particular biomass heat or CHP technology nor sector or sub-sector, but does require that systems have a rated output over 50kW. The most recent funding round has closed, but further support should be expected under this scheme throughout 2007 and 2008.

A well structured application to this scheme could provide £25,000 towards the cost of an Arcola biomass boiler. It should be noted that this would not be additive with the Low Carbon buildings Program scheme mentioned above.

7.2.2 DTI HFC-CAT – fuel cells funding

A well thought through fuel cell project could be funded by the DTI's HFC-CAT programme, which has a £15million fund to support up to 25% of the costs of early fuel cell demonstration projects. Because 25% is not a substantial fraction of the high cost of a fuel cell project, this fund I unlikely to make a fuel cell project feasible at Arcola unless matched with funding from other sources such as the fuel cell supplier themselves.

7.2.3 Funding linked to energy advice and skills development

The ongoing energy advice aspects of the renovation are potentially attractive to direct funders, who may be in a position to pride revenue funding for advice in London. Specifically, the London development agency is charged with providing a wide range of business and community advice' services on energy and resource efficiency. The LDA rarely performs well in this area and may be willing to fund another entity to provide this advice. The LDA will also be attracted to measures aimed at skills creation, if these can be properly quantified in a pitch to the LDA. A similar situation may apply in the council or GLA.

On a national level, the Energy Saving Trust is charged with promoting energy efficiency in the UK. As a result, the EST's marketing group may be prepared to sponsor the energy measures at Arcola, particularly those linked to public education.

7.2.4 Equipment Suppliers

Low carbon energy project developers often approach suppliers for support for their projects in the form of discounts on products etc. In practice these requests re rarely granted as the suppliers are operating under challenging economic circumstances themselves. However, for a project of this type, with a suitable pitch, it may be possible to encourage suppliers to provide projects at low cost. This is due to the link to the arts as well s the outreach aspect of the project. In practice the suppliers are best approached in the same way as the sponsors and non-energy funders (discussed below).

Sponsors and arts funders

The energy aspects of the Arcola redevelopment are likely to be attractive to sponsors and arts funding bodies. It is important that one these are agreed, they are included within the overall prospectus in a clear and concise fashion. The two messages of most value will be:

- the development of a net Zero carbon theatre (first in the UK) – as defined in this strategy document

- the planed outreach aspects of the project, in terms of education of theatre goers and the development of local energy related skills

Sponsors with an energy and/or educational bent could include:

- Shell (particularly the Shell Springboard)
- BP
- EDF
- Eon
- The BOC foundation (currently in abeyance following the Line takeover, but with possibilities of a resurgence)
- The Prince's Trust (young skills development)

Numerous more funds and trusts could be defined by an experienced fund raiser

8 SUMMARY AND RECOMMENDATIONS – HOW TO ACHIEVE NET CO_2 NEUTRALITY

It is achievable for the Arcola theatre to become a CO_2 neutral building. This can be achieved using a variety of energy-efficiency measures, a biomass boiler, rooftop photovoltaics and ASH. The following graph shows the amount of CO_2 saved with increasingly rigorous measures.

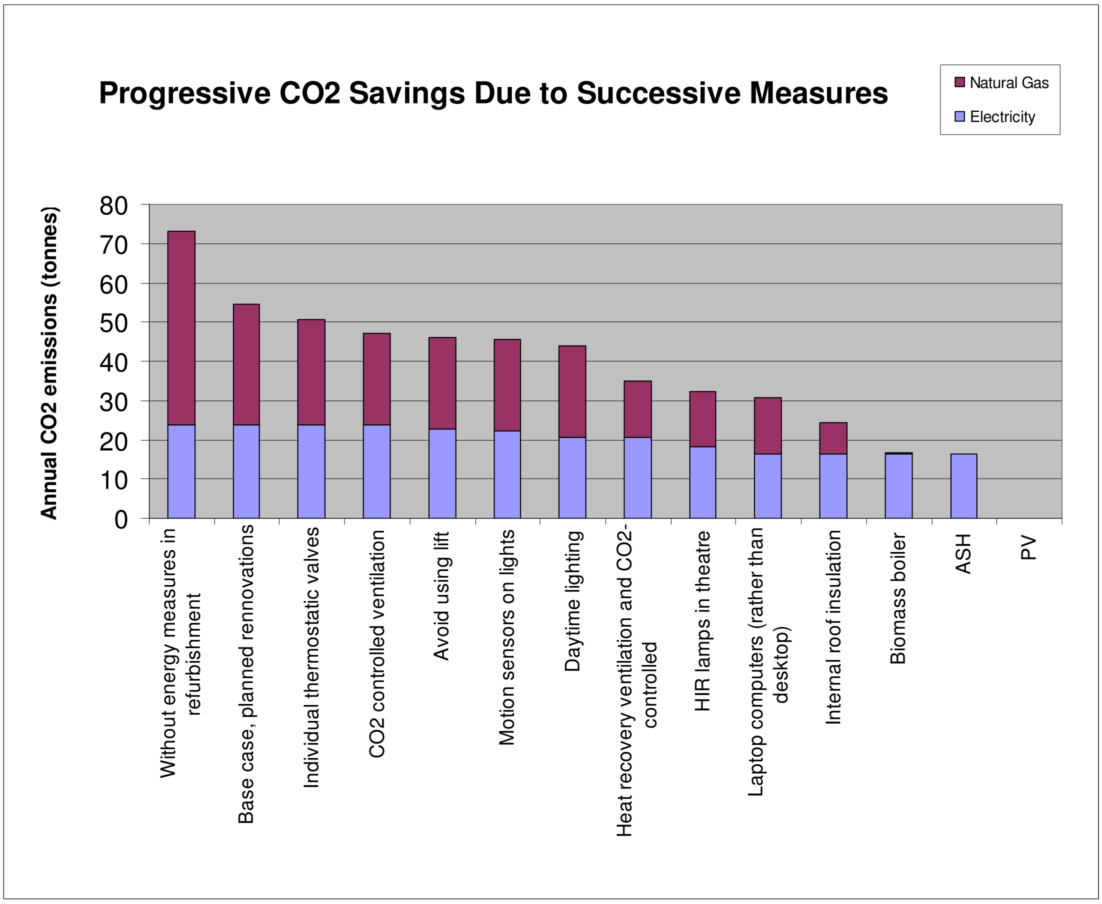

Figure 23 – Illustration of path to CO_2 neutrality

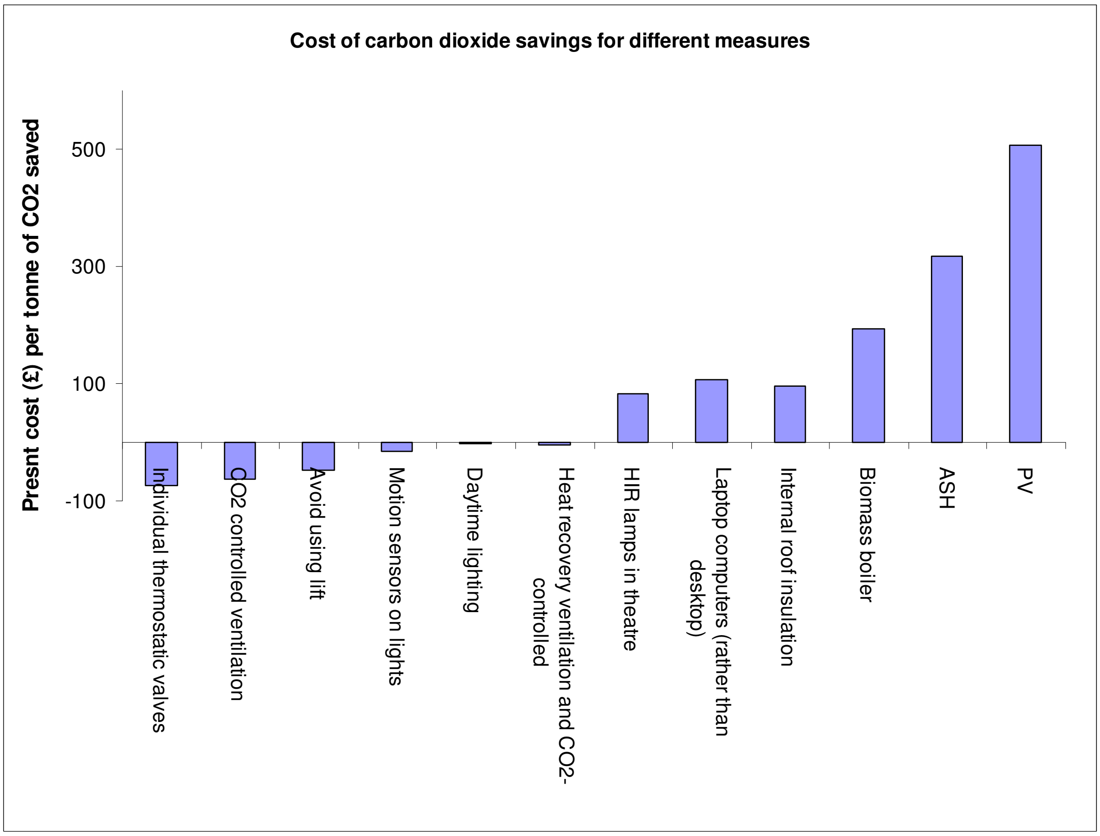

Figure 24 – Cost of avoiding carbon dioxide emissions

8.1 Stages in implementing a CO_2 neutral theatre

8.1.1 Stage 0 – Ensure baseline refurbishment takes place

CO_2 savings: 18 tonnes/year

The following measures are considered 'baseline' in this report. They are crucial, and must not be avoided.

- **Double-glazing** for all windows
- **Controlled mechanical ventilation system**
- **Fluorescent space lighting**

8.1.2 Stage 1 - Demand Reduction for Electricity and Natural Gas

CO_2 savings: 30 tonnes/year

The following further measures will be taken.

- **Natural lighting.** All potential windows must be allowed to let sunlight through. Heavy blinds will be required to produce darkness. Blinds should be kept open whenever possible. Light shelves should be considered.
- **HIR lamps for all stage lights**
- **Motion sensors on lights.** One sensor per room.

- **Energy-efficient appliances.** Laptop computers instead of desktop computers, energy-efficient fridges, fans, lift and any other electric device. Halogen HIR lamps should be sourced for stage lighting.
- **CO2 sensors to control ventilation system**
- **Internal roof insulation.** This will take place during renovation.
- **Separate thermostats in each room**
- **Encourage energy-awareness wherever possible**

In addition, the potential use of LED stage lights should be investigated. This should become feasible over the coming years, and could potentially save 5MWh/year. The possibility of forming a partnership with an R&D organisation should be considered.

The extent of the demand reduction can vary. These measure must be implemented **such that the total annual electricity demand does not exceed 35 MWh/year.** All energy-reducing measures reduce the cost of PV necessary to reach carbon-neutrality. If PV (at current UK prices) is expected to supply all the electricity, then electricity savings due to demand-reduction measures should be valued at 50p/kWh, or £7,000 capex for 1MWh/year.

8.1.3 Stage 2 – Eliminate Natural Gas Consumption[15] with Biomass Boiler and Active Solar Heating

CO_2 savings: 8 tonnes/year

Space heating demands will be met by a biomass boiler. Hot water demands will be met by a combination of ASH, a biomass boiler, and a gas boiler. The following steps need to be taken.

- A wood pellet boiler (69kW[16]) will be decided on, and its specific space requirements will be assessed.
- Discussions will take place with pellet fuel suppliers, and the required size and access requirements for the store room will be determined.
- Fireproof rooms for the boiler and a store room (10m^3) will be built according to the requirements of the pellet suppliers and boiler. An access chute and appropriate fuel transport mechanisms will need to be considered.
- ASH panels will be purchased.
- The boiler and ASH panels will be installed, and integrated together into a the combined heating and hot water system.

8.1.4 Stage 3 – Eliminate Electricity Consumption with Photovoltaics

CO_2 savings: 16 tonnes/year

A PV system will be installed on the roof, sufficient to meet the building's electricity demands, estimated to be 34 MWh/year, and additional margin to compensate for some gas use, 1MWh/year (total PV potential is 40MWh/year)[17]. This stage would benefit from waiting until PV prices drop further. The following steps need to be taken.

- If the building has been refurbished and is in operation, note the electricity (and gas requiring offsetting) directly from bills.
- Decide whether the roof will be used as a space for people or simply for power generation.

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[15] Natural gas for cooking and possibly spikes in water heating will still be required the CO2 from these will be offset by exported electricity from PV.
[16] The required will need to be confirmed by a services engineer.
[17] The PV will also offset the (small) quantity of CO2 due to gas cooking and possibly gas hot water.

- Design, purchase, and install a photovoltaic system to meet the building's electricity demands, with a margin for expansion. This may include the rooftop canopy system. If the roof is not to be completely utilised, consideration must be paid to possible further expansion of the PV system.

9 APPENDIX – ASSUMPTIONS USED IN CALCULATIONS

9.1.1 Carbon dioxide emissions

Grid Electricity (marginal CO_2 emissions)	0.57 $kgCO_2/kWH$
Grid natural gas	0.19 $kgCO_2/kWH$

The marginal emissions due to increasing or reducing grid electricity demand has been. Used. The figure is higher than 0.43 $kgCO_2/kWH$ (the average emissions) since it tends to be the carbon-intensive power stations which adjust their output to accommodate demand.

9.1.2 Building dimensions

Theatre dimensions (in metres or square metres as appropriate)	
Sunny roof area	304
Sunny roof area - no parapet	413
Sunny roof area - eaves, canopy no parapet	549
Average building height	11
Average external wall thickness	0.6
Ave roof thickness	0.3
External perimeter	111
Total perimeter	134
Window area	212
Roof/floor area	536
Door area	40
Window Perimeter	551
First floor height	3.4
Basement height	4
Basement area	337
Basement perimeter	73
Window area of current theatre	71
Door area of current theatre	20

'Sunny area' is defined as having no obstacles at an elevation of 30° or more, to the East, South or West.

9.1.3 Thermal Properties

U- Values ($Wm^{-2}K^{-1}$)	
Standard double-glazed windows	3.01
Double-glazed windows – low-emissivity coated and argon-filled	1.75
Average existing windows	5.75
Existing doors	4.8
Floor	0.25

Blinds	14
Thermal conductivities ($Wm^{-1}k^{-1}$)	
Brick walls	0.65
Concrete roof	0.49
Foam/rock wool insulation	0.03

9.1.4 Infiltration/ventilation

- Assume 10L per person per second needed for comfort.
- Assume current ventilation is adequate for average predicted day/evening occupancy (200people)

9.1.5 Use of space

Existing theatre		
Space	**Day use (10am – 7pm)**	**Evening use (7pm – 10am)**
Café	Every day	Every day
Studio 1 (150 seats)	4 days/week	6 days/week
Studio 2 (65 seats)	4 days/week	6 days/week
Studio 3	4 days/week	-

Future theatre		
Space	**Day use (10am – 7pm)**	**Evening use (7pm – 10am)**
Café	Every day	Every day
Studio 1 (250 seats)	6 days/week	6 days/week
Studio 2 (80 seats)	6 days/week	6 days/week
Studio 3 (70 seats)	6 days/week	4 days/week
Studio 4	6 days/week	-
Average occupancy	70	300
Peak occupancy	100	500

Outside lights on 6pm – 11pm

9.1.6 Theatre lighting

- Assume 10kW for 2 hours per performance in 150-seat theatre
- Assume lighting use scales linearly with audience capacity
- Assume 12 hours of technical dress rehearsal every 24 shows.

9.1.7 Assumed appliance ratings and use

Appliance	Power rating	Intensity of use	Current number	Future number
Desktop computer + monitor	320W	3hrs/day	0	18
Laptop computer	100W	10am – 6pm	4 (2 in office, 2 in cafe)	3 in office, 3 in incubator, 7 in café
Lift	5kW	Used 1hr/day	0	1
Coffee/tea	Assume need to boil 1 cup per person in café per hour, 10 people average for 10hrs/day in current café. 30 people in future			

9.1.8 Miscellaneous

- Assume 10W/m^2 for space lighting in absence of daylight
- Assume interest rate of 6%
- Assume meaningful building lifetime of 25 years (when quoting 'lifetime CO_2 savings' for example)