BLOTT MATTHEWS 2018
ENERGY FOR EVERYHING

SOLUTION BY ELECTRI.CITY

ABINGDON SCHOOL

CONTENTS

TRANSPORT

OVERVIEW

When designing the transportation system, our main goals were to lower emissions, increase fuel efficiency and increase traffic density. In order to achieve this, our initial cost of acquisition for the technology was high along with the power usage from the grid.

However, we believed that the reduced carbon production outweighs the cost of implementation as it results in less carbon storage being needed.

THE HUB SYSTEM

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Overview

The basis of the Hub System is to centralise transport into 6 locations around the city, having all connections to external transport routed to one of these, with strong transport connections between each hub, and then have smaller scale transport to disseminate commuters to their respective homes and offices.

Hub Layout

External Links

2 hubs, one North one South, will harness the current rail links in Southampton and Portsmouth to connect the city to London, via an extension of HS2 intended for passenger transit, and Dover for freight transport.

Intra-Hub Transport

Each of the six hubs will have a metro entrance with access to one line with a city loop. To supplement this, buses will run between hubs during overflow hours (roughly 8:00 – 10:00 and 15:00 - 18:00). Buses will also reach the extremities of the city (at all hours) for which covering with the Hub cars would be inefficient.

Local Transport

At the core of the hub system is our fleet of electric SUVs to work as public taxis. These would be government owned but work on a contract basis similar to Network Rail, the government would own the infrastructure of the Hub buildings and cars but the operation of these would be staffed by contactors. This will be called the Solent Personalised Official Transport System (SPOTS).

Traffic emissions

We decided to reduce private car volumes through an ambitious modal shift in urban public transport. All buses will be converted to hybrid diesel and later fully electric power. Walking, using bicycles and public transport will be increasingly encouraged, private cars would be banned because we would use a close loop driverless electric car system. Ambitious cycle route networks will push cycling rates up to 35% of all journeys. (Oxford is currently 20%). This combined will reduce traffic emissions close to zero. We believe that the efficiency of driverless vehicles and the effect of public transport would be the best solution for a carbon neutral city.

We discovered that there are 21,000 black cabs in London. We scaled this down by a factor of 4, which results in a total of 5250 black cabs in operation in our city. The combined battery storage capacity from 5250 electric cars would roughly be 5,250,000 KWh, a calculation from each car as 100 KWh. This will be available to help balance the grid through feeding back power at times of low generation. Furthermore, we calculated that each car would roughly be £100,000. This would mean a total of £525,000,000 is needed to be spent on producing 5250 electric cars. The use of electric vehicles, which are zero emissions vehicles, means there will be much lower pollution overall in the city centre, improving quality of life and allowing more space for pedestrians. This also removes the need for heavy trucks to deliver fuel to petrol stations in the city. The use of a taxi cab like service is the basis of our solution.

Cost of our idea

We decided to implement Diesel Electric Hybrid busses operating along the most used routes, and later, fully electric powered buses. We found that hybrid buses in London currently cost approximately £110,000, more than a conventional diesel bus. For example, a hybrid double decker bus for London would cost £300,000 compared with £190,000 for the diesel equivalent. Maintenance costs are roughly the same as conventional diesel buses, however, replacement of batteries after about five years will require further investment. The cost difference for single deck buses would be comparable, though from a lower starting cost. We are looking at getting roughly 2000 buses in Solent. Using these prices, the cost would roughly add up to £400,000,000. A proportion of which will be provided by the Green Bus fund.

The double deck buses in the trial fleet are achieving an average of 6.1mpg compared with the benchmark diesel buses at 5mpg. At current fuel prices, taking into account fuel duty rebate and based on average annual mileages, this represents a fuel saving of £4900 per annum per bus. The results from the single deck trials indicate more variability, but the best performing vehicle is achieving 9.9mpg compared with a benchmark of 8.0mpg giving a saving in fuel costs of £3700 per annum.

External links

In order to facilitate inter-hub transport each of the hubs will be connected to an underground electric high-speed shuttle line, running trains every 5 mins with a capacity of 60 persons. The shuttle can reach every hub and runs a simple route up and down one singular line, reversing direction at each end (Southampton Central and Portsmouth South). SPOTS cars will be prohibited from long across town journeys and will direct its passengers who've selected destinations outside the range of the car's home hub towards the shuttle for onward journeys.

Transport Technology

Batteries

We considered three types of batteries for use in our vehicles within the city:

Aluminium-Air:
These batteries are at the forefront of current research, with significant advances in energy density and weight. The vast reduction in weight can result in a demonstrated range of over 1000 miles. However, the commercial viability of these batteries (even with future technology) remains uncertain. This is due to the inability for the batteries to be recharged conventionally as the anodes must be recycled and new ones installed.

Conventional Lithium Ion:
This is the most commonly used battery technology, with predictable and well modeled degradation characteristics. Further, with significant investment from companies such as Samsung, LG and Tesla, the market price is falling considerably. However, the lithium-ion gel is prone to leaking and when in contact with air it can ignite. In addition to this, the energy density of lithium ion batteries is fairly low and the extraction of lithium salts is highly damaging to the environment.

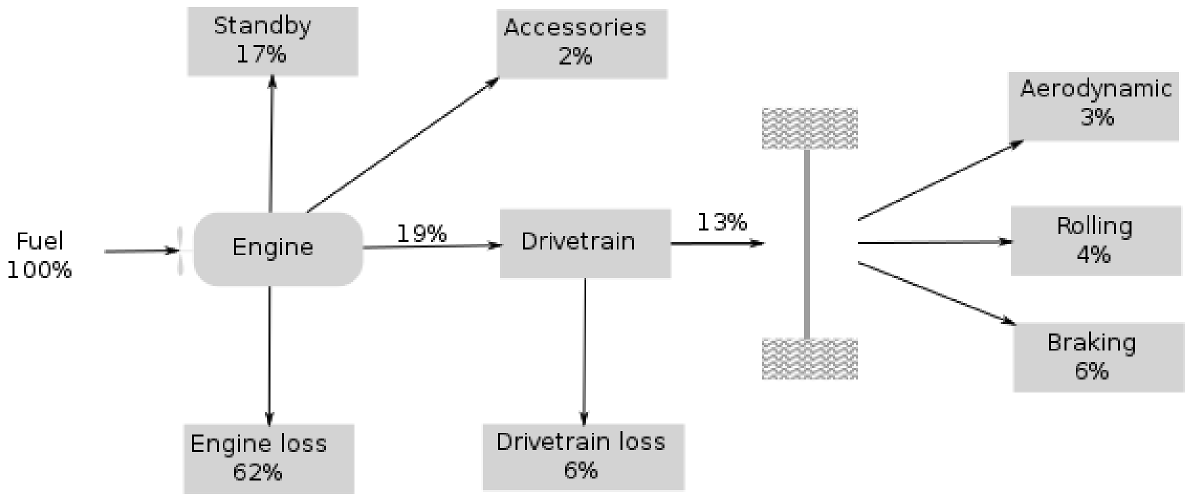
Solid State Lithium Ion:
These batteries were developed by Toyota employees specifically for use in electric vehicles. Solid state batteries allow for significantly reduced recharge times (5-10 mins compared to 20-30 mins for conventional L-ION) and repackage the cells to reduce the volume of the battery and thus increase energy density. In addition to this, these batteries are much more stable than conventional lithium ion batteries, resulting in safer outcomes in the event of puncturing and crushing. By building on existing technology, these batteries are expected to reach the market by 2022.

Conclusion:
We decided to use solid state lithium ion batteries due to the fact that they are safer, quicker to use and more energy dense than conventional lithium ion batteries while still being available to market in the near future.

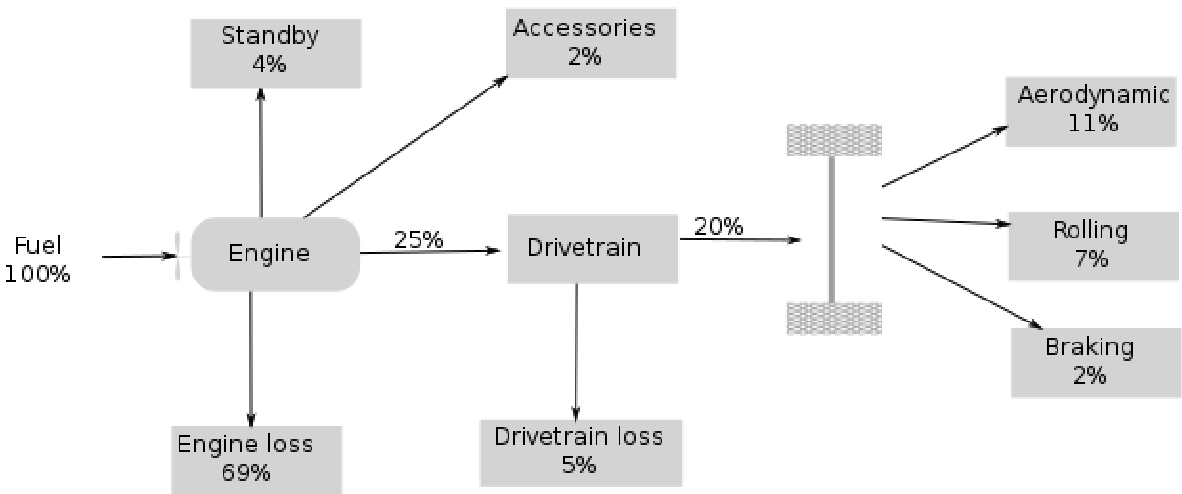
Sources:
https://in.reuters.com/article/toyota-electric-cars/toyota-set-to-sell-long-range-fast-charging-electric-cars-in-2022-paper-idINKBN1AA03S
https://www.nextbigfuture.com/2017/08/toyota-plans-to-leapfrog-tesla-electric-cars-by-2022-with-fast-charging-solid-state-batteries.html

Regenerative Braking

Due to the high charging and discharging rate of our main solid-state battery, we are able to use a small generator connected to a continuously variable transmission on the drivetrain to regain energy lost through braking. This acts in addition to normal disc brakes and due to the decreased wear of the brake system, we are able to increase the time between servicing of the SPOTS vehicles, reducing maintenance costs while increasing the range per charge.



Urban driving



Highway driving

Smart car Software

Hailing the Cars

The cars will have a GPS link up to the control centre in its resident hub. Clients will be able to call the cars via a free government provided app called SPOTS Mobile. , clients will open the app, denote a destination, decide if they wish to allow others heading the same way to share a ride (or else pay an additional tariff which scales up dramatically at busy times when cars are in demand) and broadcast their location to the hub. The client may also suggest other options e.g. the requirement for storage space if travelling with shopping/luggage or the requirement for wheelchair access space. The computer will then find the nearest car which meets these requirements and route it to the clients location. Passengers will tap in on the car (similar to the oyster system on the tube) and tap out upon journey completion with the journeys being logged against the client's account to be paid electronically at their convenience. Reduced tariffs will be available to the elderly and the young.

Smart car Algorithms

The Algorithms are needed for two primary purposes:

1. Optimise passenger pickup ranges
2. Optimise the Routes

Passenger Location Algorithm

The Algorithm should change the area the car selects its passengers from based on traveling density information in order to keep the number of requests it is responding to at a constant level

This can be written as:

$$Response\ Area = \frac{R}{Density}$$

Where R is a constant that represents the number of requests for a car in the cars active response area.
Using this changing area we can optimise the number of cars present in high traffic areas by requiring a minimum area to be covered by the cars response area forcing more cars to be present to make up for the decreasing response area size
The Response area itself could either be simply calculated as a circle whose radius changes with Density or it could be created by changing the maximum time or power the car needs to reach any point in its search radius, this would allow the car to respond to traffic incidents and display a more accurate Response area due to the different travel speed of some roads.
In the end we decided to use the simpler circle method as it then only involves the transmission of two pieces of data between the car and the control system whereas the other method would require far more communication between the car and the control system, thus requiring far too much processing power.

Optimum route Algorithm

Due to the nature of the AI cars there should be minimum differences in travel time on roads that is caused by traffic, this means that unlike most current route-finding systems our travel time for each path are unlikely to change greatly.

This means that we can store a solution to the **all-pairs shortest path problem**, as the route values don't change significantly it means that no computation is required other than searching through the database of all the pair paths.

To make sure the rare occasions of traffic are accounted for the car's onboard computer can also compare the expected routes path weighting to the original weights if there is any difference the system control will create a new path. Using this method car routes will always remain similar therefore reducing the computing power required. Using the car's onboard computer allow every car to check its own path which further reduces computing power due to the nature of parallel computing.

Self Driving Ethics

The recent advances in self driving cars have brought about further discussion of the moral implications of having driverless cars. There are many studies about the different types of implementation of a driverless car system, our transportation system for example uses a closed loop system where there are only driverless cars on the road with the exception being emergency services which are human controlled. They still do however have inbuilt communication with the Automated Intersection Management system, to allow for a fast-dynamic response time with the benefit of clear driving lanes.

Our solution means that passengers will not be able gain full control of the vehicle. The ethical problems arise from the fact that most decisions made by humans in chaotic road events are driven by impulse so therefore no blame can be attributed. However the sensory capability of the self-driving cars would allow each decision to be assigned a cost and the cost of each action would be weighted and evaluated in a crash optimisation algorithm to deduce the best possible action that the car could take. This means that the
responsibility of the collision is in the hands of the programmers as they ultimately decide what actions the vehicle takes, the act of the choice being consciousness is that makes this a ethical dilemma.

Thought experiments

There are three thought experiments that create problems that we thought were important to consider as they are difficult but necessary to answer if the system is to be successful.

Trolley problem

This is likely the most well-known dilemma associated within this field. In this scenario the vehicle is traveling towards 5 people at a crossing, however it starts to slip on some black ice on the road, the sensors calculate that a crash is guaranteed however it could change the direction of its tires to swerve and hit the pedestrian on the pavement. The dilemma is whether the car should swerve and hit the pedestrian on the pavement or continue on its original path and hit the 5 people. The instinctive answer would be to swerve and hit the 1 person as there would only be 1 life lost instead of 5. However, it could be argued that it should hit the 5 people, if the vehicle was to do nothing then it would not be responsible for the death of a person as it didn't make a decision, it just let “nature" kill the 5 people, this could be considered better than being completely responsible for 1 death.

School bus problem

This would be a related problem. Again, a crash in imminent however this time it is with a school bus. The vehicle could choose to swerve into the building next to it and risk injuring the occupant of it could hit the school bus and potentially kill several schoolchildren. If the general population were given time to contemplate this, we believe that most people would risk their own life. However, is it right for the machine to decide the fate of the people involved in the crash without their consent?

Cyclist helmet problem

In this scenario, the choice is between a cyclist wearing a helmet and one who isn’t. The risk of a fatal injury is much higher for the cyclist without a helmet so this option should be avoided. However, the cyclist with the helmet has been responsible and worn a helmet so should they be penalised for being safe? If the algorithm always went to the person with the helmet then more people would not wear helmets which could cause further problems in the long term.

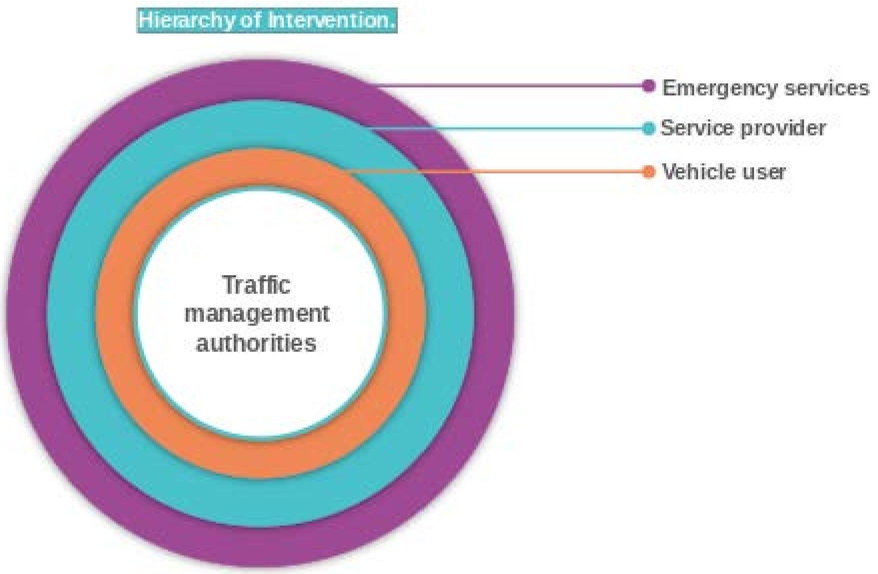
Solutions

We believe that these are all important problems to consider, however we believe that the public should be able to decide the moral code of the vehicles. When we first roll out the vehicles they would be programmed to purely avoid crashes, this means they would not calculate the risk of each outcome. This prevents the moral dilemma because it is not considering any outcome, it is simply trying to avoid all collisions. Obviously, this isn't ideal because we have the potential for the vehicle to do more have decided what code of ethics to follow, we have made a basic moral code that would underpin the vehicle's morality.

1. An automated vehicle should not collide with a pedestrian or cyclist.
2. An automated vehicle should not collide with another vehicle, except where avoiding such a collision would conflict with the First Law.
3. An automated vehicle should not collide with any other object in the environment, except where avoiding such a collision would conflict with the First or Second Law.
4. An automated vehicle must obey traffic laws, except where obeying such laws would conflict with the first three laws.

Intervention with the system

We decided to investigate intervention with driverless vehicles.
The diagram explains what systems can intervene with the driverless car, the outermost layer of the diagram shows the entity that can overrule the other subset circles. This creates a Hierarchy of Intervention.



At the bottom of this hierarchy is the Traffic management authorities. They can influence and optimise the navigation and guidance systems on the vehicle, this would ease congestion reducing time spent travelling and reducing electricity consumption needed. This system would mainly be active around peak demand of the vehicles. This manifest itself in the Automated Intersection Management system.

Then we have the vehicle's user, they can control the destination that the driverless cars travel to. The main principle of our SPOTS cars is that it would act like a taxi sharing system to get people to the hubs. Having people lift share reduces cost and electrical consumption, at off peak hours people can request not to lift share at a reduced rate as the movement of people is less. In each self-driving car there is a safe exit button, when this button is pressed the car would proceed to find a suitable place to stop quickly and safely. This is like a standard taxi service when you can request to be dropped off on the street, the taxi driver would not slam on the breaks but assess the situation quickly and perform a safe stop.

Above this is the service provider, the main purpose the service provider is to send updates about dynamic events that occur on the road. For example, if there was a large delivery or road works going on a certain street then the service provide would shut off the road from the navigation system. This takes priority over the other sectors as it is important that traffic does not go down roads that are not suitable. In addition, performing a safe exit on the closed off road could cause a disaster so it is better for the service provider to overrule these systems. It would be the job of the service provider to provide traffic updates or have a system where people could contact the service provider about a problem, or even potentially a open source system as people would be able to change the system much faster than having the service provider check for them.

Then finally the entity that can intervene above all other is the emergency services. The exclusive rights could be given by the council, these vehicles would be the only ones on the road that would be controlled by human drivers. As they are not driverless they don't have the sensory capability of the driverless cars, this means that driverless cars would give way to these vehicles to prevent any accident. For example, if a fire was to break out, then a fire engine with a human driver would be able to avoid all traffic in the proximity of the area, therefore reaching the destination much quicker. The driverless cars in the proximity of the fire engine would move over to the side of the road and then once the vehicle had past it would continue as normal. We believe that this should have the highest priority as it has the most capability to prevent harm.

Road Layout

Despite a recent trend towards complex road layouts with many twisting roads and cul-de-sacs, we decided that the most appropriate solution would be a grid-based layout. This is because it would allow us to adopt autonomous intersection management policies to vastly improve the efficiency of the transport infrastructure

Autonomous Intersection Management

Historically, it has been the case that "intersections" have been major bottlenecks in cities due to the need for traffic lights. However, with the low reaction time and high reliability of autonomous vehicles, there is no longer a need for traffic lights and other such traffic control measures. Instead we proposed a centralised control system which can communicate with and coordinate the autonomous vehicles in the city. This would act similarly to the air traffic control of major airports, allowing a theoretical decrease in travel times of approximately 10-15%, and a reduction in electric vehicle power consumption of 5-10%.

Reducing Pedestrian/Vehicle interaction

In order to achieve the increased traffic density required to ensure smooth traffic flow, the likelihood of pedestrian interruption must be reduced. However, we still wanted to promote the use of bicycles and walking. Thus, we decided to use roads lined with trees and combined bicycle and pedestrian paths alongside.
The trees provide a natural barrier between the road and the paths, acting similarly to bollards while being less intrusive. Further, the increased distance between the side of the road and the path will drastically reduce the chance of pedestrians accidentally stepping onto the road.

Sources:
http://www.cs.utexas.edu/~aim/
https://www.theiet.org/membership/types/fiet/downloads/phil-blythe.cfm?type=pdf

Bus System

We decided that due to the high gross weight and start-stop traffic in which they operate, pure electric busses would have been unfeasible, so we decided to investigate alternatives.

- **Diesel Electric Hybrids:** These are more pervasive in the UK with over 2300 in London alone. The Green Bus Fund supports the purchasing of these busses by contributing large proportions of the cost. As such we would be able to reduce the overall acquisition cost of our public transportation system.
  Further, they emit 40% less CO2 than purely diesel busses and use similar technologies in our SPOTS cars to reduce the overall fuel consumption by 20%

- **Hydrogen Fuel Cells:** These would be significantly harder to commercialise due to little ongoing research into the scale of fuel cells required for bus operation since 2009. The largest active fleet in Europe is 10 in Aberdeen. However, during the reaction no toxic emissions are produced, the only byproduct being pure water. In addition to this fuel efficiency has been demonstrated to be between 39-141% better than diesel busses on a study conducted by the US Department of Energy. The use of fracking as a means to obtain the Hydrogen remains a concern.

Source:
https://www.hydrogen.energy.gov/pdfs/progress10/viii_0_technology_validation_overview.pdf
https://www.ncbi.nlm.nih.gov/pubmed/21608490

Due to the concerns about fracking, in addition to the fact that little active research is ongoing, we favoured Diesel Electric Hybrid busses over Hydrogen Fuel Cells. These would be used to supplement the metro system for use in the extremities of the city and in peak hours.

Shipping and Boat Transport

We decided that ferry transport across Solent and the Isle of Wight will be fully electrified. This is because power settings are almost constant throughout journeys, meaning battery electric technology is able to work most efficiently.

Passenger Transportation: We decided to use a modified version of the Ampere design of electric ferry. On top of this design, we proposed changing the lithium ion batteries to the same solid state design used in our SPOTS cars. This enables us to increase both the instantaneous and continuous power output, resulting in a ferry that can be operated at higher displacements. By using such a design, we are able to reduce carbon emissions from each boat by over 2680 tonnes when compared to diesel ferries.

Source: https://www.siemens.com/innovation/en/home/pictures-of-the-future/mobility-and-motors/electromobility-electric-ferries.html

Cargo Transport: Although fully electrified cargo ships for international transportation are not commercially available as of yet, the world's first fully electric container barges will begin operations in the summer of 2018, from Antwerp, Amsterdam and Rotterdam. The "Port-

Liner" barges would operate from Solent, providing access to European ports. This allows Solent City to import goods without emitting any particulates or gasses.

Source:
http://www.maritimejournal.com/news101/industry-news/port-liner-building-electric-container-barges

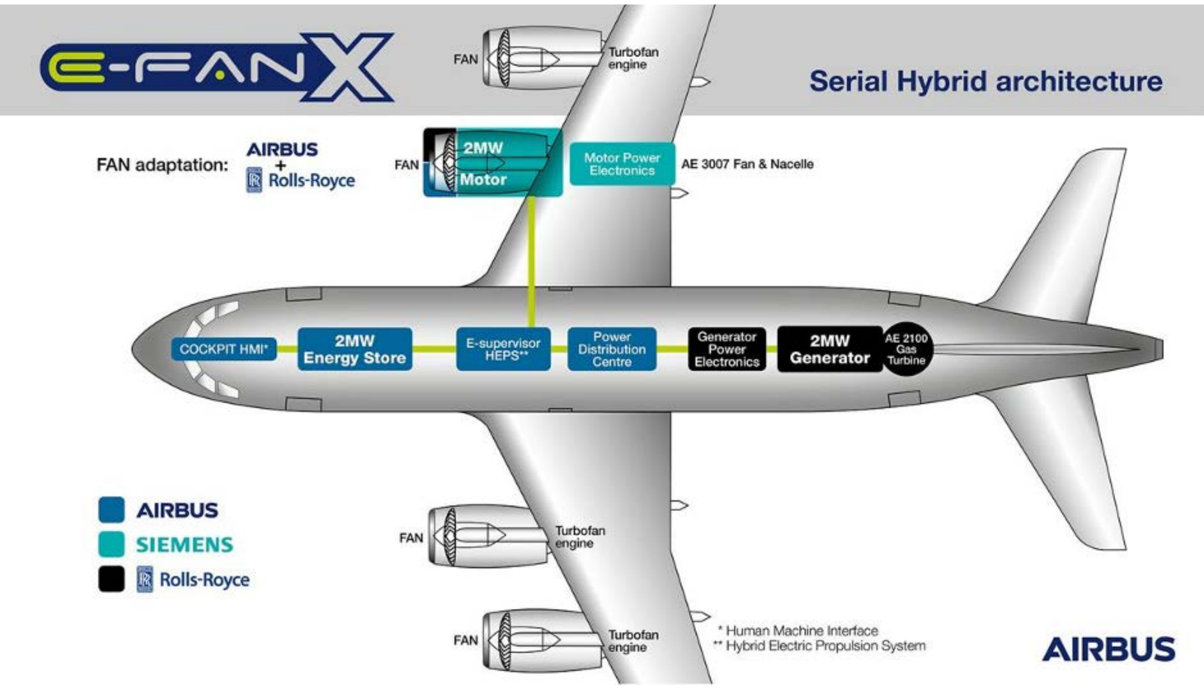
Air Transport

It is highly unlikely that completely emissionless aircraft will be available for commercial operation in mass transit for the next 15 years. This is due to both the significantly lower energy density of both current and future battery technology when compared to aviation fuel and the low thrust generated by electric aircraft motors.

However, demonstrator aircraft such as the Airbus E-Fan X have shown that hybrid electric aircraft are feasible. Small electric hybrid commuter aircraft will operate from Solent City providing transport to domestic and European destinations, along with cargo being transported in the hold. This will negate the need for cargo aircraft, further reducing the city's dependency on emissions generating transport.

By using the advanced form of the E-Fan X, with both inboard engines being electric motors, we are able to halve fuel consumption. This not only reduces emissions but also results in significantly reduced noise pollution around the airport, with the target being to reduce CO_2 by 75%, NO_x by 90% and noise by 65%.

Source: http://www.airbus.com/newsroom/press-releases/en/2017/11/airbus--rolls-royce--and-siemens-team-up-for-electric-future-par.html



CITY

Energy Requirements

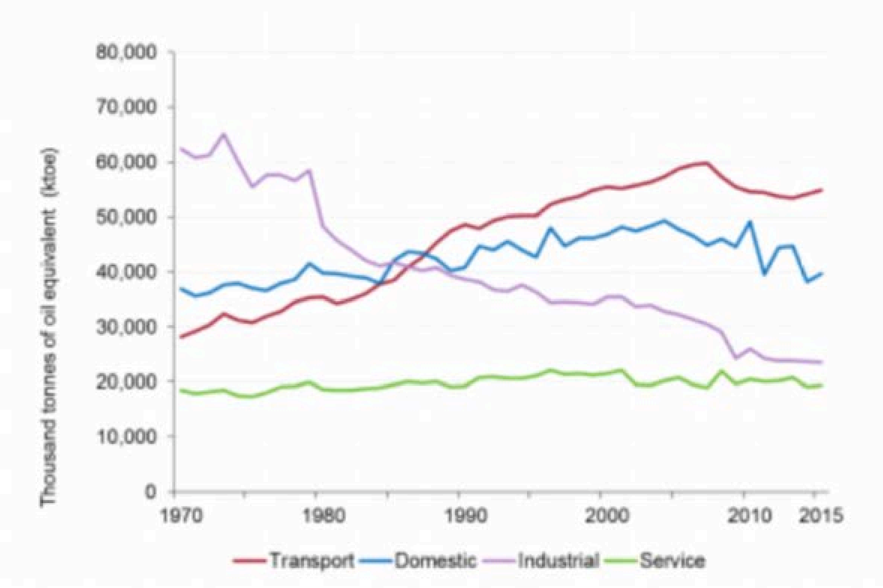
In order to identify the energy requirements by sector for our city, we took the data for the UK in 2015 from BEIS ECUK, before scaling that down from 65 million to 2 million (i.e. multiply by 2 / 63. We used the conversion rate of 1 KTOE is equivalent to 11.63 GWh. We then estimated the percentage reduction in this figure due to new energy saving technologies or greater efficiency, as would be expected in 10 years' time.

Transport was calculated by alternate means.

Sector	UK / Kton	UK / GWh	Scaled / GWh	% reduction	Final / GWh
Domestic	40,000	465,200	14768	25	11,100
Industrial	23,000	267,490	8492	20	6,800
Service	20,000	232,600	7284	20	5,800
Commerce	-	*50373	11852	20	9,500

ENERGY REQUIRMENT ANAYLISIS

*commerce data is taken from London figures



Maximum Hourly Forecast

Our power supply is required to be able to meet the maximum hourly forecast at any time of day or night. As our power supply does not depend on external conditions, we will be able to provide maximum power at any time.

In the UK the electricity generation capacity (i.e. the maximum power available at any one time), was 81,026 MW at the end of 2015. The maximum demand was 73% of the UK capacity, which is 59,149MW. Scaling this down to the population of Solent City brings it to 1,878MW. Data was taken from DUKES 2017 Chapter 5. With our energy saving technologies, and not having anything that would draw large amounts from the grid over a short period of time, we estimate a 20% reduction in this value, bringing it to 1,502MW. Our power plant has a maximum power capacity of 1654MW, not taking into account any distributed energy resources, so this works out well.

Energy Saving Technologies

Improving energy efficiency via energy saving technologies is an effective way to reduce energy use while providing the same service, thus reducing overall energy demand. Avoiding a kilowatt-hour of demand would be cheaper than supplying that amount with another resource, so energy efficiency is a cost-effective way to spend money; in fact, the IEA estimates that every dollar spent on energy efficiency is equivalent to $2 in supply investments. We believe that the most important place to improve efficiency is in buildings, as whilst 42% of the world's electricity is consumed by them, on average ⅓ of the energy put in is wasted. Whilst one of the challenges in improving efficiency is the long replacement cycles for most appliances, creating this city from scratch gives us the opportunity to install high quality appliances.

Technology such as heat pumps, rather than boilers, for heating and cooling would be able to significantly cut the heating costs by up to 25%, as well as reducing CO_2 emissions by 70%. Heat pumps work by evaporating and condensing fluid known as a refrigerant - the heat pump compresses the liquid to make it hotter on the side to be warmed, and releases the pressure at the side where heat is to be absorbed.

In addition, technology such as cogeneration and trigeneration can reduce energy wastage, particularly from industrial plants. Cogeneration allows the wasted heat produced by generators and engines to heat water, which can then be used normally. Furthermore, trigeneration uses some of this heat to generate chilled water for air conditioning or refrigeration - an absorption chiller is linked to the combined heat and power to provide this functionality. Some benefits of this include high efficiency production of electricity and heat, lower electrical usage, and no harmful chemical pollutants. Waste of energy plants can generate energy from the primary treatment of waste, producing heat and electricity from combustion. The use of modern incinerators in these plants can reduce the volume of the original waste by up to 95%, and the use of lime scrubbers, electrostatic precipitators, fabric filters, and catalysts, destroy or capture other regulated pollutants.

Energy usage could be cut significantly if systems worked more holistically. Currently many buildings often have both air conditioning and heating running at the same time, as they are all separate systems. According to The Climate Group's Smart 2020 study, incorporating technology like this could cut 15% of global emissions in 2020. Other automated systems could include LED lights, which only turn on when people are in the room and if the natural light isn't bright enough. This principle can also be carried over into street lighting, with 8 Spanish cities reducing their electricity consumption by 64% and saving over 4,300 tonnes of CO_2 in 2014, due to Archimedes LED devices with smart controls at every lighting point which both improve the lighting quality and save energy, with a lifespan of over 60,000 hours.

Finally, demand response allows control over energy use during the peak demand and high pricing periods, reducing peak demand, and so it is important in a cost-effective low-carbon electricity system - by some estimates demand-response programmes could reduce the annual investments in the US grid by up to 10%. One of the ways in which a demand-response programme could be implemented domestically is by alerting citizens about peak times, and showing them the financial incentives. In addition to this some devices such as pre-cooling air-conditioning, smart refrigerators and shallow lighting that can respond to automated price signals, and the new technological capabilities of aggregation, make demand response programmes even easier for residents.

Thus, we plan on implementing these ideas in our city, allowing us to dramatically improve our energy efficiency, both reducing the overall demand and decreasing the peak demand in a more cost-effective way.

ENERGY SUPPLY

OVERVIEW

The Industrial Revolution caused a giant leap in the quality of life of humankind, it was also primarily powered by coal. From then on, the usage of fossil fuels has increased drastically and it remains one of the best power sources for impoverished countries. England, however is not an impoverished country so why do we continue to use a fuel source that is both non-renewable and damaging to the planet and ourselves?

Burning fossil fuels produce CO_2 and other toxic by-products such as Sulphur Dioxide, Ignoring the immediate effect of these toxic by-products, the long-term increase of CO_2 in the atmosphere causes global warming which has severe implications for the future generations of humanity.

As such it is critical to find new ways of producing energy cleanly regardless of cost. Fortunately, there are now many new ways of creating power whilst reducing or completely eliminating any CO_2 produced.

ENERGY SUPPLY RESEARCH

Renewable energy sources

Renewable energy sources refer to a category of energy production whose energy source is not depleted with use.

With the rising fears over global warming, renewable resources have seen a massive growth in research and development to the point where some are reaching prices similar to fossil fuels.
The lack of a cost of fuel makes renewable energy very tempting as the only costs involved are setup and maintenance.

Photovoltaic cells

Photovoltaic cells convert sunlight into electricity, also commonly referred to as solar panels, they have seen are dramatic decrease in price due to the increase in research and along with wind power are publicly seen as the symbols of renewable energy

Advantages

No moving parts so maintenance is infrequent and cheap. It is relatively cheap to implement a single cell so they can be placed on houses if the residence chooses to. They can be placed as solar farms which would be more space efficient.

Disadvantages

Amount of energy produced is completely dependent on the amount of sunlight that they can access, England is famous for its poor weather which makes solar power very inefficient compared to other options available.

Wind turbines

Wind Turbines produce energy from the wind which spins a turbine, often thought of as a similar design to the picture on the left there are in fact many other designs which are often especially built to reduce noise or reduce size

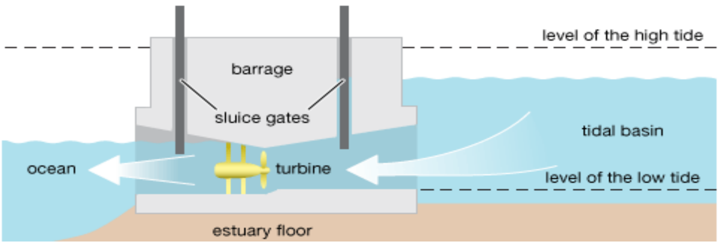
Advantages

As our city is being built by the coast we could use offshore wind which is far stronger than most inland wind. They produce relatively high amount of electricity per module at 1.5-3 Mw of energy. Recent developments in offshore wind turbines would allow them to float making them more versatile in their placement.

Disadvantages

A bit harder to implement as the location has to be just right otherwise efficiency is lost. The space required for an onshore wind farm would be vast and there are areas that the offshore farm could not be placed because of shipping lanes and the close proximity to the port. Once again, the power produced would vary wildly due to the unreliability of wind speeds

Tidal



Tidal power comes from harnessing the forces from the movement of the tide. The rising and falling tide causes water to flow over a turbine which generates electricity

Advantages

The main advantages of using tidal would be that it's guaranteed generation at certain points throughout the day. Unlike solar and wind whose outputs can vary tidal has a consistent output. The sluice gates can also be lowered allowing it to store the water in basins so it can be released at peak requirements. Due to the high energy density of the tides it makes the tidal power very cheap after the high initial setup costs.

Disadvantages

Tidal sources have the potential to affect shipping lanes. It has a relatively high set up cost for a renewable source so implementing new modules would be more expensive than other renewables. More importantly the effectiveness of the tidal system would depend on the change in height of the tide so our location may not be suitable. The location of the barrage would have to be close to the land as deep water makes implementing the system much more expensive as the system has to have firm grounding. In addition, it could have large effects on the ecosystem as it would disrupt the natural flow of the water.

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Hydroelectricity

Hydroelectric power uses the natural flow of water or flow generated by dams to spin turbines to generate energy, It is currently the largest form of renewable energy source in the world, it may account for 65% of renewable energy sources worldwide.

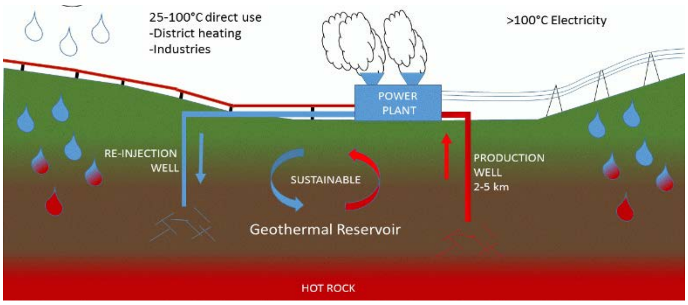
Advantages

Ignoring the possibilities of severe droughts hydroelectric power is continuous and reliable, similarly to tidal power water can be withheld at off-peak times in order to be released later on.

Disadvantages

There are no suitable locations along the Solent that provide enough energy, similar to tidal power hydroelectricity can cause negative impacts to wildlife and would be likely to obstruct shipping routes along the Solent

Geothermal



Geothermal energy uses the heat from the ground to either be used to heat up homes or used in industry, however if the ground is hot enough it can be used to heat water and turn turbines using the steam. In volcanically active countries such as Iceland geothermal energy makes up a large section of the energy output.

Advantages

It is a cheap energy supply once it has been set up. It is isolated from the environment so it would not affect wildlife and furthermore it could be run continuously which would be guaranteed generation.

Disadvantages

In our location there are no areas of geothermal activity that exceed 100° so geothermal energy could only be used to heat houses rather than helping to power the city

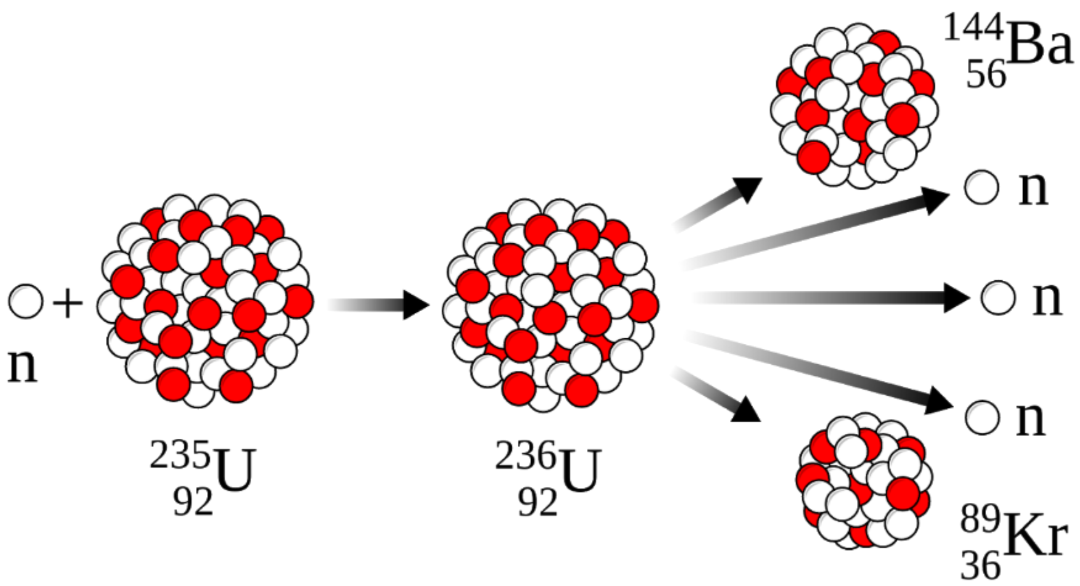
Conclusion

Our team decided that in order to use renewable energy as a primary power source it would need to be reliable and unaffected by day to day changes, unfortunately all of the reliable renewable sources would not function ideally in our location as they would effect the ability of ships to travel in the Solent. We decided that we could use the renewable sources as modules that would power the city as backups in case not enough energy was produced by the main source due to failure or unexpected amounts of usage.

Nuclear

First tested in 1951 nuclear energy promises centralized cheap and clean energy. Instead of using chemical energy to heat water, nuclear energy uses the energy held within atoms to heat water. The immediate advantage is that energy is produced without producing any CO2. There are two types of nuclear energy to go for, the current implementation is nuclear fission which involves the splitting of a larger nucleus into daughter nuclei whilst releasing energy. The other implementation is nuclear fusion, where two smaller nuclei combine to form a larger nucleus increasing energy in the process. We decided to research into both methods to find if either were desirable.

Nuclear fission



The standard process of nuclear fission uses enriched uranium in a controlled chain reaction to produce heat energy, the heat is then used to produce steam which drives a turbine.

The isotope uranium-235 is bombarded with neutrons, the neutron is absorbed which causes the isotope to become unstable and break down into the smaller atoms of Barium-141 and krypton-92 whilst in the process releasing 3 other neutrons. The 3 other neutrons have a chance to interact with neighbouring uranium atoms to keep the reaction going. The speed of the reaction in controlled by lowering in control rods made of dense metals such as iridium or cadmium which absorb any excess neutrons reducing the rate of the chain reaction.

Advantages

It is a proven technology *as it has been around for so long*, so many of the technical questions have been solved *about how to implement it*. No CO2 or harmful gases are released when the energy is produced. Hundreds of years of fuel are left so even if it is a finite resource there is plenty more available.

Disadvantages

There are a few problems which could be very harmful to the nuclear solution. We thought they were important to expand upon.

Waste

One microgram of nuclear material could kill a human and an average nuclear plant produces 100 kg of nuclear waste in its lifetime. Spent nuclear waste takes about 10000 years to decay into human safe isotopes. This process can be sped up by using reprocessing plants which can turn spent fuel into useful fuel again, however there are currently no reactors that could use this reprocessed fuel. To make sure this nuclear waste is contained the normal protocol is to store the spent material in water baths where constant flowing water stops any radiation escaping, this requires a constant energy supply otherwise the water would evaporate quickly. A more permanent solution implemented in places in USA would be storing the spent material in concrete containers, this is more expensive however this process still requires human contact to ensure no leakage. Yet again we cannot ensure that in 10000 years people would still be able to check on the containers so humanity needs to find a permanent storage solution. 30 countries have nuclear reactors however only Finland is building a permanent storage for their nuclear waste. They are digging deep into remote ground in an earthquake proof zone where they will be placed and covered in clay to prevent any future civilisation accessing the potentially fatal material.

Accidents

Even though modern reactors have triple redundancy technologies to prevent catastrophic event, it is undeniable that there is still a risk involved with using nuclear reactors. Even with the best technology of the time, catastrophic events still do happen with the most recent one being Fukushima, Japan in March 2011. On average there will be a major disaster at a nuclear facility around the world once every 30 years. These events cause huge lasting damage to the environment and the cost of clean-up is vast, the question is, is it worth the risk? Recent regulations for nuclear plants require multiple layers of protection to prevent this from happening the three principles that the ONR (Office for Nuclear Regulation) state are that:
faults do not occur,
if faults do occur they are controlled,
and if the protection fails systems are in place to mitigate the consequences
The ONR has authority over the construction of nuclear stations so any station built would have to have additional safety systems put in place to adhere to the regulations set out.

Cost

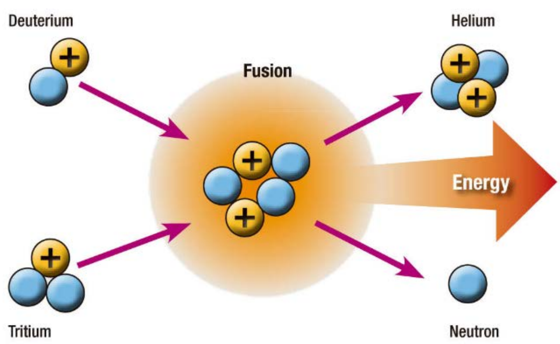
The initial start-up cost of the nuclear plant would be a lot however there are so many other factors that would need to be considered all of which would add to the overall cost for example the multiple layers or redundancies required and the permanent storage solutions of the harmful waste materials.

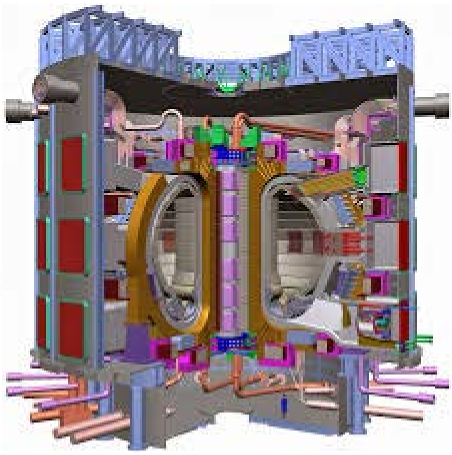
Conclusion

Although it had fantastic potential at providing clean energy it had many hidden costs and drawbacks which really make it a tough choice. We decided that because of the environmentally dangerous waste is too much of a risk using a nuclear reactor and that there must be an alternate way of generating carbon neutral power.

Nuclear Fusion

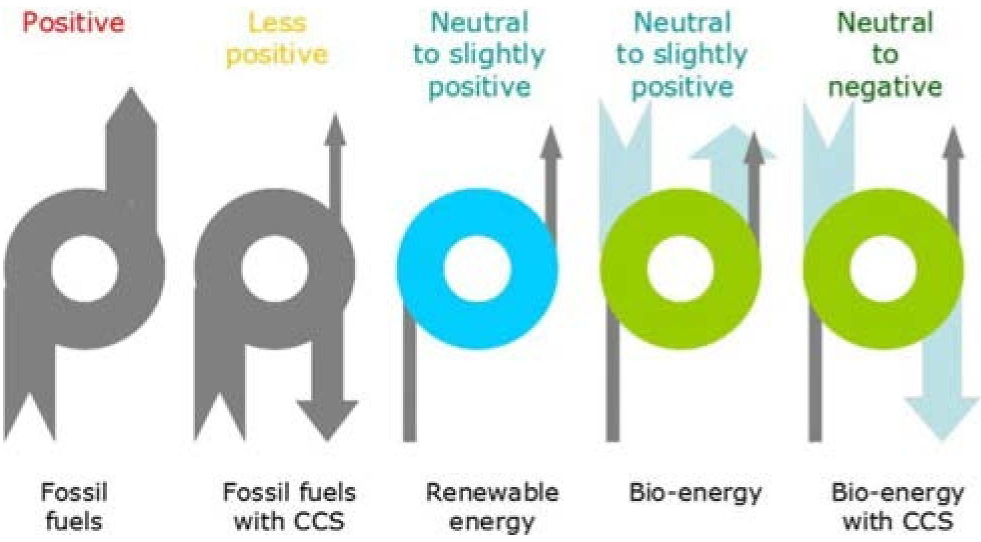
Nuclear fusion is the opposite of nuclear fission, it provides lots of energy from relatively inexpensive sources by smashing deuterium and tritium nuclei into helium nuclei. Now this system would truly revolutionise energy production as it would basically provide unlimited energy. However, we quickly decided that the system would not be possible in the next 10 years. There has been much testing of Nuclear fusion however it is very difficult to achieve and no system in the world has yet produced an implementation that outputs sufficient energy to keep the plant running. We agreed that it would be amazing if fusion could be realised however many experts in the field predict that it won't be commercially viable until the next century or ever due to sever underfunding.





Carbon Negative BECCS

A relatively recent technology is combining biofuel with carbon capture and storage. Once we have extracted the CO2 we need to find some way of not releasing it back into the atmosphere. The carbon neutrality arises from the fact that we are using a BECCS (Bioenergy with Carbon Capture and Storage) system so that the overall net CO2 in the atmosphere is reduced.



How this system works is that when we grow the biofuel CO2 is extracted out the atmosphere through photosynthesis and is used to grow the biofuel. However, the captured CO2 is released when the biofuel is burned instead of releasing it back into the atmosphere we then use our carbon capture method of choice to store the CO2. The overall effect is a reduction in CO2 from the atmosphere creating a carbon negative system.

Conclusion

We think that Biofuel and CCS have their problems individually which may not make them suitable (or carbon neutral) for the task. However, the problems of each are reduced if both systems are implemented together in a BECCS system. The carbon negative city would cost a lot of money and there will be hard technical problems to solve but we believe that it is the best solution to the problem.

Distributed vs Centralized power

Having researched into different solutions to generate power we found that there were two systems for providing power centralized and distributed.

Distributed

Examples of distributed systems would be Photovoltaic cells, and onshore wind turbines. Distributed systems provide energy to a specific local area and do not have to be connected to the grid, they are stand-alone units that would provide power to services that would need it. The advantage of this is that it can be expanded or reduced depending on the demand for energy, for example if an area experienced population growth then more solar panels could be provided to account for the more energy needed. The relative proximity of distributed systems to the consumer would reduce energy loss through transmission, increasing efficiency. Recent development can allow distributed systems to link to the grid and provide energy to the grid if an excess of energy is being produced. The disadvantage of such systems would be that more space overall would be required as the systems are not very energy dense.

Centralized

Centralized systems are the conventional approach to providing energy. Examples include Nuclear and BECCS. They provide all the energy needed for a large area in one location, this allows them to be more space efficient. Having all the energy provided from one location allows for a greater energy production and it gives industry and dense housing the energy they require. The disadvantage is that around 8-15% of energy is lost during the transmission [i] meaning that the energy produced is wasted.It is also harder to meet additional demands from small population growth, for example an additional increase of 1000 people would require 3 wind turbines [ii]which could be worth the cost to build however it would not be worth to expand on the centralized plant as there then would be an excess of power, this means that the energy demand has to increase a lot before the centralised system could be considered to expand, this increase in energy demand would put a strain on existing systems until the expansion took place. Furthermore if there are any problems with the centralized system it would create power shortages for a lot more people, whereas the distributed system would only affect the local proximity.

Conclusion

We believe that having a centralised system is necessary to provide energy to the large population, however we will implement a version of the distributed system that would allow for the increase in population.

How we are going to produce the power

We concluded that it would be far too costly and unreliable to run the city of entirely renewables and that we wanted to avoid nuclear energy. So therefore our system has a centralized source of power coming from a large BECCS system that will produce most of the power required. We also decided to implement smaller distributed sources of power such as photoelectric cells which would produce additional energy allowing for the future increase in the population of the city as they could be built as needed to meet the demands of the increased population. We believe that the combination of the two will be the best way of meeting the energy demands of the population whilst being environmentally friendly and carbon neutral.

Bioenergy

Appendix of terms:

CHG = Catalytic Hydrothermal Gasification

PBR = Photobioreactor

HTL = Hydrothermal liquefaction

CAPEX = Capital Expenditure (initial cost)

OPEX = Operating expense (running cost)

Figure 1 - Artist impression of a PBR plant

We decided the most cost effective and environmentally positive route to go down would be biofuel, due to its potential to be Carbon Negative. Subsequently we looked at the various types of biofuel crops, extraction methods and fuels.

Choice of most efficient crop

To start with we found there were two branches of biofuel, the conventional biofuel crops such as Miscanthus and corn and then Algae Fuels the so called '3rd generation biofuel'. Miscanthus was deemed to be the highest output and efficient of all the land grown algae crops.

Miscanthus (2nd gen biofuel crop)

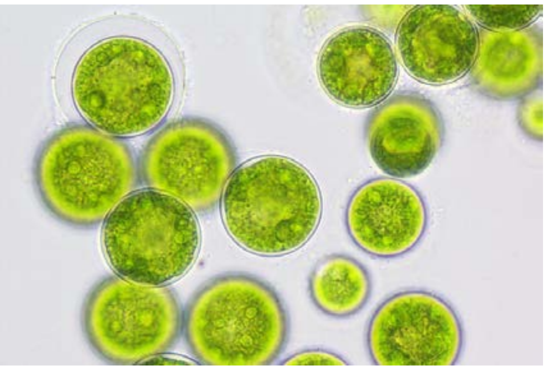
Advantages:

- Grows 3.5m in one growing season, 25 tonnes per hectare per year.
- Can be converted to ethanol or burnt or even added 50:50 to coal in coal-fired power stations.
- No need to replant after year.
- No need for fertilizer, grows in low quality soil and has large temperature range.
- Sequesters carbon.
- Already used extensively around world especially in USA.
- 1 Tonne of Miscanthus could produce 18MW of electricity (Source: SEIL)

Disadvantages:

- Already reached maximum efficiency.
- Requires large areas of land to grow.
- Requires large amount of fresh water to grow.
- Low productivity.

Algae fuels (microalgae)



Advantages:

- 3rd generation biofuel which is seen as way forward in biofuels.
- High energy yield – up to 30x more than 1st and 2nd generation fuels (100 times more fuel per acre than soya beans).
- Easy to industrialise – continuous growing and extraction cycle possible.
- Very resilient and grows in many temperature ranges.
- Can have up to 55% dry weight as lipids which can be extracted to oil.

Disadvantages:

- High initial capital required, all processes very expensive to set up.
- Higher running costs than conventional fuels.
- Still in development, only just starting to be implemented.

[iii, iv]

Thus, as we had been given a 10-year leeway in technological advances we decided to go for Microalgae as our bio crop due to its enormous potential and increased yield.

Choice of Microalgae

There are many different types of microalgae that are in contention for being used in future biomass generators. We were focused on using the most optimised algae in the best media possible due to our ability to scale up for 10 years' time. Thus, we chose the Chlorella family (strains such as Chlorella Sorkiniana are still being developed and expected to increase in growth rate in future). They offer a 250% increase in biomass yield over the current algae crops.[v]

Strain name	Isolate ID	Suggested laboratory scale media	Maximum growth rate on suggested media ($g/m^2/d$)	Maximum growth rate on optimized media ($g/m^2/d$)
N. salina	CCMP1776	f/2 10 ×[a]	15.5	17.9
N. oculata	43-AM	f/2 10 ×[a]	16.7	18.6
Chlorella sorokiniana	DOE1412	BG-11	20.4	25.2
Desmodesmus sp.	DOE0043	BG-11	18.3	17.3
Chlorococcum sp.	DOE0202	BG-11	11.4	11
Chlamydomonadales sp.	DOE0101 (polleum)	BG-11	14.8	15.6
Scenedesmus obliquus	DOE0152	BG-11	16.9	14.8
Scenedesmus obliquus	EN-0004	BG-11	16.4	15.7
Chlorella sp.	DOE1095	BG-11	21.2	24

Figure 2 - Strains of algae vs growth rate

Growth methods

To start with we needed to focus on the growth and harvesting methods of the algae. There are currently two major methods of growing and extracting algae. One is using the open pond method (shown as Green) and Photobioreactors (PBRs – shown as Dark Green)

Culture type	Advantages	Disadvantages
Indoors	A high degree of control (predictable)	Expensive
Outdoors	Cheaper	Little control (less predictable)
Closed	Contamination less likely	Expensive
Open	Cheaper	Contamination more likely
Axenic	Predictable, less prone to crashes	Expensive, difficult
Non-axenic	Cheaper, less difficult	More prone to crashes
Continuous	Efficient, provides a consistent supply of high-quality cells, automation, highest rate of production over extended periods	Difficult, usually only possible to culture small quantities, complex, equipment expenses may be high
Semi-continuous	Easier, somewhat efficient	Sporadic quality, less reliable
Batch	Easiest, most reliable	Least efficient, quality may be inconsistent

PBR's are a closed loop system consisting of a series of plastic or glass pipes in which algae culture is continuously pumped round, this optimises growth and prevents contamination. In this system you can exactly control the amount of nutrients and CO2 (or flue gases) thus is by far the fastest method of growing algae. It can also be used in a cogeneration system with waste heat from a plant going into heating the algae. This process is continuous allowing you to get a constant output of algae. [vi]

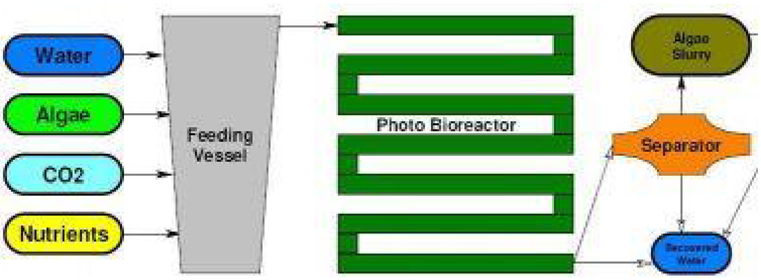


Figure 3 - Schematic of a PBR system

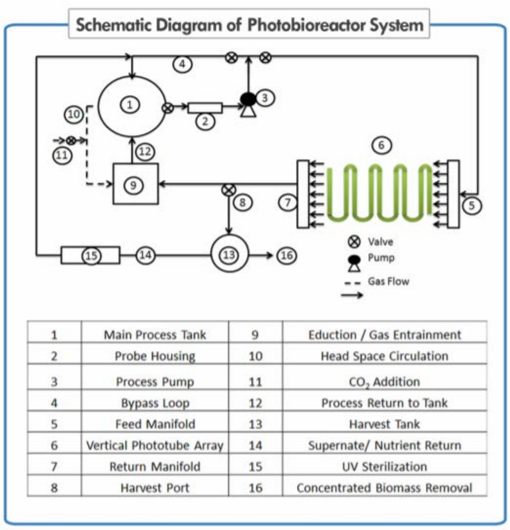


Figure 5 - detailed schematic showing PBR processes

Figure 4 - Example photo of a PBR

Open raceway ponds are a much cheaper alternative to PBR's in which the algae are grown in circular ponds in which the water circulates. After a set period the algae is removed and filtered out and the process starts again, thus is a batch method. It is a less efficient method and more susceptible to diseases or a culture crash, however is much cheaper than PBR's and can still be done in artificial lighting.

Figure 6 - A photo of an open pond raceway

Initially we focused on PBR's as we felt that the output yield was more important than the cost which we felt would drop in the near future. We based our data off the table above given by Algae Fuels. However due to the lack of information provided on their research and the large estimated area required for such a plant we decided to use a hybrid system as proposed by NAABB (National Alliance for Advanced Biofuels and Bioproducts). They propose using PBR's to inoculate the algae and generate 80L of culture before being seeded in open raceway ponds to grow tens of time larger.

Sample data for a 1 Ton/day algae photobioreactor system is given below.

Price AlgaeTube system:	€ 148,000	Cubic meters:	1,333 m^3
Required area m^2 System Only:	5,526 m^2	Required Hectare:	0.55 Hectare
Length in Meters:	13,500 m	Required Acre:	1.5 Acres
Tube diameter Ø:	320 mm	Required electricity:	4 Kw per hour

Source: Algae Fuels; Please note that the data below is based on growing the algae Nannochloropsis and is only representative in nature

Capacity (Tons of dry weight biomass per day)	Length (Meters)	Carbon dioxide (Kgs per day)	Area (Acres)	Electricity (Kilowatts)	Cost (Euros)
Demonstration	36	10	0.01	12	69,000
1	1,068	2,881	0.4	55	580,000
10	10,692	28,805	4.3	545	2.5 million
50	53,466	144,027	22	2,727	6 million
100	106,932	288,053	44	5,455	10 million

Figure 7 - Original data used for calculations: Later discarded

PBR	Chlorella % dry weight to oil	55
	Efficiency of oil extraction / %	99
	Efficiency of transesterification / %	98
	Energy in biodiesel / MJkg^-1	37.8
	Cost of 100 tonnes dry weight per day / euros	10,000,000
	Dry weight per day / capable to oil	55
	Dry weight oil per day	54.45
	Mass of diesel (after all processes)	53.361
	Energy efficiency from combustion / %	70
	Energy per day / MJ	1411932.06
	Conversion MJ>kWh	0.277777778
	Energy per day / kWh	392203.35
	Energy input per day/ KWh per 1.5 acres	96
	Per 100 tonne a day (100 tonne = 44 acres)	2816
	Overall output per 10mn euro per day/KWh	389387.35
	Per hour / MW	16.22447292
	Number needed	236.7602756
	Cost / euros	2367602756
	Conversion euros>£ (15/12/17)	0.88
	Cost / £	2083490425
	Acres	10417.45213

Figure 8 - Initial calculations: Later revised

To keep conditions optimised we propose using a series of set colour LED's to provide the optimum frequency of light reaching the algae and heaters to keep the algae at optimum temperatures. In order to keep costs down we plant to recycle the water, the graph below shows that reusing the water whilst replacing lost nutrients does not affect algae growth. In order to prevent dead spots, the raceway has a paddlewheel to make sure all the algae keeps flowing.

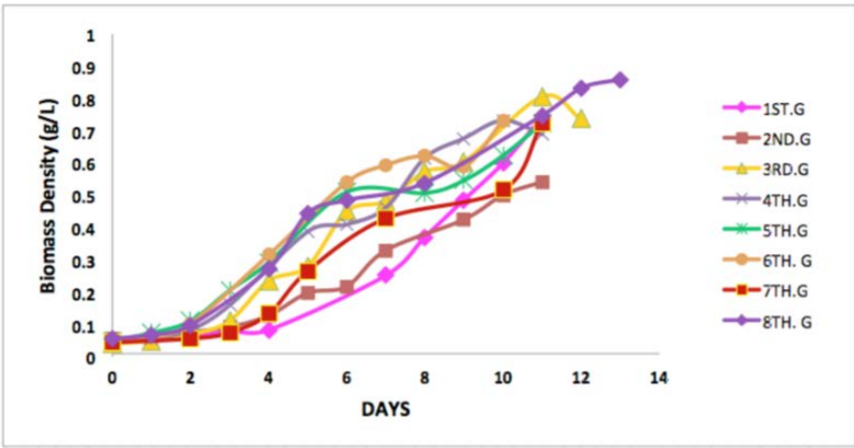


Figure 9 - The effect of reusing recycled water (each generation reusing water from the last)

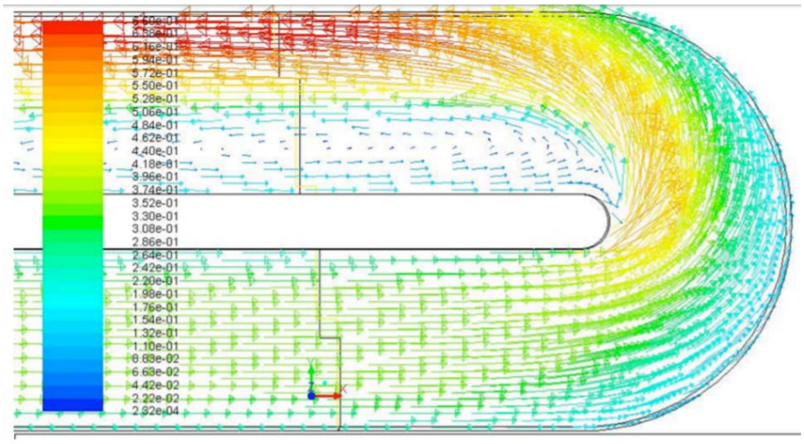


Figure 10 - A diagram of water flow showing stagnant spots

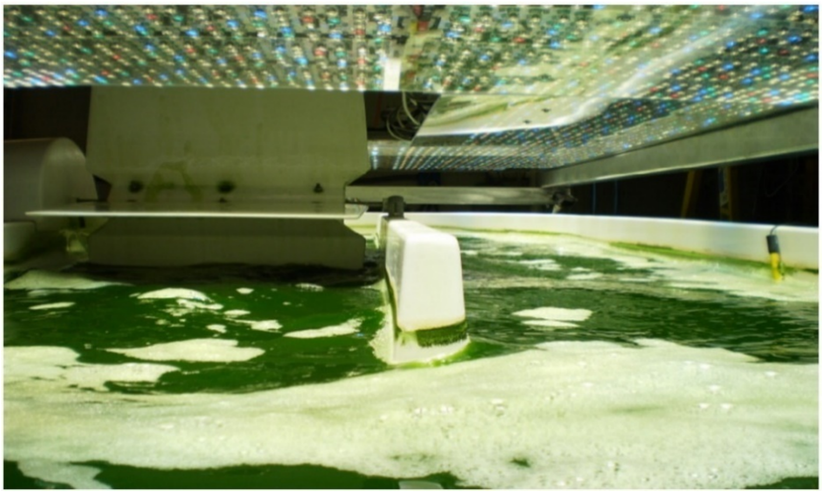


Figure 11 - Example of using LED's to optimise light conditions (here shown on a pondway)

Optimum conditions for Chlorella Algae

Salinity	22-34 ppt	
pH	8-9 pH	
Temperature /C	35 - 37C	
Nitrogen Source	Urea	
Cultivation medium	PE-001A	

Figure 12 - The optimum conditions for Chlorella Algae [vii]

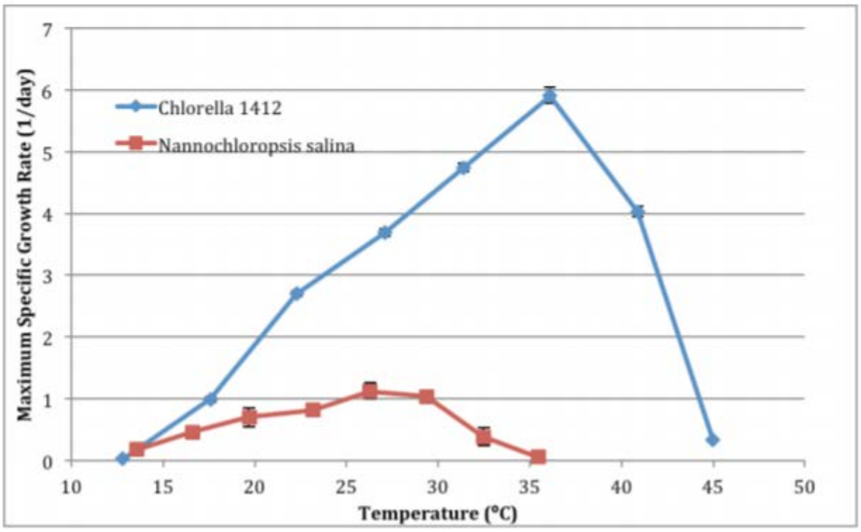


Figure 13 - The effect of temperature on different strains of algae

Extraction methods

Initially we looked at ways of generating biodiesel. We proposed a dual stage method, first using supercritical fluid method to extract algae oil. Supercritical fluid extraction is more efficient than solvent separation methods. Because supercritical fluids are selective, they provide high purity and product concentrations and can extract nearly 100% of the oils.[viii] In the supercritical fluid (CO2) extraction, CO2 is liquefied under pressure and heated to the point that it has the properties of both a liquid and gas. This liquefied fluid then acts as the solvent in extracting the oil. After oil extraction from algae, the remaining biomass fraction can be used as a high protein feed for livestock. This gives further value to the process and reduces waste.

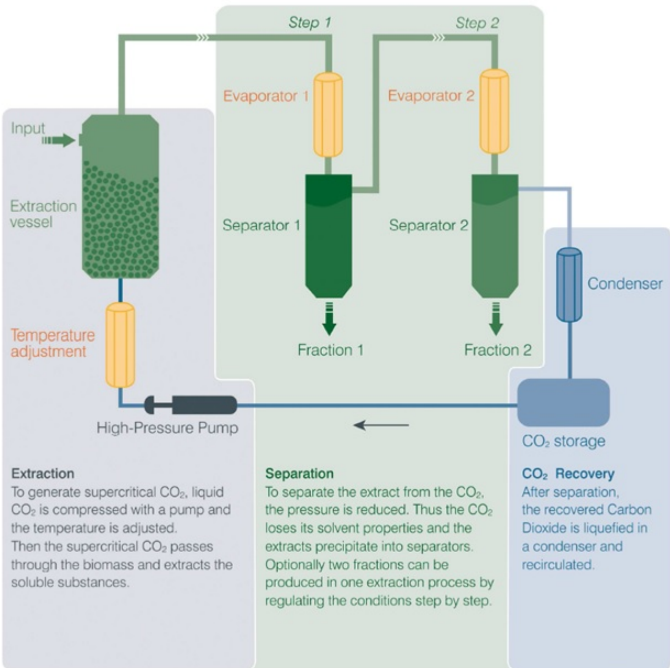


Figure 14 - Schematic of supercritical CO2 extraction method

The algae oil we then proposed to convert to biodiesel using the transesterification method. This however requires methanol and an acid or alkali catalyst. This process is said to be up to 100% efficient (see below).[ix]

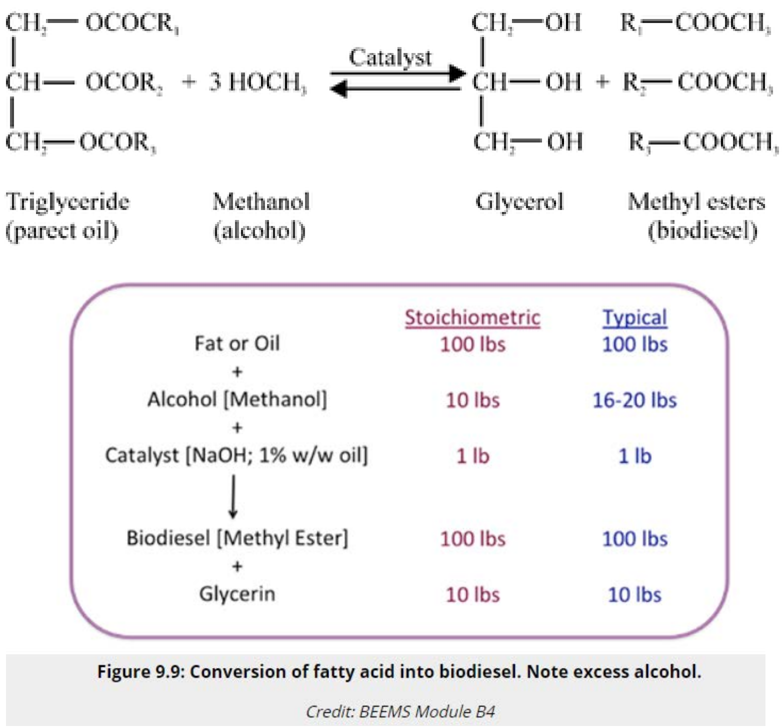


Figure 15 - Transesterification process and efficiencies

We next contacted JS Power, one of the world leading constructors of biodiesel generators, at the viability of using biodiesel generators in the future. They construct up to 500MW biodiesel generators capable of running non-stop all year round entirely off biodiesel. Their data was comparable to one of a usual oil powered generator, so we decided rather than scaling up individual generators we would model our power station on an oil-fired power station and as we were allowed 20 years further ahead in time than the numbers we could find we estimated a 30% reduction in cost. [x]

kWh Formula				
500kVA Biodiesel			Annual Cost	
Initial Cost =	£50,000.00		Fuel per litre	£0.55
			LPH usage of Genset	102
Expected Life =	10		Hours Runtime per Year	8560
			Fuel Cost per Year	£480,216.00
Annual Operating Cost (Fuel + Maintenance) =	£490,586.00		Maintenance Cost per Year	£10,370.00
Annual Cost =	£495,586.00			
KW Rating of Unit =	480		ROCs value approx £45 -£55 per MWh	
Hours Usage (per Year) =	8560			
Annual Energy Output =	4108800			
Cost Per kWh =	**£0.121**		ROCs = 5p pkWh	
ROC	£0.05			
Running Charge	**£0.71**	Approx		

Figure 16 - Data provided by JS Power

Table 5.9	300-MW Oil-Fired Power Plant—Costs for 1 x 300 MW Subcritical Oil-Fired Plant		
Each Item Costs for Equipment, Material, and Labor (January 2008 US$)			
Conceptual Cost Estimate Summary	**U.S. (thousands $)**	**India (thousands $)**	**Romania (thousands $)**
Earthwork/Civil	34,400	22,900	21,200
Structural Steel	17,800	11,400	19,600
Mechanical Equipment			
Boiler	86,600	74,300	70,000
Steam Turbine	40,200	37,800	38,800
Coal Handling			
Ash Handling			
Particulate Removal System			
Wet FGD System			
Selective Catalytic Reduction	17,600	0	16,800
Total Mechanical Equipment	144,400	112,100	125,600
Electrical	33,300	23,000	26,100
Piping	26,900	12,800	15,100
Balance of Plant/General Facilities	70,900	68,500	99,600
Direct Field Cost	327,700	250,700	307,200
Indirect Costs[1]	24,000	14,200	11,600
Engineering and Home Office Costs[2]	34,000	18,100	22,000
Process Contingency	0	0	0
Project Contingency	77,100	70,700	85,200
Total Plant Cost	462,800	353,700	426,000
Total Plant Cost, US$/kW	1,540	1,180	1,420

Source: Author's calculations.

[1] Field office nonmanual labor, craft support labor, and temporary facilities.

[2] Engineering, start-up, and general and administrative costs.

Figure 17 - Data from ESMAP Technical Paper 122/09

Power plant	300-MW oil power plant cost /$	462,800,000
	Total plant cost US $/kW	1,540
	Total raw plant cost for biofuel (2008)	5915618446
	% reduction estimated	30
	Final cost /$	4140932912
	Conversion rate $>£ (14/12/17)	0.74
	Final cost /£	3064290355
Transesterification plant	Mass biodiesel required (per day) /tonnes	12633.76507
	Mass biodiesel required (per year) /tonnes	4611324.249
	Cost for 60,000 tonne plant / euros	5100000
	Number of plants needed	76.85540415
	% reduction in plant costs	30
	Overall cost / euros	274373792.8
	Overall cost / £	241448937.7

Figure 18 - Original calculations: Later revised

However, we then decided to consult expert advice from Dr Mark Crocker, Associate Director CAER Professor of Chemistry, University of KY, Biofuels and Environmental Catalysis, Centre for Applied Energy Research, University of Kentucky. Who, among other things recommended the process of hydrothermal liquefaction (HTL) to us. This method allows wet algae slurry to be converted directly into biocrude which can be burnt in an oil power station and some biogas which can be compressed and burnt as usual in a gas turbine.

The algae is first extracted by a process of electrocoagulation. Electrocoagulation uses reactive metallic electrodes to produce positively charged ions that induce coagulation of the negatively charged microalgae cells. This results in the algae cells being removed from the solution through settling. This is the most cost effective, efficient, and safe method.[xi]

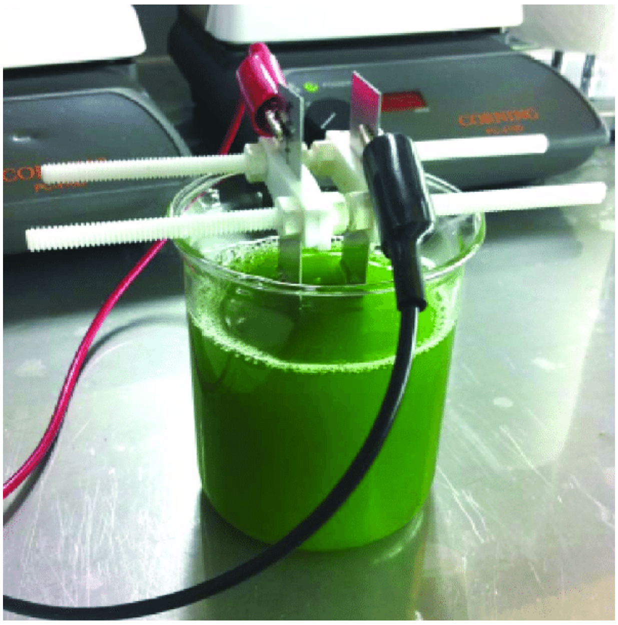


Figure 19 - Small scale demonstration of EC method

We plan to use a join HTL and CHG method of extracting the bio crude and gas from the wet algae, this involves first running the algae slurry through a HTL plant which produces an oil stream and an effluent water stream (water with some organic compounds not converted left in), this effluent water is then treated by CHG whereby 99.99% of the organic compounds are removed and converted to methane gas and CO2 with the other by-product being clean water which can be added back to the ponds. Overall this system captures 85% of the carbon in the algae as fuel-grade components.

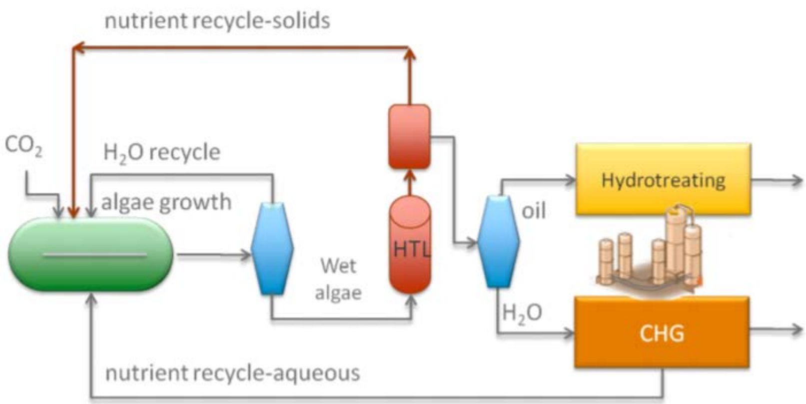


Figure 20 - System for extraction of biocrude

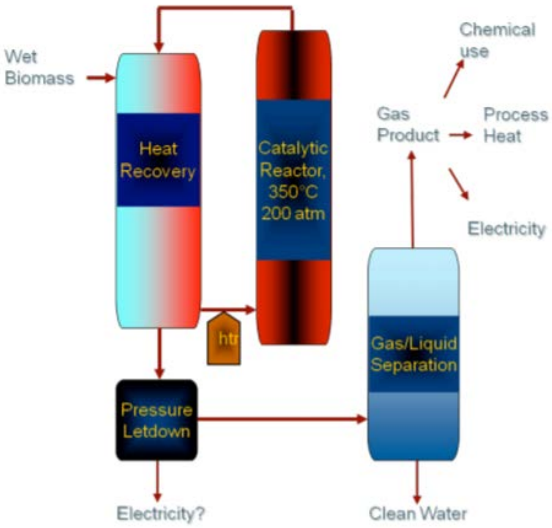


Figure 21 - CHG process

We would then use steam reforming to convert the methane gas into hydrogen and carbon monoxide:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

This process would be followed by a water gas-shift reaction to convert the carbon monoxide into both carbon dioxide and more hydrogen:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

With this hydrogen we would use the process of hydrotreating. Hydrotreating includes desulfurization, removal of substances (e.g., nitrogen compounds) that deactivate catalysts, conversion of olefins to paraffins to reduce gum formation in gasoline, and other processes to upgrade the quality of the fractions.[xii]

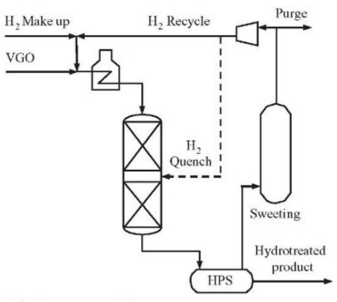


Figure 22 - Hydrotreating process

Again, we were planning to use a system of cogeneration (as shown below) to enable us to keep running costs down. This process has the added benefit of requiring no added chemicals such as did transesterification, thus is easier and less damaging.

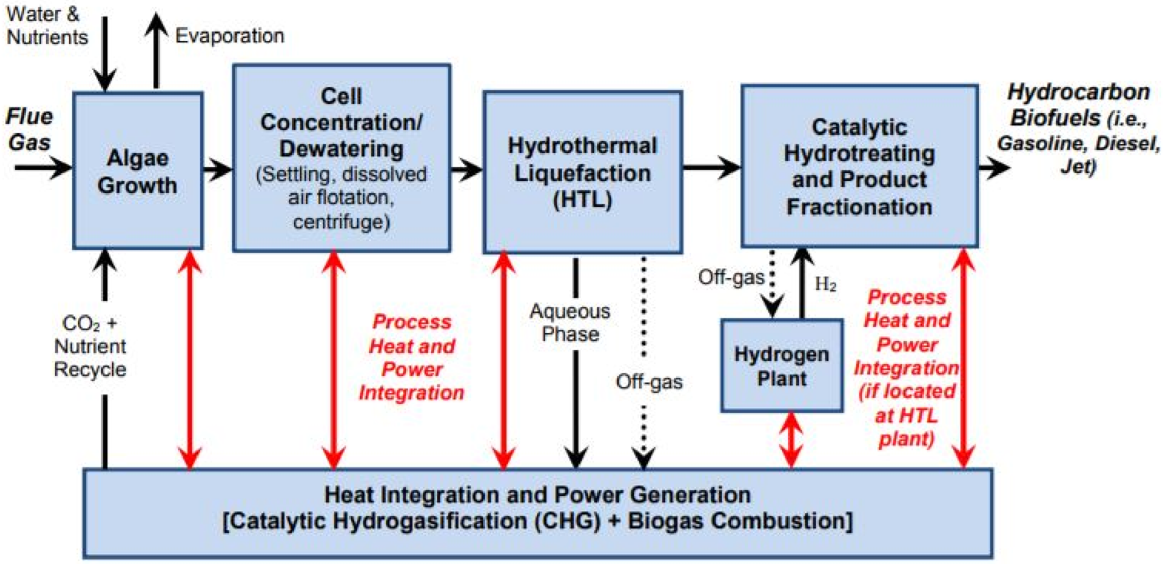
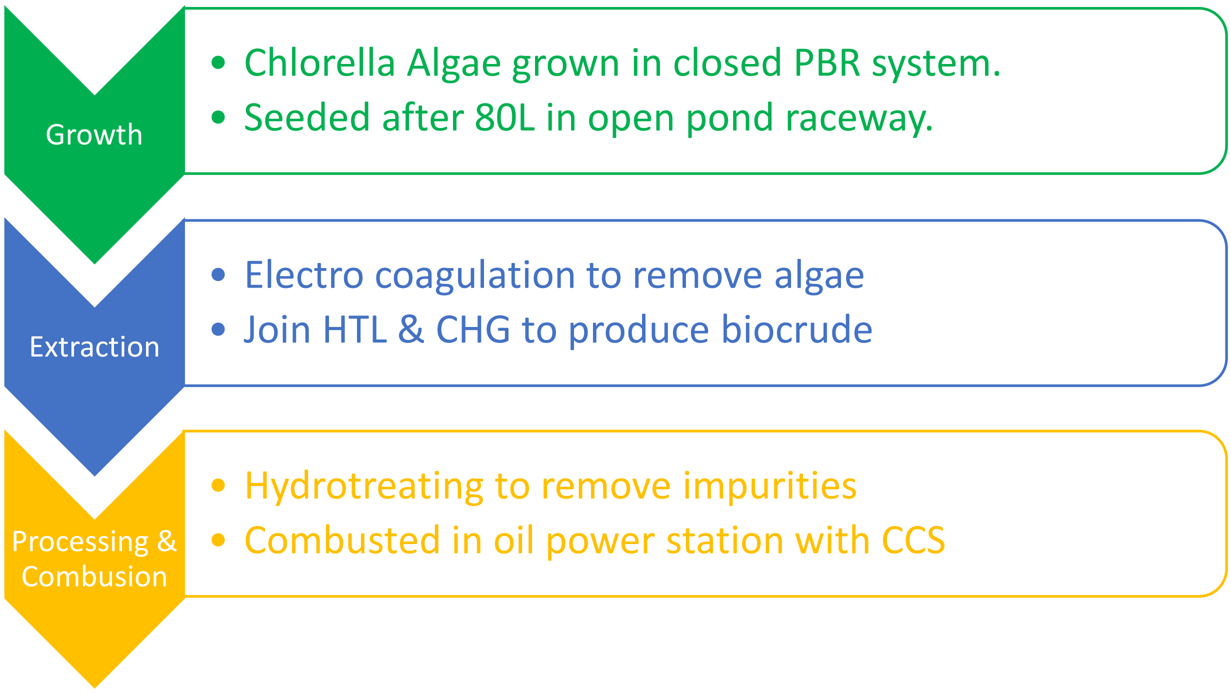


Figure 23 - Full refining process showing use of cogeneration[xiii]

In order to make this process carbon negative we decided to extract CO2 from the atmosphere and add it to the initial algae growing process alongside some of the flue gases. The rest of the carbon dioxide from the flue gases we plan to sequester.

Overall process & calculations

In conclusion our system consists of:



- We then used data provided by NAABB and ESMAP to conduct our calculations.
- We went off data given for one unit by NAABB and scaled it up. They projected a 70% reduction in CAPEX and an 80% reduction in OPEX in 10 years' time due to the development of new technologies, the projected rise in funding in this field, the widespread

roll out of new PBR's and raceways, the development of new lighting and heating systems to maximum efficiencies and many more facts.

- It is also projected that the PBR's and raceways can be stacked on top of each other to reduce the land usage, we did not have data on this so decided to estimate the size based on our previous calculations.
- Using cogeneration also reduces the heating costs thus also reducing electricity usage by up to half.
- We plan to provide the electricity to run the Algae and HTL plant from our own power plant to reduce OPEX costs further, as you can see *(below)* before doing this electricity made up over three quarters of the overall OPEX cost. We used the data of electricity cost per year and the average cost (in US as US data) of industrial electricity (around 8 cents per KWh) to work out how much extra electricity we would need to produce per year to make up for this.

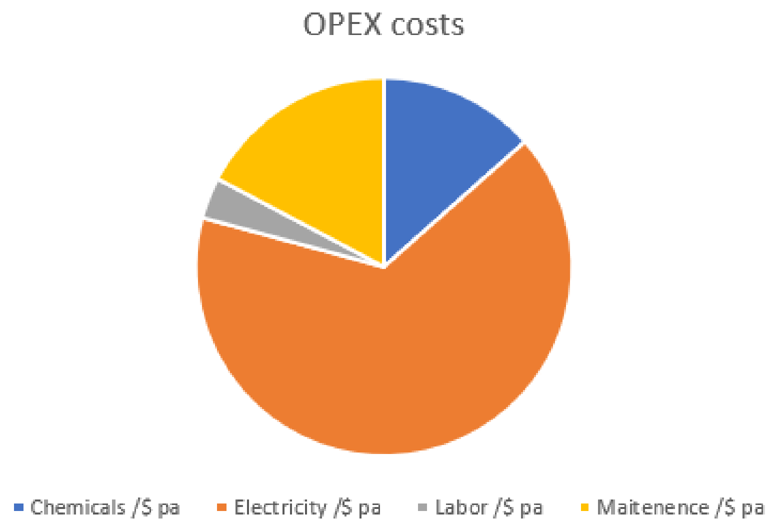


Figure 24 - OPEX costs before electricity removed

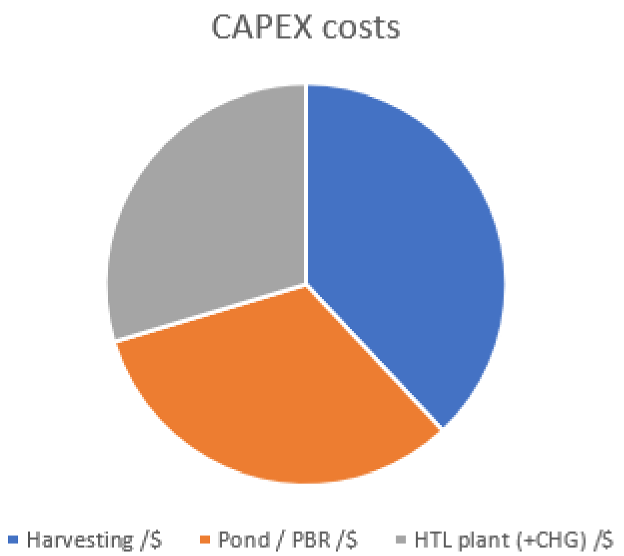


Figure 25 - The make-up of CAPEX costs

Algae + HTL plant - Per unit	Source:
	NAABB full report II
Technologies used	EC, HTL-CHG, GMO
Products	Bio-crude & Methane
Cultivation	Mixed PBR & pond
Biomass production / tonnes a year	316,800
Crude Oil production / gallons a year	42,321,000
Average cost per gallon (bio-crude)/$	2.1
Hectares of Land	4850
Hectares of Pond	4050
Harvesting /$	403,000,000
Pond / PBR /$	343,000,000
HTL plant /$	314,000,000
Total raw CAPEX / $	1,060,000,000
Reduction in CAPEX	0.7
Total CAPEX / $	318,000,000
Chemicals /$ pa	19,520,000
Electricity /$ pa	95,000,000
Labor /$ pa	5,100,000
Maitenence /$ pa	25,000,000
Total raw OPEX / $	144,620,000
Reduction in OPEX	0.8
Total OPEX / $	28,924,000
Biomass productivity - g/m2/d	150

Figure 26 - Data per unit of Algae + HTL plant

Required Increase in Energy Output			
		Source:	
Ind Cost per KWh USA /$	0.08	US Energy Information Administration	
Electricity OPEX per unit /$	19,000,000	See previous spreadsheet	
Projected % drop after Cogeneration	60%	Constellation	
New Electricity OPEX per unit	7,600,000.00		
Overall Electricity OPEX /$	97,888,000.00		
KWh for electricity pa	1,223,600,000.00		
Rise in total power output / MW	139.6803653		
Original Power output /MW	1514		
Original GWh required pa	13263		
Adjusted Power output / MW	1653.680365		
Adjusted Gwh require pa	14,486.60		

Figure 27 - Calculations behind the increase in energy power due to production of electricity

CO2 Required		
		Source:
Tonnes Biomass pa	4,455,232.26	NAABB full report II
Tonnes CO2 per tonne algae	1.8	Dr Mark Crocker
Tonnes CO2 pa	8,019,418.06	

Figure 28 - The amount of CO2 required to grow algae

Total GWh require pa	14,486		
Total power output / MW	1654		
			Source:
Oil Power plant CAPEX	300-MW oil power plant cost /$	462,800,000.00	*ESMAP Technical Paper 122/09*
	Total plant cost US $/kW	1,540.00	
	Total raw plant cost for biofuel (2008)	2,547,160,000.00	
	% reduction estimated	30.00	
	Final cost /$	1,783,012,000.00	
	Conversion rate $>£ (19/2/18)	0.71	
	Final cost /£	1,265,938,520.00	
HTL & Algae plant CAPEX	Crude oil production /gallons pa	42,321,000.00	*NAABB full report II*
	Crude oil production /m3 pa	192,395.07	
	Crude oil density /kg per m3	920.00	
	Crude oil production / kg	177,003,468.90	
	Crude oil energy content / MJ per kg	41.90	
	Energy content / MJ	7,416,445,346.86	
	Energy efficiency in combustion	0.50	
	Energy output / MJ	3,708,222,673.43	
	MWh per MJ	0.0002778	
	MWh pa	1,030,061.85	
	GWh pa	1,030.06	
	Number of units needed	14.06	
	Overall oil required / kg	2,489,241,048.13	
	Cost per unit /$	318,000,000.00	
	Overall cost /$	4,472,108,135.67	
	Overall capital cost/£	3,175,196,776.33	
			Source:
Oil Power plant OPEX	Running cost £/KW	22	*UK MARKAL Model*
	Total power output required /KW	1,654,000.00	
	Total running cost /£ pa	36,388,000.00	
HTL & Algae plant OPEX	Total OPEX per unit	9,924,000.00	*NAAB full report II*
	Number of units	14.06	
	Total OPEX pa / $	139,563,525.59	
	Total OPEX pa / £	99,090,103.17	
Total CAPEX /£	4,441,135,296.33		
Total OPEX /£	135,478,103.17		

Figure 29 - Final calculations

Thus, overall our system would cost £4.44 billion to build and thereafter cost £135 million per year. We estimated our entire system would require around 2000 acres of land (roughly 8 km^2) of which around 80-85% would consist of PBR's and Ponds and 15-20% would consist of the HTL/CHG plant and power plant.

Carbon Capture

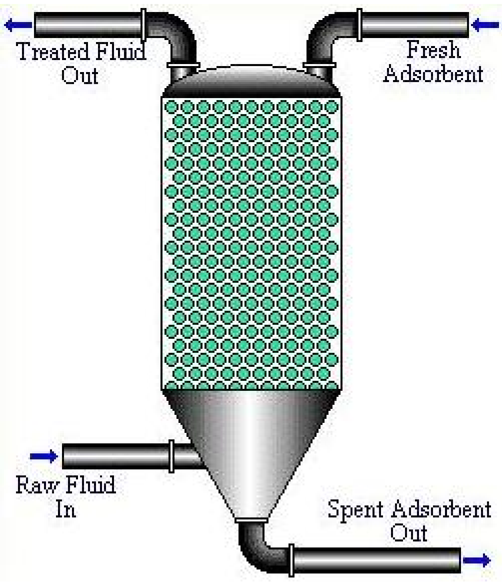
To create a power solution that was carbon neutral it would necessary to capture the carbon emitted from the powerplant. This process needs to adsorb as much carbon as possible for the lowest cost possible. Then once the carbon dioxide had been successfully isolated it needs to be reused or stored safely. In this section we will show our research to these problems and our actual solutions.

Post combustion amine CC

Our first cause of action was researching the current methods of carbon capture. One common current solution that we found was the use of carbon dioxide scrubbers post combustion to remove the CO2 from the ejected flue gas. Such a system was tried and tested in Aberthaw power station in south wales. The implementation used amines and a conventional gas adsorber to capture the CO2 ejected. The CO2 would bind to the liquid amine at lower temperatures, then this liquid can be transferred and heated to release the CO2 for further processing. This separates the CO2 from other flue gases.

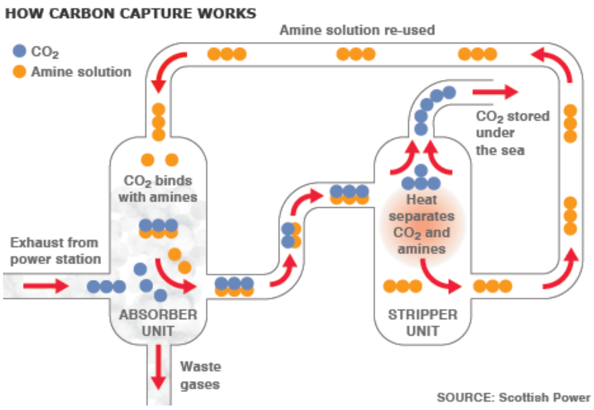
The reversible reaction between CO2 and monoethanolamine

$$CO_2 + 2\ HOCH_2CH_2NH_2 \leftrightarrow HOCH_2CH_2NH_3^+ + HOCH_2CH_2NH(CO_2^-)$$



adsorber system

This process can be made more efficient by maximising the surface area that the amine can contact the co2. The conventional adsorbers use packing beds or trays to increase the effectiveness of the adsorbent, in the diagram the raw fluid would be flue gas, the spent adsorbent (amine carbon mix) would then be transferred to the regenerator.



Baseline amine CO2 separator

Once the liquid mix of co2 and amine is pumped out the system it is brought to a regenerator where heat is applied to separate the co2, the co2 stream is of very high quality which makes it easier to store. Any amine solution that can be recovered is then sent back to the adsorber.

Implementing the most effective adsorber and amine (monoethanolamine) can yield from 85% to 90% capture of co2 which with current technology it is the most effective solvent to capture co2 [12]

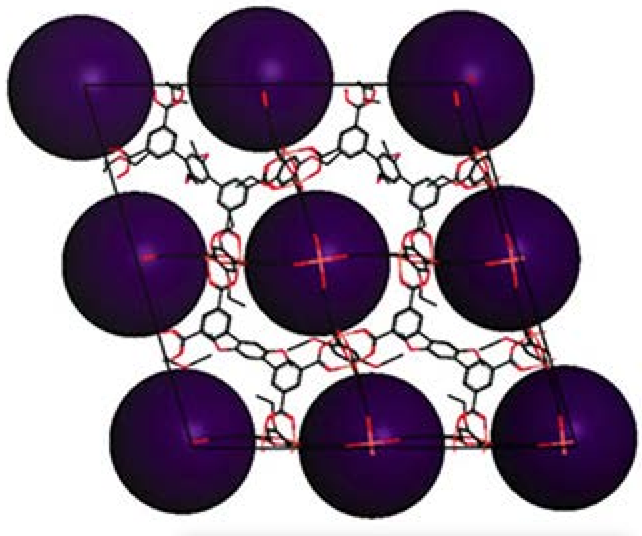
Pros of post combustion amine CC:

It has been proven to work on actual power plants and the capture percentage can be very high.

Cons of post combustion anime CC:
It has a very high energy cost to run to regenerate the co2 and amine solution, as well as using costly chemicals which have to be replaced because of solvent losses when reaction with impure gas stream. The capture rate is good however it costs too much to run continuously each tonne of CO2 removed would cost $72 to remove.
It is for this reason why the amine separator in Aberthaw did not run continuously.

Future alternatives to the amine solution

One of the most promising future technology for gas separation that is currently being researched is MOFs or Metal Organic Frameworks. Historically the most porous materials were zeolites which have been used for breaking down petrochemicals and removing calcium from water. However in 1999 a new class of porous materials arose crystalline macromolecules constructed using metal ions conjoined by organic molecules. This type of material is incredibly versatile as you can not only modify the strength of the bonds but also the geometry of the structure. MOFs with custom built geometries could be a potential way of storing or processing CO2 as the molecules of co2 could fit within the gaps created by the structure, this has been identified by the US government as a promising future capture method [xiv]An example of MOFs amazing properties is the material DGC-MIL-101 which has a surface area of 4164m^2/g. [xv]The gas captured or stored in the MOFs can be released using heat or pressure. One of the top identified materials that could be used for carbon capture is NOTT-101, Randall Q. Snurr a chemical engineer at north-western engineering claims that using NOTT-101 or a variation of it could yield up to 90% carbon dioxide adsorption. The use of MOF does not only have to apply to CO2 capture but it can also be used to separate SOx and NOx from the flue gas.



3D representation of NOTT-101, the purple spheres is where the CO2 molecules would be found.

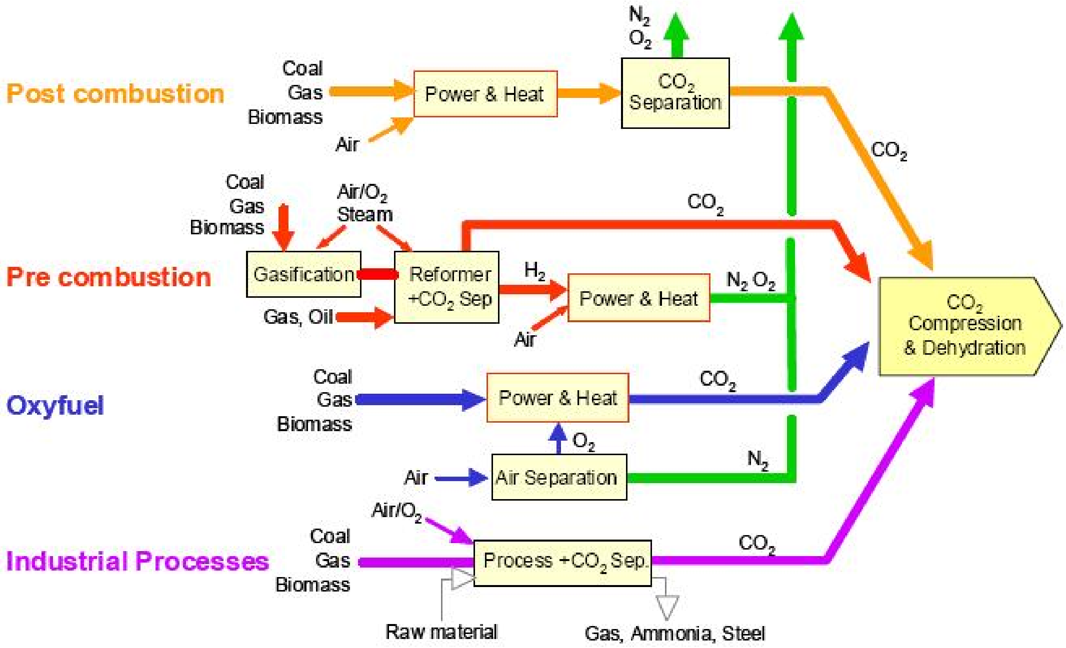
Even more recent developments show that mofs could be implemented as liquids to allow them to used like amine solutions, the advantage of having such a tunable material in liquid form is that it could be pumped into a generation chamber where the waste heat from the PowerStation would be enough to release the trapped CO2, in addition there is no reaction taking place only absorption so there would be very little or no replacement needed of the MOFs. This happens because of the fact that the flue gas would be a lower temperature than the boiler.

The disadvantages of MOFs is that they are currently very expensive to produce, the running cost can relatively low because of the small amount of heat needed to regenerate the gas but the set up cost is too high as they have to be synthetically made, because of this no large scale test has been done using MOFs but small scale tests have been very successful.

We believe that in the next 10 years we would be able to produce of a tuned liquid MOF that could capture up to 90% of the CO2 from the flue gas and be regenerated with the waste heat produced from the plant. We believe that progress in MOFs is going to be rapid as it has potential to revolutionise industry. More and more research has been published each year with last year producing 20,000 papers studying MOFs more than 5000 more than the previous year.

Combustion

Whilst researching MOFs we found that concentration of CO2 produced was a very key aspect in determining what MOF to use. The concentration of CO2 in the flue gas is determined by the way the fuel is burned, through this we found alternative ways to access the CO2.



Post combustion

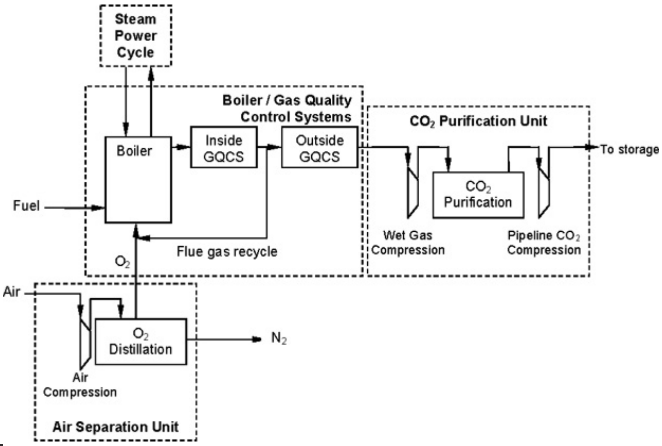
Post combustion is the most common method of CC, the fuel source is burned in standard air then the flue gas is then treated by amine scrubbing and desox/nox processes. The advantages of this that it can be retrofitted to the power station after it has been built so it can make older power stations cleaner. The disadvantage is that the quality of co2 that comes from the flue gas is relatively low.

Pre-combustion

Pre combustion is less used than the other method of generating co2 however it has some interesting properties, it takes the carbon fuel and burns it is steam and low oxygen conditions producing the products H2 and CO this process of combustion of the fuel source is less efficient however the syngas (H2 and CO mix) can be recombined with steam then using a catalyst form CO2 and more H2, then the H2 can be burnt as a fuel source or can be kept for use in a hydrogen fuel cell. The result from this process is a purer form of CO2 and H2 which can be then used as a power source. Advantages is that it produces a storable unit of fuel which can be transported easier(possibly using MOFs) and burnt at site for more effective energy transfer (i.e. hydrogen powered cars) and it produces a high concentration CO2 stream. Disadvantages is that it cannot be retrofitted onto existing power station and that there is a loss of energy efficiency in the process producing H2.

Oxy-fuel

Oxy-fuel is when you burn fuel in unnaturally high oxygen levels instead of just burning it in air, because of the higher levels of oxygen the combustion is more complete allowing a more efficient and high temperature burn. Classically oxy fuel systems were used in welding because of the higher flame temperature however there has been plans to implement it in power stations.



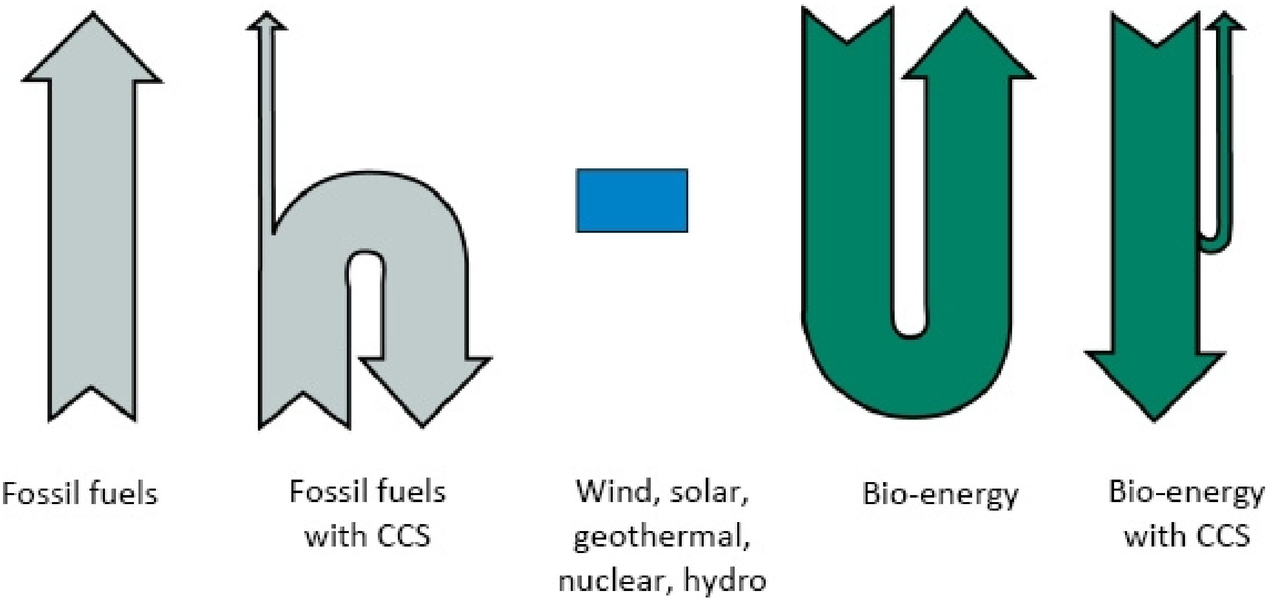
an example of how an oxy fuel system works_

Oxy fuel has great potential however to get the correct burn the right percentage of O2 must be used. When it is done right it can lead to a much faster burn and a more efficient burning of fuel, To increase the oxygen content you can inject pure O2 into the system or use oxygenated fuels. The advantages of oxy fuel system are that the combustion is more efficient meaning for higher energy output and cleaner meaning it produces a higher concentration of CO2 in the flue gas allowing for easier separation, it could produce such pure CO2 streams that chemical separation of flue gas would not be needed. However even though the properties would be desirable in the plant it has its disadvantages. For example, it requires energy to generate pure O2 from the air using air filter this could increase cost dramatically.

Captured Carbon Usage

Carbon Negative

Once we have extracted the CO2 we need to find a way of not releasing it back into the atmosphere. Our carbon neutrality arises from us using a BECCS (Bioenergy with Carbon Capture and Storage) system meaning that the net CO2 in the atmosphere is reduced.

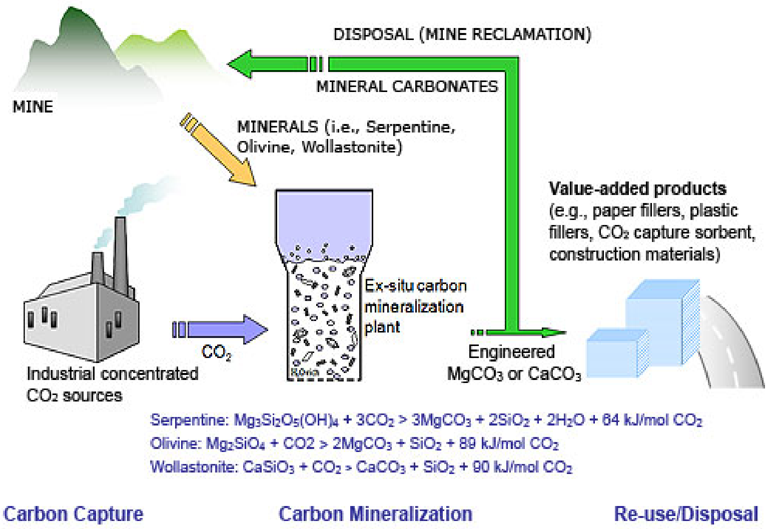


Carbon Storage

However for our BECCS system to work we had to find a suitable way of storing the CO2 long term. The 3 solution that we found were mineralization, ocean injecting and storage in geological formations.

Mineralization

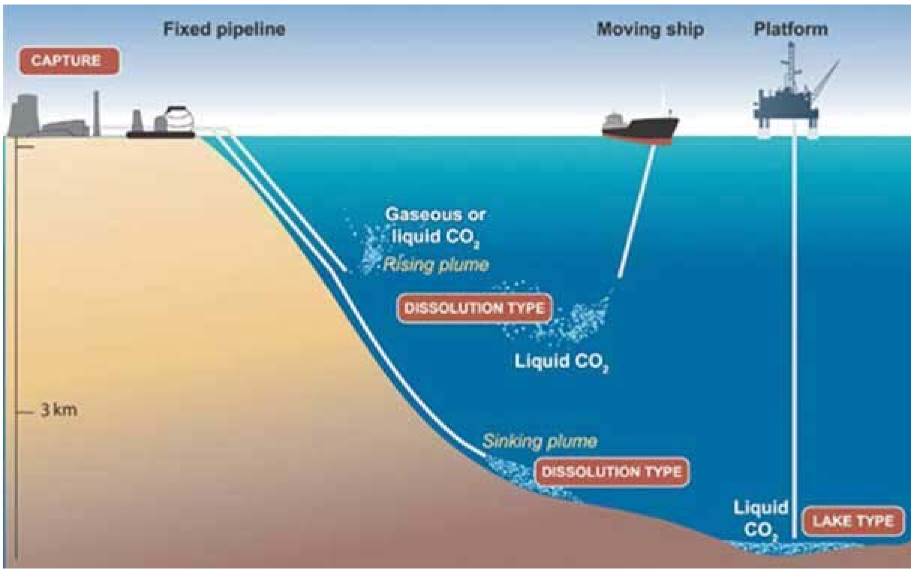
A potential solution for storing carbon would be to react the CO2 in industrial purposes, during mineralization the CO2 from the flue gas is separated and then passed through special minerals that would from carbonates and get rid of the CO2. Then these carbonated minerals could be engineered into new plastics or construction materials. So instead of releasing the CO2 into the atmosphere the CO2 would be “recycled” into useful materials.



The advantages of this system are that you from a physical product from the separation of CO2 which could then be sold off to pay for the cost of CO2 separation. This storage method can also be done on site depending on its location to save on cost. However, the major problem with the system is that it requires finite minerals mined from the ground, which increases emissions and is harmful to the environment, it also greatly increases cost as the ores and salts that are used are expensive.

Ocean injection

The ocean provides the world greatest carbon sink absorbing the most amount of carbon emitted by humans, the basic premise of this solution would be pumping the captured CO2 deep into the water where is would dissolve and be stored through the pressure of water above. This provides a simple solution of storing CO2



Although the ocean provides a great way of storing CO2 and once it is stored it can be forgotten about and the infrastructure is relatively less expensive there are a few obvious flaws in the solution. The main one would be that pumping CO2 into the water would increase the acidity in that sector of water which could drastically affect marine life and would be disastrous for the lower ends of the food chain which are more susceptible to changes in Ph. This would cause a collapsed in the food chain so this solution is generally not accepted as being viable. Secondary would be that more than likely a pipeline would have to be created to pump the CO2 from site to the ocean this pipeline would cost money to create and money to operate.

Storage in geological formation

Geological formations combine the best aspects of both ocean storage and mineralization. It involves pumping the CO2 into rock formations that are porous in them they must also contain a large layer of cap rock impermeable to leaking of CO2. The usual candidate for this are depleted oil and gas reservoirs as they have already been used to store gas for thousands if not millions of years and if harnessed correctly could hold CO2 for that time. As well as the possibility of using depleted oil and gas fields the other suitable location to store CO2 would be in saline aquifers. The saline aquifer contains salty water covered by a layer of cap rock to prevent any CO2 from escaping. The porous permeable rock allow for efficient storage of gases the CO2 would also dissolve in the water increase storage space as well as this the salt water would react over time with the CO2 to form solid carbonates which would permanently store the CO2 underground . In addition they have served no purpose to humanity so far as they are deep underground and contain nothing of value, this means that there is a lot of untapped potential if they are used for carbon storage.

There are a lot of good things about storage in geological formation: there is a high capacity of carbon that can be stored as well as that it doesn't affect the water life in the area. It also doesn't require any mining or destruction of the environment to store the carbon as the carbon sink is already there in nature. There is also plenty of viable locations that would work making the solution quite versatile. Although there are plenty of locations where this could work it is still a finite resource and will eventually run out, also the pumping of gas underground would require careful monitoring to ensure no leakage into the surrounding which would create the same problem as found in the ocean injection, the monitoring would add to the costs as well as the necessity of a pipeline to transport the CO_2 to the correct geological formation.

Case studies

Once we had researched capture methods, combustion methods and storage methods we decided to look to real life implementation of systems to help inform us on which system would be the most viable.

Decatur Illinois cc case study

Plans have been put forward to produce a BECCS system in America in Illinois, the biofuel would be grown and produced using high energy corn turned into ethanol the growing of high energy corn does require a lot of growing space. Then once combusted the CO_2 would be separated using classical amine separation and then injected into the mount Simon Sandstone a deep saline reservoir. What makes this location good is that there's plenty of space to grow the corn and that the natural geography is suitable for CO_2 injection. The CO_2 injection works as follows,

What we have learned from Decatur

It is viable to store the captured CO_2 in saline aquifers underground and that there should be a lot of storage space and there would be plenty of saline aquifers around the world and in the UK that could harbour CO_2 storage. This also helped reinforce our choice of using algae as a biofuel source instead of using corn as the algae is more energy dense and therefore more space efficient.

White rose cc project case study

A CCS project was planned to be implemented in North Yorkshire at Drax, a smaller power plant at 426MW called White Rose. It was going to be built and was predicted to power 630,000 houses. White Rose would burn a coal/biomass mix using oxy-fuel systems producing a high concentration flow of CO_2, the CO_2 would then be delivered to the Yorkshire Humber CCS Trunk line pipeline to be sequestered in a saline aquifer beneath the North Sea it would capture two million tonnes of CO_2 per year. The Yorkshire Humber CCS Trunk line would be a pipeline 75Km in length and would transport liquified concentrated CO_2 to a permanent geological storage pipeline in the North Sea. The pipeline would run past major CO_2 contributors like PowerStation and heavy industry and intake the sites CO_2.

What we have learned from white rose cc

If we use oxy-fuel system, we may not need to depend on chemical or MOF separation of CO_2 which could save on costs dramatically and would seem a viable solution. Also, the best way of storing CO_2 in the UK would be using a pipe to pump the CO_2 to the saline aquifers offshore, the CO_2 would be in pressurised liquid form to save the cost of transport through the pipeline.

Conclusion

The conclusion from our research and case studies is that we would use an oxy-fuel combustion method as our method of CO2 extraction as it does not require any chemical or MOF separation techniques. Then proceed to pump the CO2 via a pipeline into an offshore saline aquifer for permanent storage as saline aquifers offers vast amounts of storage space.

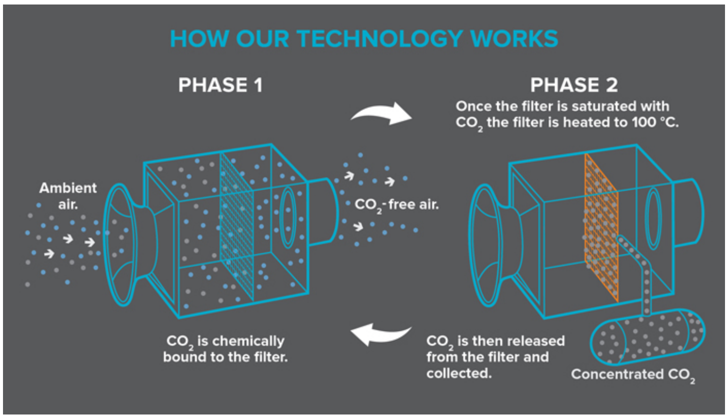
Technical details

Our oxy-fuel system has fantastic potential however the main cost of using this system would be the oxygen extraction from the air, in addition to needing oxygen for the combustion we also needed pressurised pure CO2 to allow for the biofuel to grow in the PBRs. Because of this we had to make our air separation as efficient as possible.

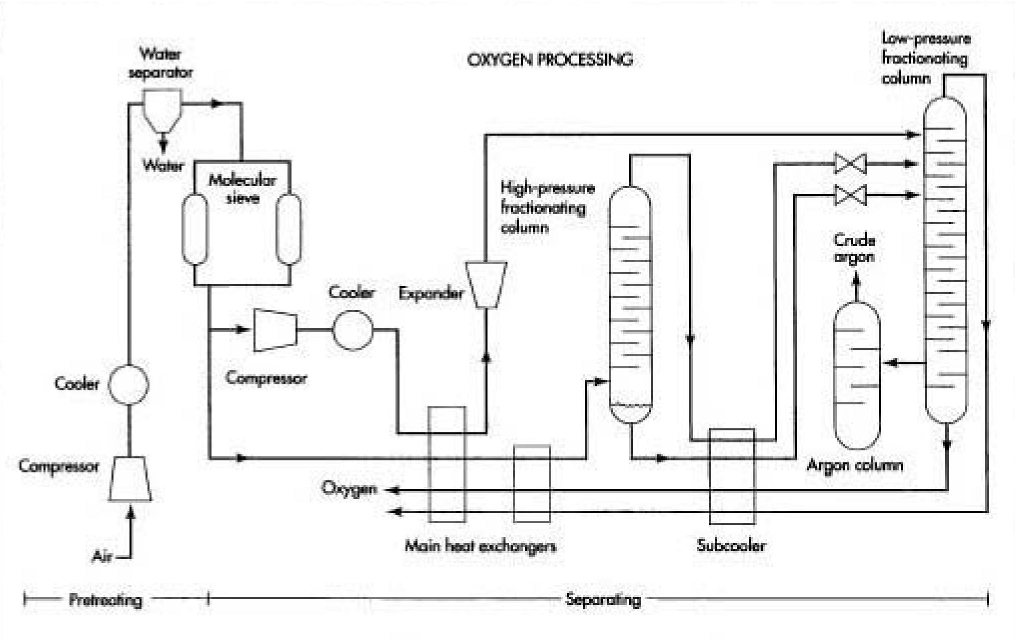
How our air separator works

Having looked into a range of methods to extract CO_2 and O_2, we concluded that the best methods to use would be to use Clime works Technology to chemically remove the CO_2, and using cryogenic distillation of air to obtain O_2, which would also give N_2 as a by-product.

The technology to extract carbon dioxide uses a filter made of porous granulates which are modified with amines, to which the carbon dioxide can bind. The process takes two phases. In the first phase, air is drawn into the filter, allowing the carbon dioxide to chemically bind. Then, once the filter is saturated, it is heated to around 100°C, breaking the bonds, releasing the CO_2, which can then be collected as a concentrated gas, whilst the air is all released back into the atmosphere. The heating can be done with low-grade heat, or waste energy from the power plant. The carbon dioxide will go into a CO_2 conditioning module for liquefaction, before being stored as a liquid.



There are a range of benefits to using this technology as opposed to other methods. The modular design means that we can easily expand if we need more carbon dioxide in the future. The fact that the modules can be stacked also means that only a small amount of land is required. At a cost of less than $80 per ton of CO_2, this is also one of the cheaper methods available. Most of the energy required to run this system comes from low-grade/waste heat.



In order to obtain O_2 and N_2, we will use cryogenic air separation, as it is currently the most cost-effective technology available, despite it being energy-intensive. The process involves pretreating, separating, purifying, and then finally distributing.

The air must be pre-treated to remove any impurities. First it will be compressed to 650kPa, before being passed through an aftercooler to condense most water vapour, which is then removed. A molecular sieve, usually containing silica gel absorbents and zeolite (we have the potential to use a tuned MOF again), then traps CO_2, hydrocarbons, and the rest of the water. Once it has been pre-treated, the air is separated by fractional distillation. A small amount of air is diverted into a compressor, which increases its pressure, before cooling and expanding the air rapidly, and then using this air in the cryogenic section to provide the low temperatures. The rest of the air passes through one side of two plate fin heat exchangers, whilst the cold oxygen/nitrogen which has already left the cryogenic section passes along the other side. This allows the oxygen/nitrogen to warm up whilst cooling the unseparated air. At this point the air becomes cold enough that the oxygen liquifies. In the fractionating column, the oxygen liquifies fully and sinks to the bottom, whilst argon and nitrogen move further up. The liquid oxygen flows out at the bottom, before being cooled further in a sub cooler. The argon and nitrogen from the top of the column are cooled more too, before being allowed to expand, with nitrogen (as it has the lowest boiling point) turning to a gas first and flowing out of the top of the column. With these techniques, we are able to obtain 99.995% pure nitrogen, and 99.5% pure oxygen.

To calculate the cost of the air separator we needed to know how much CO2 and O2 we needed so we decided to try and calculate it.

How much O_2, CO_2 we need to grow and power

Our biofuel system produces bio-oil as the main product. Liquid hydrocarbons can range between 5 and 16 carbons, we are assuming that our fuel has the average value of 10 carbons. As we are using a oxy-fuel system we can also assume that complete combustion occurs, in addition we are also assuming a saturated hydrocarbon as the variation in the stoichiometry between isomers of C10 would have a small impact in the amount of O_2 and CO_2 needed

CO_2 needed grow

We contacted Dr Mark Crocker who is the associate Director of Biofuels and Environmental Catalysis, a professor of chemistry at the university of Kentucky and his main research is in biomass conversion. He advised that it would take 1.8 tonnes of CO_2 to grow 1 tonne of microalgae.

Per year we require 4.455 million tonnes of microalgae.
So, our total CO_2 needed to grow the fuel would be 1.8 times 4.455 = 8.019 million tonnes per year

We require 8,019,000 tonnes of carbon dioxide per annum. This equates to 21970 tonnes per day. 36 collectors yield 4,920 kg per day, which means we will need around 160,000 collectors. This many collectors will cost around £11 million, with a daily running cost of around £220,000 per day, which is £80,000,000 (with reductions coming from the use of tuned MOF as air filters).

O_2 needed to combust and CO_2 produced

Through our assumptions we concluded that the equation for the reaction would be
$2C_{10}H_{22} + 31O_2 \rightarrow 20CO_2 + 22H_2O$
Using this formula and some chemistry we calculated the amount of O_2needed to combust 1kg of the oil.

RFM of $C_{10}H_{22}$ = 142
RFM of O_2= 32
RFM of CO_2= 44
Moles of $C_{10}H_{22}$ in 1kg:
1/142 = 0.007 mol

Moles of O_2reacted
0.007*31/2= 0.1085 mol

Kg of O_2required
0.1085*32 = 3.472Kg

Moles of CO_2produced
0.007*11= 0.077mol

Kg of CO_2produced
0.077* 44 = 3.388 Kg

Per year we will need 2.49 MT of fuel to power the city
Now scaling up these numbers for the amount of O_2 we need
3.472 * 2.49 = 8.65 MT/ year

This will equate to around 23600 tonnes of oxygen per day. At an overall cost of £15 per tonne of oxygen, this will mean an average daily cost of £355000 per day or £130,000,000 per year. We will obtain 3.7 times more nitrogen than oxygen in this system.

Maths

Capex of air separator

It would cost £11,000,000 to build the air separator system

Opex of air separator

80,000,000(cost of CO_2) + 130,000,000(cost of O_2) =
£210,000,000 per year

This value is high because the air separator is a relatively simple device to produce however the cost of splitting the air is high.

Nitrogen produced from air separator

3.7* amount of O_2(8.65) = 32MT/year

CO2 taken in

8.0 MT per year to grow

CO2 for pumped storage

Also from this we can conclude how much CO_2we would capture. The oxy-fuel system would be able to produce high concentration CO_2 flue gas and capture 90% of the CO_2released Source

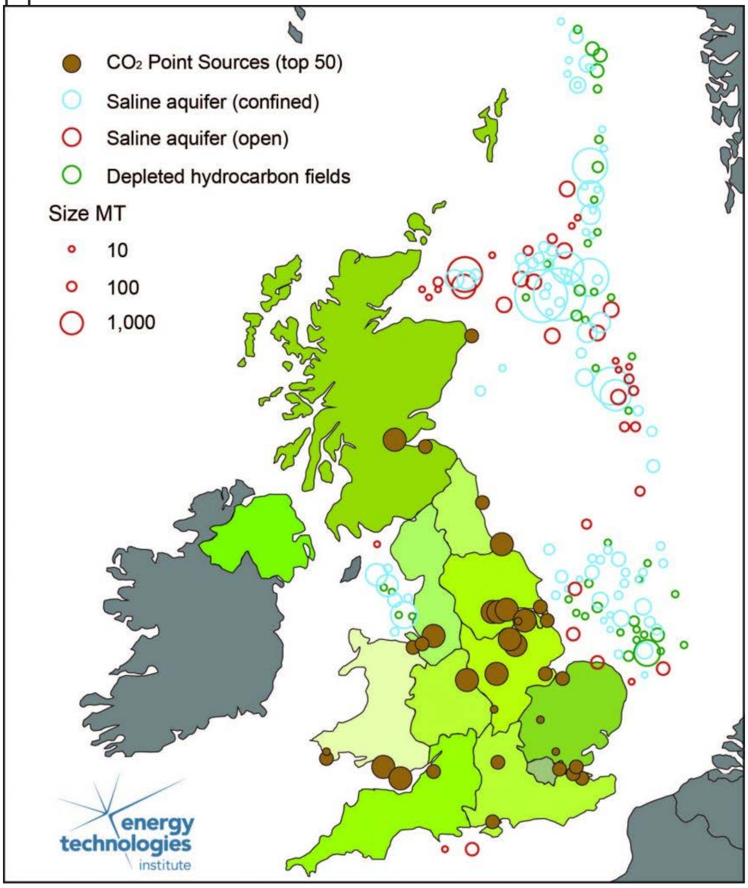
We are using 2.49 MT of fuel per year so we would capture
(2.49*3.388) * 0.9 = 7.59 MT of CO_2per year.

Storage solution

Storage solution

Now that we had obtained our solution for combustion in the oxy fuel system, we looked at the storage solution of the CO_2.

For the CO2 that is not fed back to the PBR, it will be transported to the nearest saline aquifer by pipeline.

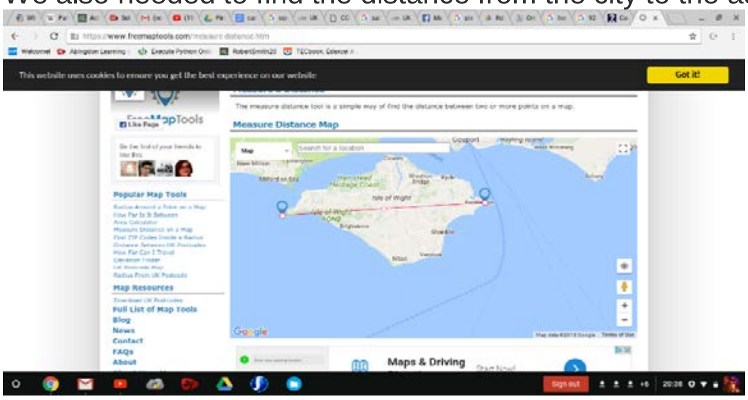


We planned to use the saline aquifers closest to our city, but much of the data was private and required up to £4,000 to obtain. We got around this problem by using the official data plot shown above and using scale factors from a photo editor to calculate the capacity and distance from the city.

The 1,000MT circle had its leftmost edge at x=68,y=372 and a rightmost edge at x=92,y=372 so it had a diameter of 24 units.

Now from this data we calculated the saline aquifers capacity.
Diameter of small circle = 5 units
Capacity of small circle= (1000/24)*5 =208 MT
Diameter of large circle = 13 units
Capacity of large circle = (1000/24) *13 = 542 MT

We also needed to find the distance from the city to the aquifers.



We used the width of the Isle of Wight as our comparison which we found to be 36km.

As with the 1000MT circle, we converted this distance into the photo editor's units, and found that the 36km was equal to 29 units.

The pipeline would go around the Isle of Wight, so to get from the city to the 542MT saline aquifer it would take the rough unit coordinates path:
(574,962) → (550,964) → (546,985)
Calculating the distance travelled required Pythagoras to find the distance between points.
(964-962)2+(550-574)2 + (985-964)2+(546-550)2= 45.46 units
Now converting between photo editor units and kilometres we get
(36/29)*45.46 = 56.43 km

Now the offshore pipeline would cost $100/installed ft source
Meaning $320/installed meter or £230/installed meter
Therefore, it would cost around £13,000,000 to install the pipeline to the large saline aquifer.
230*56430 = £12978900

We can also calculate how many years that the large saline aquifer would take to fill up by dividing the capacity by the amount of CO_2 captured per year.
CO_2 captured per year = 7.59 MT
Storage capacity of saline aquifer = 542MT
Years' worth of storage= 543/7.59 = 71.4 years

We believe that there would be no need to connect the pipeline to the smaller aquifer as this would increase cost, by the time 71 years had passed we would have better technology that would replace the BECCS system however the option would still be viable, if the smaller saline aquifer was connected it would be filled in a further 27.4 years.

OPEX of pipeline source
A rough estimate is that it costs £1 to transport a tcm (thousand cubic meters) over 100 km, so it should cost £0.50 for tcm over 50Km

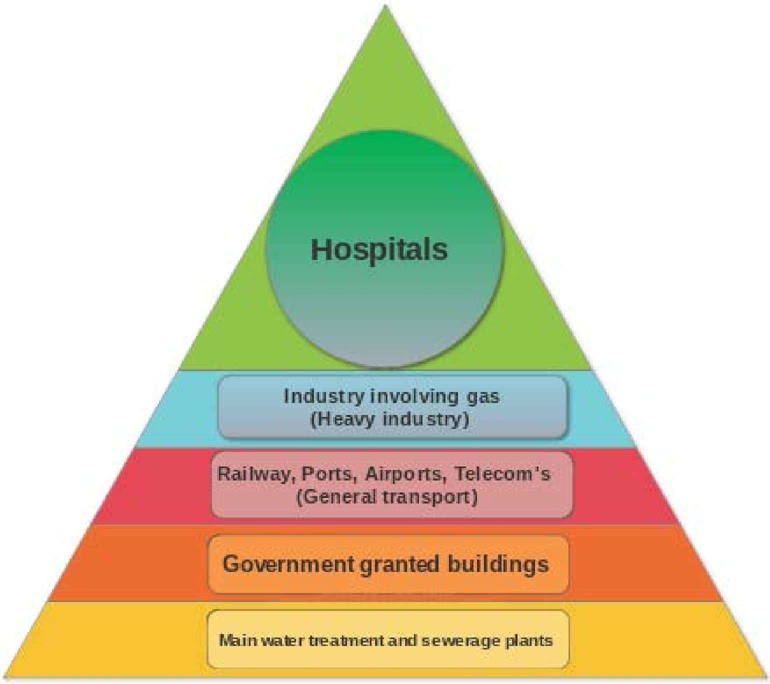
The density of liquid CO_2 is 1.98 kg/m^3
We capture 7.59 MT of CO_2 per year
7,590,000,000kg/ 1.98 = 3,8300,000,000 m^3 per year
3,830,000 * 0.5 =£1,915,000 per year to run the pipeline to the aquifer.

Moderating the saline aquifer source
We believe that it is crucial to monitor the CO_2 injection process as we intend for it to be as environmentally friendly as possible and we don't want any spillage or leakage because of the pressure being too high. From the oxyfuel the flue gas is 90% co2 Source. We found a study of the cost of monitoring a saline aquifer for 20 years, which was 20 billion yen or 0.15 billion British pounds. Therefore, this comes to around 7.5 million pounds per year in monitoring costs.

Additional details

What to do in case of a power reduction

Problems are bound to happen in the lifetime of the power station. If we were to assume that we would have to run of 20% power we decided we needed to have a protocol of what should be kept running. The first stage of the energy loss would be deciding what services would be kept running immediately, then once the problem is fixed or the backup power solution kicks in then we need to decide what sectors are given power back first.



We decided on creating a hierarchy system where the top of the pyramid has priority to the access of power generation or it regains power first once the backup energy supply has kicked in. Once the power has dropped the immediate action is to activate the backup storage solution which would require some energy but after that the highest priority sector is hospitals.

Hospitals

There are obvious reasons why hospitals should have first access to power in a power cut. Medical equipment such as life support turned off would end in disaster so it is very important that we do not allow this to happen. The preservation of life is more important that all other sectors.

Power consumption
Average ft^2 of a hospital = 74600 source
Cost of average hospital per year per ft^2 = $1.67 per ft^2 source
Cost of average hospital 74,600*1.67 = $120,000 per year
Estimate for number of hospitals for 2,000,000 people = 7
Electricity cost per kwh = £0.15
Dollars into pounds = 0.72
Energy consumption of the cities hospitals 120000*7*0.72*(15/60*60) =2.5MW

Industry involving gas (Heavy industry)

Next on the list is Heavy industry, or more specifically, industry involving pressurised gases. Continuous processes in industry require constant energy to keep running. The cost of starting up the process is high and any power loss can be incredibly dangerous. For example, the build-up of pressure in pipes in a gas refinery plant could lead to an explosion. The food industry also requires electricity for cooling produce, which could be disastrous if lost. Although those type of plants must have a backup generator of their own, we think that it is important to give them power as soon as possible so they do not have to rely on it.

Power consumption
Electricity consumption of heavy industry = 7000ktoe/ year source
Estimate for energy consumption = 40MW

General transport

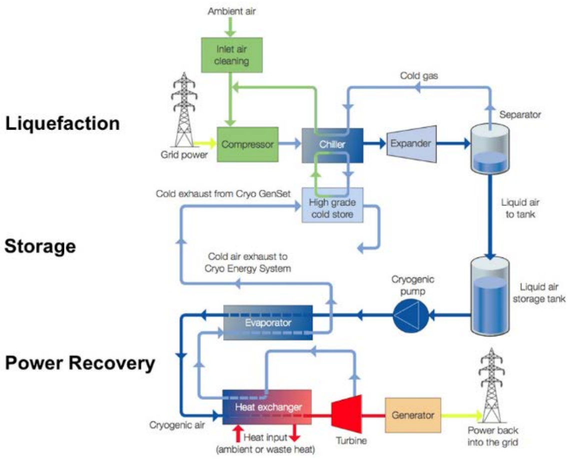
The movement of goods and people is a process integral to the modern city, keeping the airport and ports running is vital as the movement of ships or planes depends on communication with com-towers. If communication goes down with these towers it could cause chaos in the sky or on the water.
Estimate for energy consumption for major transport = 30MW

Government granted buildings source
If a building or a household has any special requirements in a power cut it can request help from service providers or the government. The types of buildings include nursing homes, households of consumers who have a disability, and households of customers who are chronically ill. We believe that these people should get priority over the general population as it is important that they are cared for.
Estimate for energy consumption = 15MW

Water treatment and sewage plants
Just before we are back to full capacity we believe that this should be considered as well. We thought that it was important to keep treating and running water as this is a continuous process. It can afford to lose power, yet it is bad for the infrastructure if it is left for too long, and can cause permanent damage in places which are difficult to reach.
Estimate for energy consumption = 5MW

Backup storage solution
From our air separator as well as getting CO_2 and O_2 we get a lot of N_2 which is the most common element found in the air, instead of releasing the N_2 back into the atmosphere we thought it would be more productive to use the N_2 as our backup storage solution. So we set about looking for a suitable backup system.

Compressed air storage is the second biggest method of storing energy aside from pumped water storage. The advantage is that the energy can be stored for a lot longer than conventional batteries. Highview power storage uses liquid air energy storage to help meet peak demands in the grid.



It employs a 3-stage process. During low energy demand, when electricity is cheap, air is taken in via an inlet and compressed into a high-pressure liquid. It is then stored until it is needed. When pressurised liquid is heated, it expands greatly; through this principle, when energy is required the store gas is heated, which causes expansion which is then harnessed using a turbine.

Liquefaction
As liquid air is 78% nitrogen we are assuming that it acts like liquid air and has similar properties. Turning the nitrogen into liquid form nitrogen would be done through any excess energy that the power plant generates, the energy produced would go towards pumping the nitrogen into the storage system, because the nitrogen is already very cold once it comes out the fractionation column less energy is required to pump the nitrogen into liquid form.

Storage

A problem that high source power storage solve is that storing the gas requires lots of space. For some air generator systems, the air is stored in mines or other geological formation, but this only applies when gases are involved. Liquid air can be stored in a lot less space as it is denser, if there is a loss of 80% power then the 20% that is left would go towards heating the compressed nitrogen which would expand into a turbine and generator creating electricity; the start-up time would be fast as there is no combustion involved only heating of the stored liquid.

How much for 24H supply source

We are required to provide back-up energy for at least 24 hours, using the high-power storage solution calculator and some estimates we predicted the amount of nitrogen that would be needed.

To generate 80% of power loss we would need
1654(full MW) *0.8 =1300MW needed

So we decided to use
4x300MW plant running for 24H
liquid capacity= 60000*4= 240000 tonnes
Capex= 75 million*4 = £300 million (reduced through using only a single type of gas)

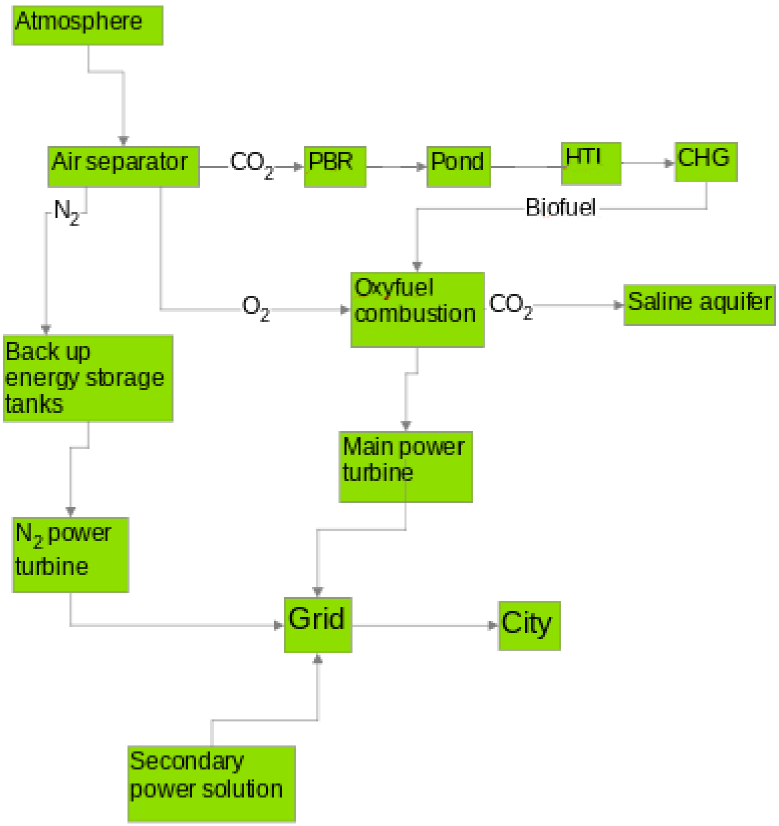
Calculating how long it would take to fill to capacity
Amount of MT of N2 produced per year= 32
Amount of N2 per day in tonnes =88,000

Therefore if we wanted to charge it as fast as possible to would take
240000/88000 = 2.7 days this would require 100MW, However, there would be no need to charge it as fast as possible so we could reduce the energy consumption for a slower fill rate.

Through this system we can be sure that we would be able to provide power back to the city from a 80% power loss.

Energy Summary

The air separator, separates out the CO_2 from the air using tuned MOF filters. Then left-over air is cryogenically distilled to from oxygen and cooled nitrogen. The CO_2 is pumped into the PBR where it is used to grow microalgae to a large size, then the biomass is transferred to the growing ponds which are pumped with more CO_2. Once it has reached critical mass it is extracted by electrocoagulation (EC) and transferred to the HTL plant where it is converted into biocrude oil, the waste water is treated by CHG to remove any remaining organic compounds. These are converted into methane which is converted to hydrogen and used in hydrotreating the biocrude oil to remove impurities and increate the combustion quality. The oxygen separated from the air separator is then used to combust the fuel in a oxyfuel system. This reaction forms a high concentration of CO_2 in the flue gas. The flue gas is then pumped through a pipeline into a saline aquifer for permanent geological storage at our rate of CO_2 production we fill the aquifer in 71 years. The nitrogen produced in the distillation process is then used to fill storage tanks for our backup storage solution making the air separation as efficient as possible.

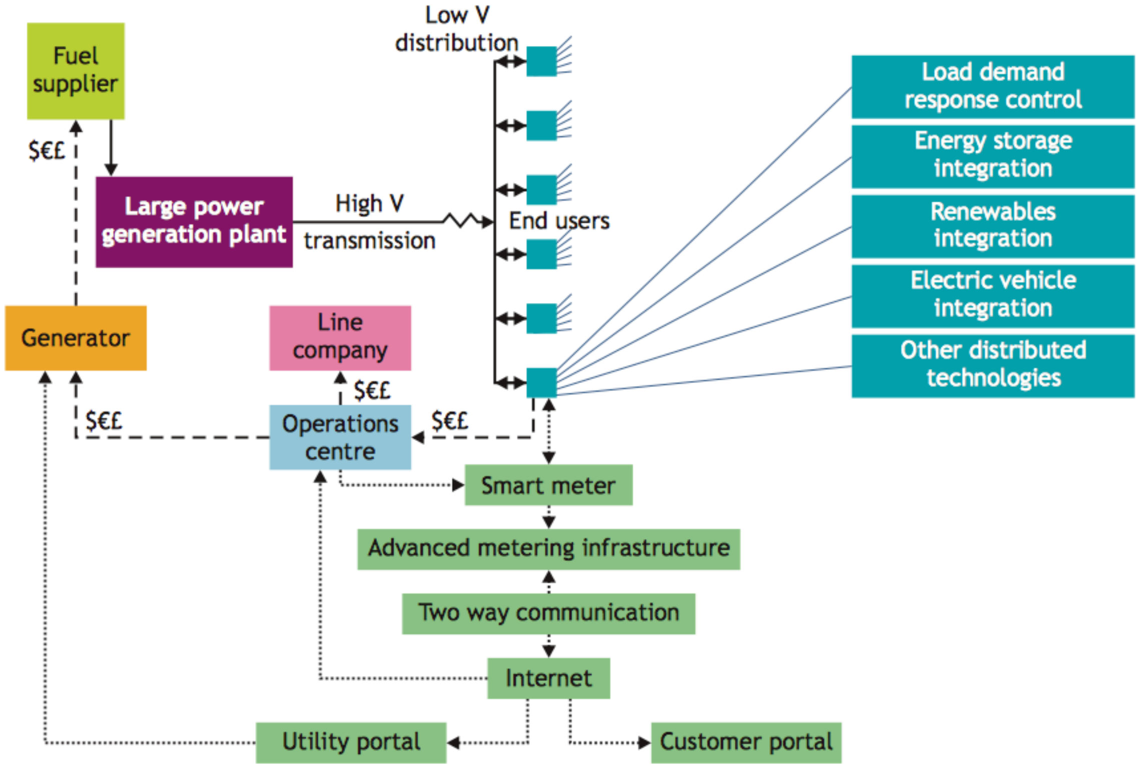


ENERGY DISTRIBUTION

Summary

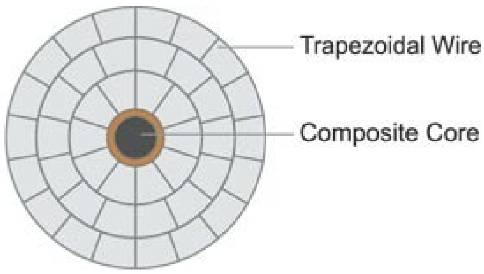
We decided to use a distribution system with a ‘smart grid’, utilising smart meters and other technology to ensure communication to allow the most efficient distribution of the electricity. This would allow us to fully integrate our electric vehicle system, so that the vehicles can act as an energy storage facility, and so that we can use a load demand response system, which will enable greater control of energy usage during peak demand and high pricing periods. If we choose to introduce more distributed energy resources, such as more solar panels on house roofs, the two-way electron flows will allow us to fully integrate this with ease into our grid. Thus, our energy distribution system maximises efficiency and utilises all our available resources.

Figure 11 • *Representation of a distributed generation system with two-way flows of electrons (solid lines), revenue (dashed lines) and information (dotted lines) through smart meters and intelligent grids*

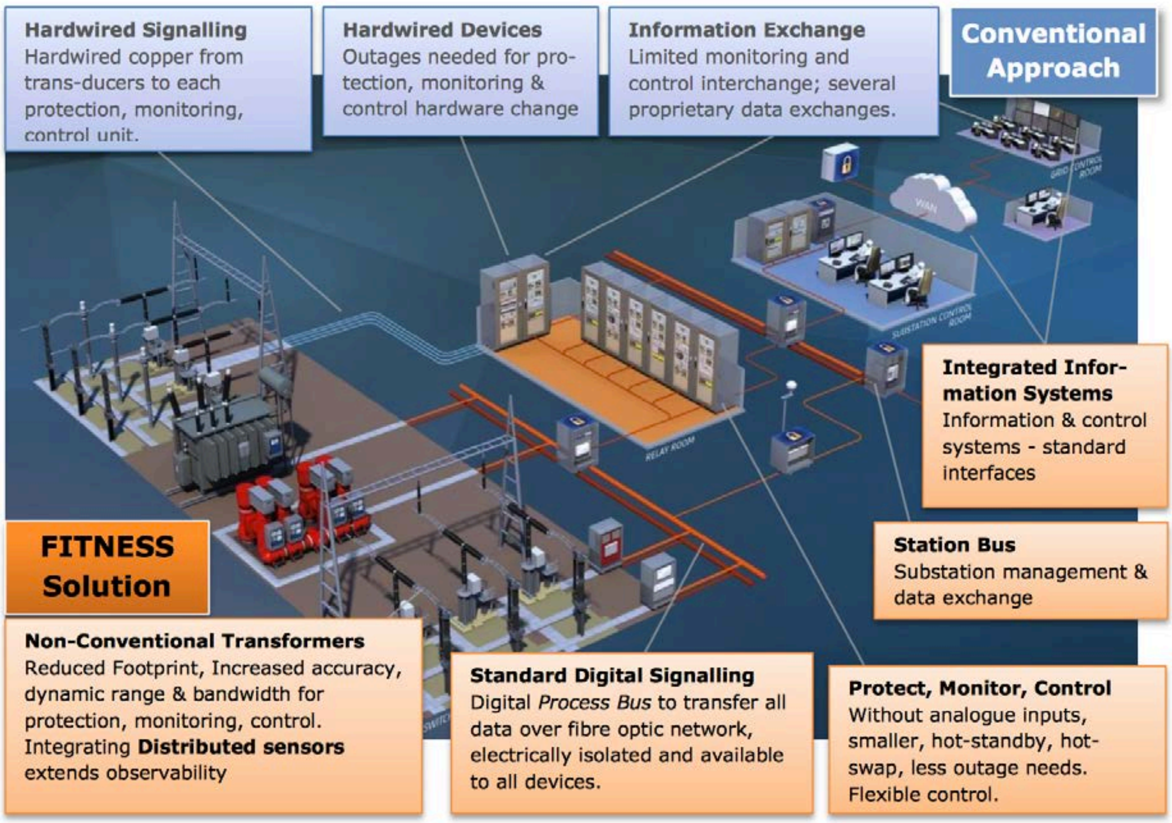


Transmission and Distribution

To distribute the electricity, we will need transmission from the power plant to the substation, before distributing it throughout the city. From the power station, we will use high temperature, low sag (HTLS) overhead line conductors. These would continuously be



at a temperature of 150°C, and would slag much less, whilst remaining strong and operating at low noise levels compared to current overhead cables. As a result of this, conductors of a similar size to conventional conductors can be used which will allow much more power to be transported. This will also allow for any current pylons to not have to be replaced, helping to keep the costs lower. The cable will be made out of aluminium composite carbon core (ACCC), which has a capacity of twice the current, for the same size and weight, than the usual aluminium-conductor steel-reinforced cable (ACSR). The fact that it is lighter means that more aluminium can be used, and the trapezoidal shape means that less space is wasted. We decided that using superconducting cables would not be a viable option for within the next 10 years, due to the extortionate costs of low-temperature superconductors, and a belief that high-temperature superconductor will not be around by then.



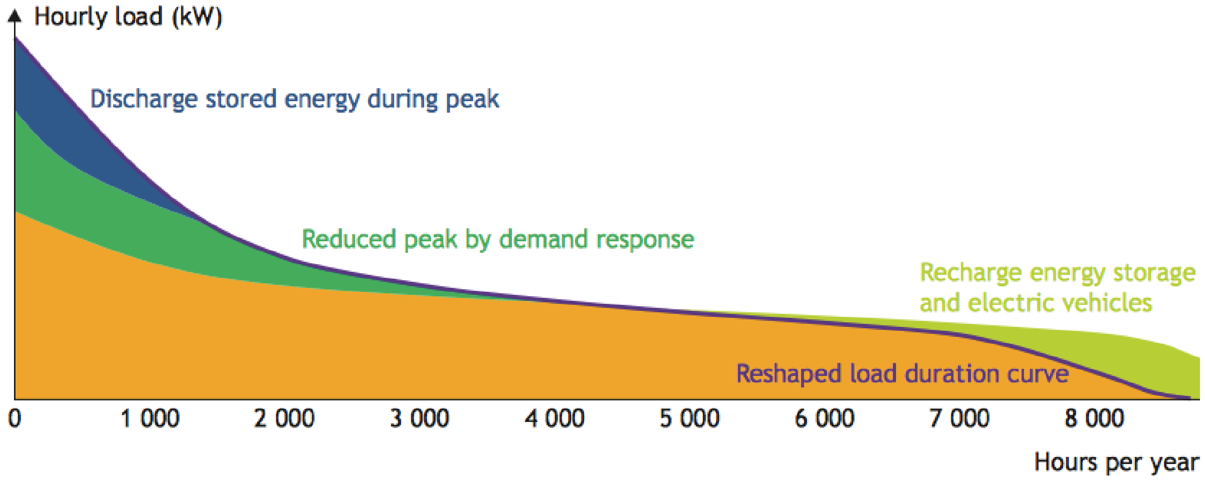
Our substation design is based on the ‘Future Intelligent Transmission Network Substation’, which aims to be safer, more efficient, and cheaper to run. As with the majority of our network, emphasis is placed on using technology for advanced communication, in order to allow for smooth management. The use of Non-Conventional Voltage Transformers will allow for greater accuracy, as well as reducing the overall footprint of the substation. By using fibre optic cables instead of analogue inputs, digital communication will be more reliable, and can be monitored much more easily.

The distribution of electricity, after the substation, will largely be underground. This is for multiple reasons, but mainly as it looks significantly neater and doesn’t get in the way of anything. Larger customers, such as industries, will be fed directly from the primary distribution, at a higher voltage, whereas most utility customers will be connected to a transformer which will reduce the potential difference to the mains voltage that can be used by lighting and interior wiring systems. The distribution cables will all have two way electron flow, ensuring that all generation and storage sources can be connected to the end-use appliances, instead of the common radial design with electrons moving in one direction from the generation station. This would also require constant two-way communication between the consumers and suppliers, ensuring the electricity is distributed in the most efficient way possible.

Smart Metering

Digitising the grid will allow devices to communicate and provide useful data for management of the grid. In addition to smart meters, network remote control and automation systems, along with digital platforms focusing on aggregation and optimization, will allow for constant live operation of the network, and will collect network data to improve utility services and situational awareness. Using an intelligent grid will allow communication with the customers so that peak demands can be managed live, which would reduce any large amounts of strain, lower infrastructure costs, and eliminate the need for a large surplus energy generation. The use of demand response technology will enable the control of energy use whilst it is at peak demand with high prices. This will lower the peak demand, helping to reduce overall costs.

Figure 12 • *Example of electricity load duration curve reshaped by peak load reductions (blue) using discharged energy storage and demand response techniques and by lower load increases (green) as a result of recharging energy storage including electric vehicles*



Building Integration and Electric Vehicles

Our grid system will allow a significant amount of electrification to take place, which is important for carbon neutrality. Technologies such as heat pumps will be made more efficient, and electric vehicles will be able to act as a storage and distribution resource. The vehicles would charge when usage of the grid is low, such as at night, or when the supply is high. Furthermore, vehicle-to-grid technology would allow electricity from the batteries to go back into the grid. This would allow for more consistent energy demand, flattening both the peaks and valleys in the load of the grid. In Europe there are several utilities and automakers who are joining together to develop energy storage facilities that rely on electric vehicle battery modules, or ancillary services from the vehicle-to-grid technology.

Inclusion of Distributed Energy Resources

Having two-way electron flow has a large range of benefits, one of which is that the inclusion of distributed energy resources will be made easier. Despite our main source of energy being biofuel, as our city grows we may need more energy. With this distribution system, energy resources such as the solar panels on houses will be able to play an important role in powering the city, whilst helping to maintain carbon neutrality.

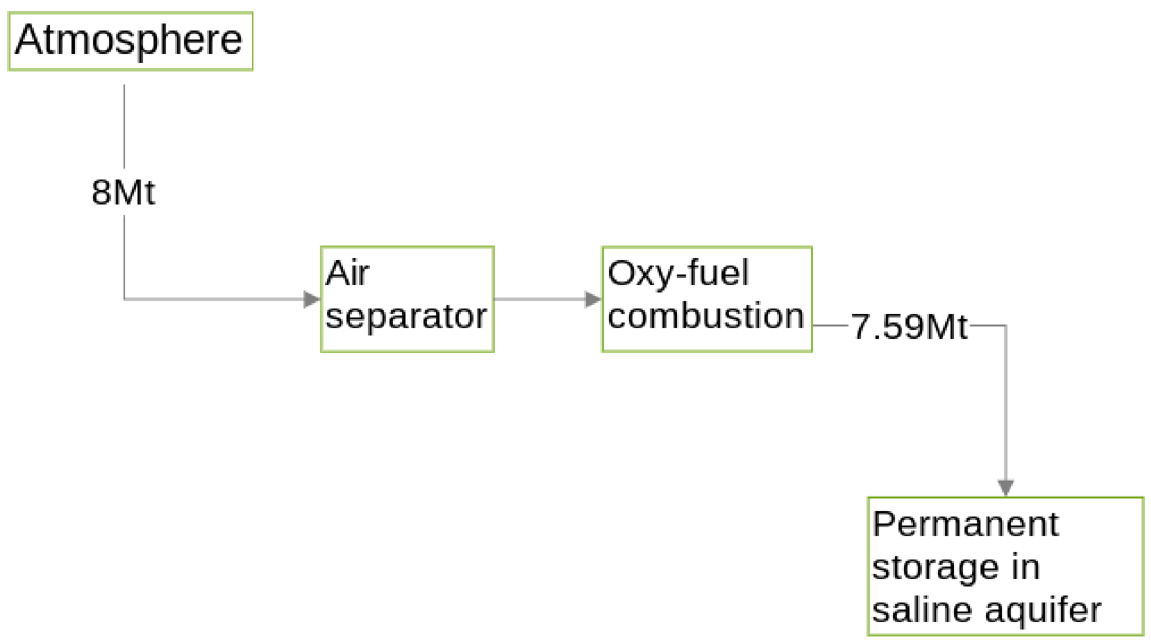
Implementation and Costs

Current transmission cables will be able to be replaced relatively easily with ACCCs, as existing pylons can be used. Throughout the city all cables will be underground, and will be one of the first aspects to be constructed.

Conclusion

PROOF OF CO_2 NEUTRALITY

In conclusion, our energy distribution system will be focused on digitalisation and electrification to minimise costs and maximise efficiency. It will partner with the use of electric vehicles as storage systems to have a more constant load on the grid, whilst using smart meters to constantly manage demand. Finally, the two-way electron flow will allow adaptability with the
ability to add additional distributed energy resources if they become necessary.



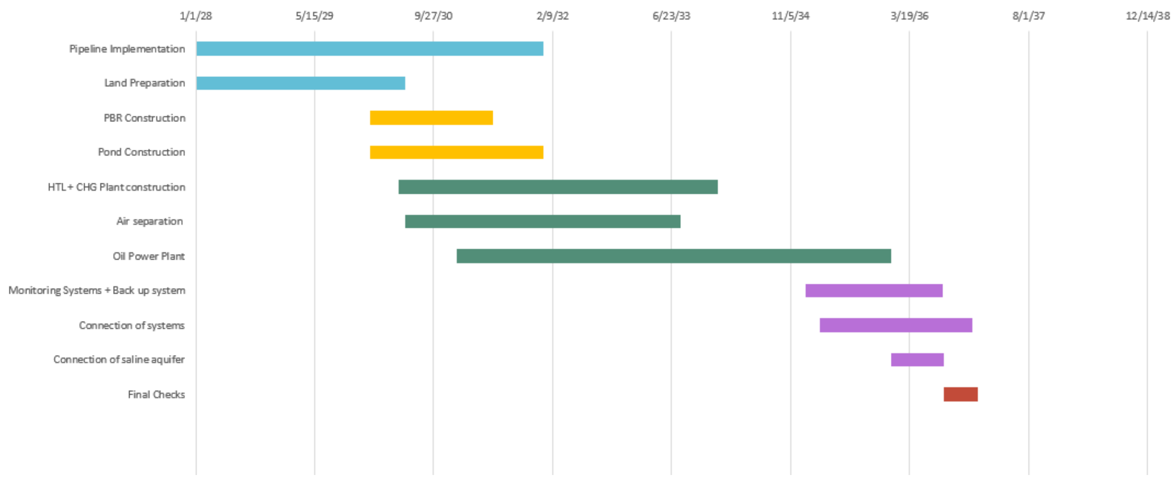
IMPLEMENTATION

We take in 8.0Mt per year
We store 7.59 Mt per year (CO$_2$ calculated in previous energy supply section)

There is a loss of 0.41Mt of carbon per year
Therefore, the process is 7.59/8 *100 = 94.875% efficient

Therefore, our BECCS system is carbon negative system reducing the net CO_2 in the atmosphere. This offsets the CO_2 used for building the system and any system in the city that uses CO_2 for example our hybrid bus system, in addition because of the lack of nitrogen in the combustion process no nitrogen oxides are formed and any sulphur oxides formed are stored in the saline aquifer. The loss of carbon is attributed to the conversions of bio-fuel.

ENERGY IMPLIMENTATION



Note: This assumes that all construction has been approved and we are ready to begin construction from 2028. We had no numbers for the length of construction for any of the algae systems, however we did for the pipeline implementation and power plant. The rest of our numbers are estimates based on looking at similar systems.

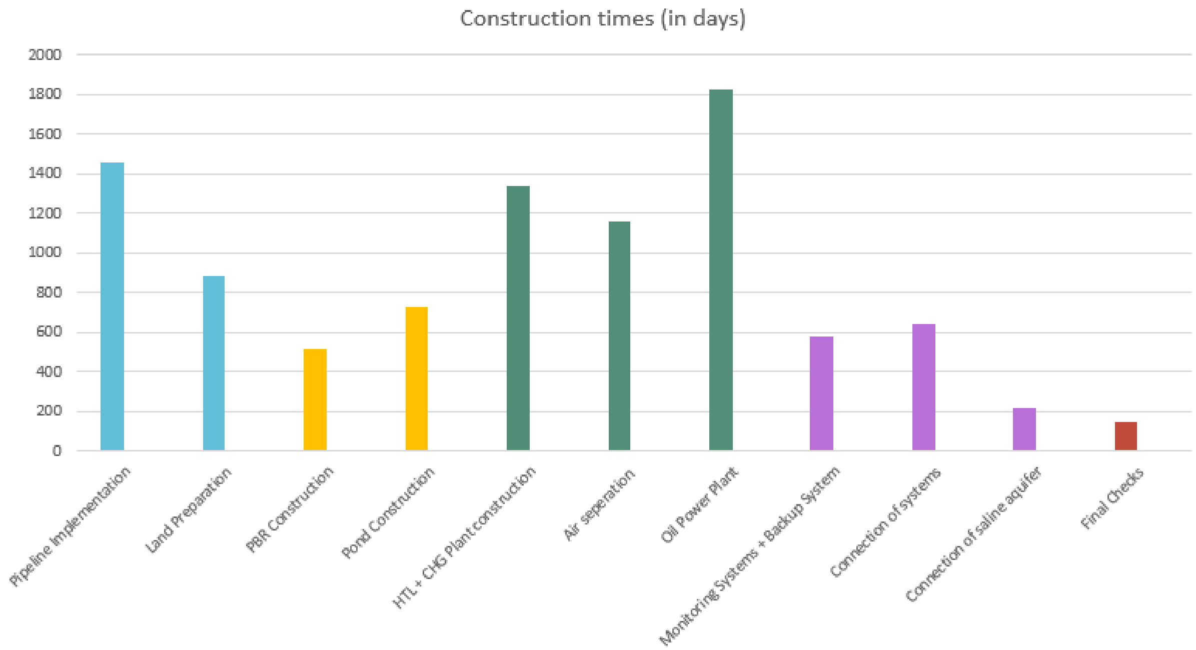
Stage 1
To start off with our system requires a large distance of pipelines between the power station and saline aquifer. We decided, since these would require a large amount of time to construct and are away from the main site, we would begin constructing them first alongside the land preparation. The ponds and PBR's require a large area of relatively flat and empty land and so we would require a large amount of land preparation and clearing to begin with. This would take quite a reasonable time

Stage 2
From there we can begin the construction of the open pond raceways, which are relatively simple to build but require some time for the landscaping. The PBR's would be constructed alongside them, once again with the materials prepared beforehand these should be relatively simple to construct.

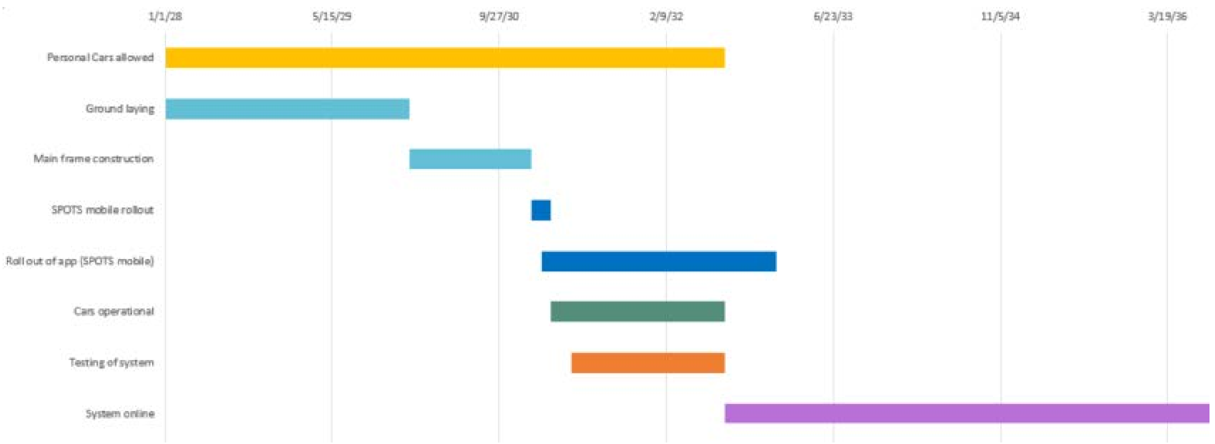
Stage 3
The third stage would involve the construction of the extraction, processing and combustion facilities. To start with the HTL + CHG (+EC) plant would be constructed first alongside the air separation facility, both we would assume would require around two and a half years to build. Finally, we would begin the construction of the oil power plant which out of all the facilities would require the longest to construct; we estimate around 5 years.

Stage 4
This penultimate stage would require the implementation of monitoring systems and back up systems (liquid nitrogen storage) alongside connecting all facilities together, tapping into the saline aquifer and finishing the pipeline.

Stage 5
The final stage would involve the checking of all the facilities, fine tuning the flow rate in the PBR's, and checking all systems work as expected before the whole system goes online. The total time begin first construction and first power output we estimate to be around 8.5 years.



TRANSPORT IMPLEMENTATION



For the implementation of the transport system we would allow personal cars in the city up to the first day the system is online, and from then on they will be banned.

Stage 1

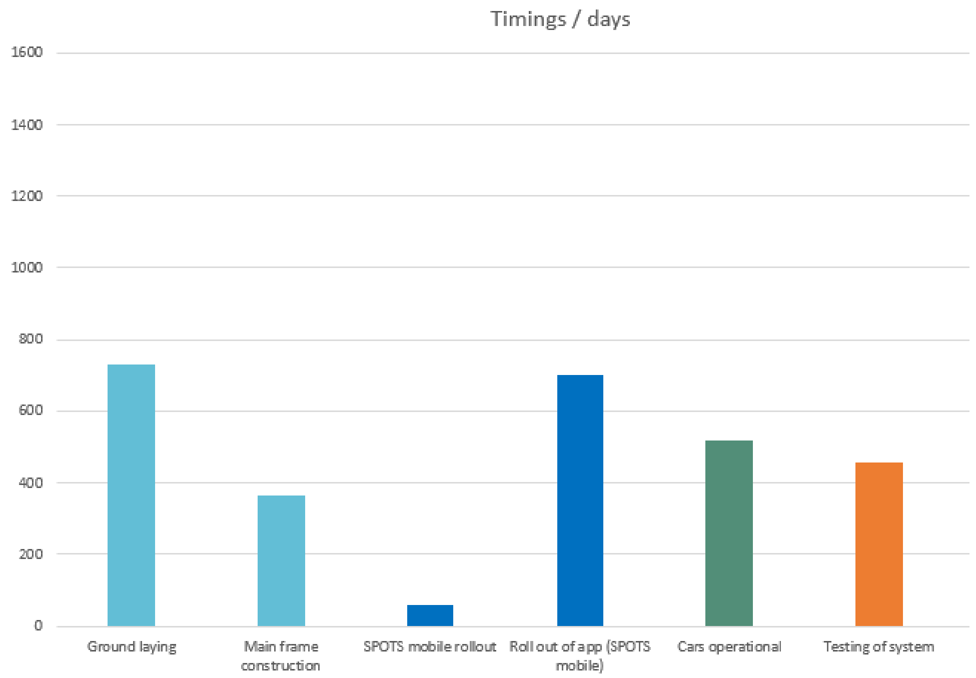
To first build the system, the ground laying (construction of roads, creating the tunnel) must occur. We calculate that this will take around 2 years. From then the construction of the main frame will begin (building frames and laying track), this will take around 7 months.

Stage 2

From then the SPOTS system will be rolled out; first the cars and then the app. The roll out of cars will take roughly 3 months whilst the app will remain out for long enough that all persons in the city have time to get it before the system becomes operational.

Stage 3

When the cars become operational the testing of the system can begin; after that the system becomes fully operational.



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