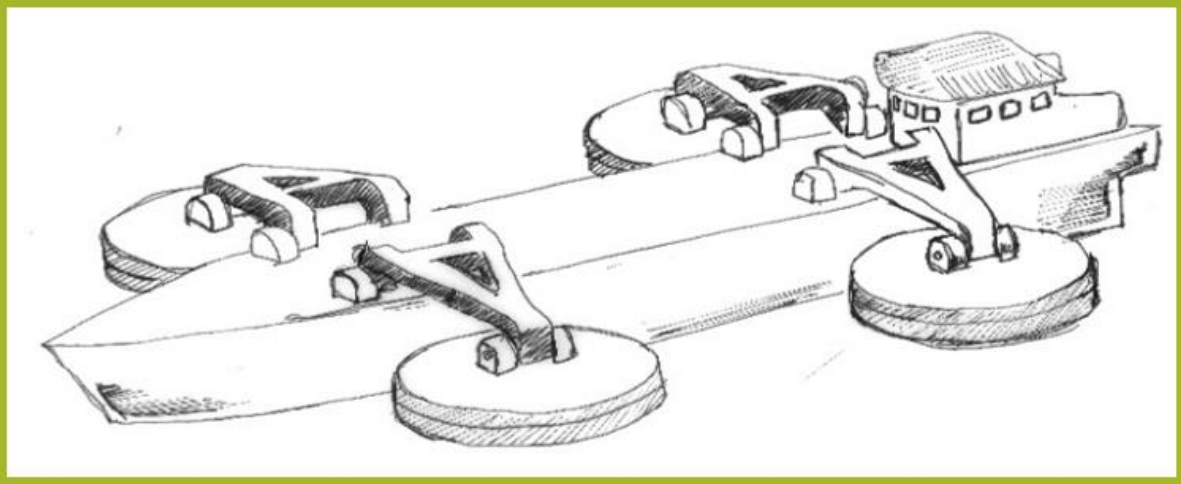
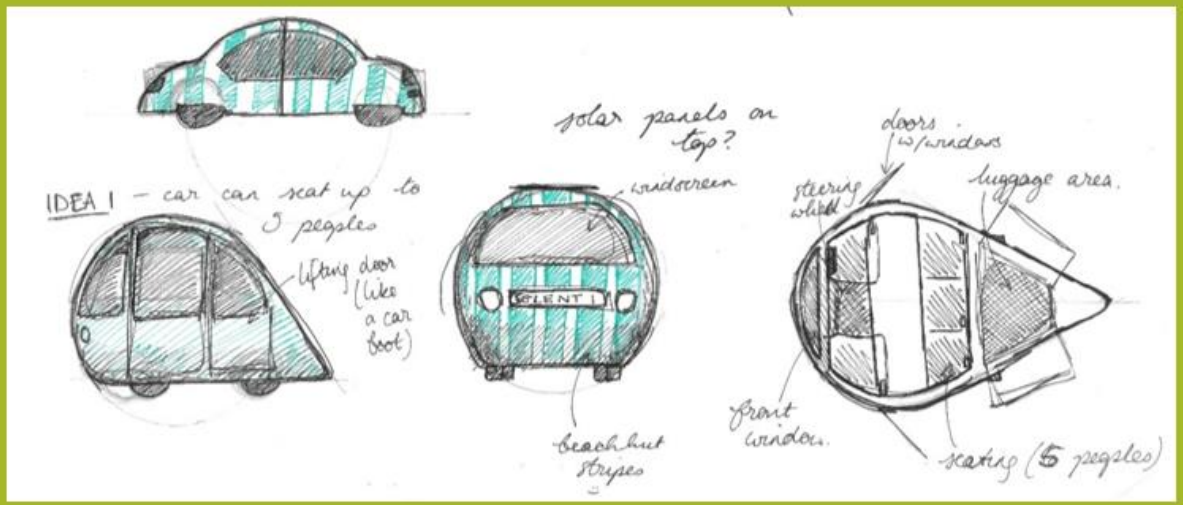
BMC

E4E (ENERGY FOR EVERYTHING)

A proposal to create carbon neutral energy and transport systems for an imaginary Solent City



GreenSteps Solent City Nuclear Solent City Wave Solent Auto



Team name: Raiders of the Lost Quark

John Mason School

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INTRODUCTION

MEET THE TEAM

OWEN ATKINSON-EVANS

This project has been an exceptional opportunity to research and understand topics that would otherwise go by unknown to me. I've always had a fascination with new and upcoming technologies, and as a result I was focused more on the technical side of the new technologies, such as the Mobile Wave Crawlers ("Bobby Boats"). I especially enjoyed the opportunity to test a proof-of-concept design for the Mobile Wave Crawlers; combining that with my physics studies was a great experience. I'm currently studying Maths, Physics, Biology and Chemistry at A-level and hope to take a biomedical course at Oxford or Edinburgh and continue to do research into new medical technologies afterwards.

THEA MARSH

I am currently studying Computer Science, Maths and Biology at A Level, with the aim to study Computer Science at university and ultimately become a software engineer. I love how this field combines technical skills and creativity to solve real world problems; this is also the reason that I was interested in taking part in this challenge. In this project, I really enjoyed researching innovative systems of power generation, such as the modern nuclear reactors and the wave power generators in the form of boats. I also enjoyed annoying everyone with random project ideas, logo designs and occasional science puns at unearthly hours of the morning. Aside from programming, my main hobby is music - I play the Euphonium in two brass bands and have recently taken up the Cornet. I also enjoy playing board and card games and doing crosswords with my friends and family, as well as doing logic puzzles.

ELIZABETH MCGINNITY

I am currently studying Biology, Chemistry and Art at A-Level at John Mason School. I particularly enjoy the area of ecology/animal biology, which is one of the reasons I took part in this project. I also have an interest in the design side of the Solent City - how things work and look when put together. My other hobbies outside of school include jewellery making and card-making - putting a theoretical design into practise to see how it really looks.

ROSIE SHAW-MOORE

I am currently studying History, Biology and Chemistry at A-level, and my long-term plan is to study Zoology at Exeter University and become a research scientist. I have really enjoyed researching for this project and talking through our ideas as well as writing up the report. One of the main things that I enjoyed about the research was learning about things I wouldn't ordinarily look at and being able to put some otherwise obscure and mildly useless facts to use. My research was on topics such as the benefits and drawbacks of using trams in the city, our "Mobile Wave Crawlers" and wave/tidal power. I also helped on the electric car chargers and emergency energy requirements. My hobbies include aikido (a martial art that avoids causing permanent damage to an opponent), origami and shouting at my evil rabbit who has decided that my mum's wallflowers are far nicer than the rest of his food.

KATE TILLEY

I am studying Biology, Chemistry, Maths and Further Maths at A-Level, and want to go on to study some form of Biological Science at university, preferably Natural Sciences at Cambridge. I'm interested in a career in research, and the idea of gaining experience in writing technical reports and perhaps finding a way to sustainably power an entire city was incredibly enticing. I also loved the idea of being able to find a way to sustainably power a city, as I am very concerned about the state of the environment, and how downhill it is going. I have worked on aeroplanes, carbon neutrality, the emergency power section, and some of the calculations. My hobbies include reading and baking, especially pancakes (even after setting a previous attempt on fire).

GEORGE WEBBER

This project has been a great contrast to traditional studies, giving me the opportunity to learn in depth and truly understand a topic, instead of abstracting away any unwelcome details. Although I had technical input on a wide range of areas in this project, including the descriptions of our nuclear power plant and transport solutions, the area I found most inspiring was the subject of autonomous vehicles. I have always marvelled at the concept of an autonomous car, and so researching how physics, maths and computer science (three of the subjects I am taking at A-Level) can be combined to achieve such an incredible feat has

been fascinating. Aside from scientific pursuits, I enjoy playing saxophone and piano in school bands, as well as going running at the weekends. My current ambitions for the future include reading either Computer Science or Maths at Oxbridge, and potentially working in a field related to autonomous vehicles (such as designing a kitten delivery system based on autonomous cars).

TRANSPORT SOLUTIONS

INTRODUCTION

The transport solutions have been split into three sections; land, sea and air, as each of these present different challenges and opportunities. All of these methods currently run primarily using fuels derived from crude oil: a finite resource that produces polluting gases such as carbon dioxide into the atmosphere when burned. There have been many advances in green technology in recent years, including in the transport industry, fuelled in part by a fear of climate change. In order to find the best and most economical ways to travel in an environmentally friendly way, we have weighed up the advantages and disadvantages of each of these methods of travel before arriving at our proposed solution.

Our overall aim for this section was to create an eco-friendly integrated system that will allow easy transportation around the city and beyond, saving the residents of Solent City time and money in the process.

INTRA-CITY TRANSPORT

Upon developing our concepts for an intra-city transport system, we realised that there were a number of considerations key to any transport design. We therefore had to ensure that our intra-city transport service satisfies these requirements in order to create a functional and successful solution.

INITIAL CONSIDERATIONS

COST

For a resident of a large city, owning a car is not always practical, hence the public transport system should be affordable for all. This is the case currently, with a range of bus options in Portsmouth costing less than £5, as well as free off-peak travel for over 65s. Our transport system for Solent City must maintain the affordability of public transport, and expand the network across the entire city area. It is also important that the system is cost-effective for the city, so this will have to be balanced alongside the other requirements.

CARBON EMISSIONS

The average car burns 4.7 tonnes of carbon dioxide per year, and with a population of 2 million people, Solent City is predicted to have about 1 million cars on the road. This would result in an approximate carbon footprint of 4.7 million metric tonnes per year. This estimate is likely to be higher than the true value, because on average there are fewer cars in a city than the surrounding areas. However, it is clear that in order to meet the requirement of carbon neutrality, we must find solutions to reduce the number of petrol

and diesel cars on the roads in Solent City, and an integral part of this strategy must be a system of public transport that is widespread, efficient and affordable.

PARKING SPACES

In the city of London, there are 6.8 million parking spaces, to cope with the large volume of tourists visiting the city. If the average car parking space is 2.4m x 4.8m, then this figure corresponds to 78 million square metres of space used for parking, or 55 times the area of Hyde Park.

However, due to the sheer number of people who live in, work in, and visit large cities, many car users are frustrated by a lack of parking spaces available within them; indeed, one study found that the average driver spends four days a year searching for a parking space. With so many parking spaces, and yet still a lack of available parking, it is imperative that our transport system resolves the parking space issue, either by providing more distributed car parks, centralised large-scale parking solutions, or designing our transport system so that parking spaces are a relic of the past.

SPEED OF TRANSPORT

In urban areas, the average minimum journey time to key services by public transport is 14.7 minutes; in contrast, the average minimum journey time by car is just 9.7 minutes. This disparity is one of the key reasons that many road users still favour transport by car over public transport. In order to reduce the number of petrol/diesel car users, the public transport systems in place must be more efficient, and as a result, faster.

SAFETY

Our transport system should be safe, but must also appear safe to the residents of the city. Our transport system should therefore work to minimise road traffic collisions, as well as reassuring the public that any new concepts that are implemented are completely safe and that suitable fail safes are in place in the unlikely event of failure. For example, if a transport system that involved driverless cars were implemented, it would need to be certain that they will function as intended and would not have a negative impact on road safety. It is vital that the public are convinced of this, otherwise any systems we decide to implement may not be used due to unwarranted fear.

INITIAL CONCEPTS

When first presented with the opportunity to design the transport network for Solent City, we considered many alternative transport models. However, it was clear that the transport network had to incorporate transport powered by alternative fuel supplies, as hydrocarbon powered transport will always generate an unacceptable amount of CO_2 (120 million tonnes in 2015). We considered schemes to subsidise the purchase of electric cars, but concluded that while this would have a positive impact, many petrol car users wouldn't switch to an electric car unless it were a legal requirement. We therefore decided that a direct intervention in the way the transport system is run was necessary to enact meaningful change.

TRAMS

One initial idea was to place trams in the city as a long-lasting method of public transport. However, this method has many disadvantages. To begin with, trams cost £10.2 million/km (according to the Publications of Parliament in 2003/4). This is still significantly cheaper than trains or an underground system, but trams are much more of a hazard to the general population.

Tram tracks have a reputation for being problematic for cyclists, as bike tyres can easily get trapped in them. Trams usually have metal tracks which, when wet, become quite slippery; this could pose health risks for pedestrians, cyclists and even other vehicles on the road. On top of this, trams produce noise pollution when running, which, according to the US library of medicine, can cause more harm than one may think. The squeaking of trams on their tracks, and other noise pollutions, have been associated with "anxiety, hearing damage, and stress-related cardiovascular health problems". These negative effects could not be easily avoided if a tram system was used.

UNDERGROUND OR METRO SYSTEM

An underground system would provide an easy and quick route for many commuters around Solent City. However, to build an underground system would involve designing and constructing hundreds of miles of track, as well as hundreds of trains and numerous stations. This would be extremely expensive, and would also take many years of development.

The best-known example of an underground system in the UK is that of the London Tube. The first line of the London underground (the city circle) originally took 21 years to build in the late 1800s. For the last 150 years since that work started, more lines and stations have been opened to make way for a more accessible method of travel within the capital. To make this happened, billions have been invested into the London Tube with Transport for London reinvesting all of its profits into maintaining the current lines and planning for the future of the underground.

An underground system would reduce traffic around the city as many residents and tourists would use instead of taking their car, therefore decreasing traffic volume at peak times and so increasing the average traffic speed around the city. This would make travel much easier for residents and tourists alike, vastly benefiting the local community in the city.

Furthermore, an underground system can be a quicker method of travel in a city than road transport. Trains in the Metropolitan line can reach speeds of 60 mph (including station stops), while traffic in urban areas struggles to reach 40 miles per hour at peak times. Decreasing travel times can also have a wider positive impact, giving more free time back to residents in which to work more (thus increase their productivity) or relax more (thereby increasing wellbeing in the city)

However, when constructing the underground system, the cost of laying the tracks and the trains would be prohibitively expensive; the London underground cost billions of pounds over a period of 150 years, and is still incomplete, with work still being planned for the future. The recent 16-km Jubilee line alone cost £1.5 billion to construct; this vast sum of money is more than 1,500 times the combined local authority income of Southampton and Portsmouth (£912,133).

An underground system would also take a long time to build, during which much disruption would be caused. The distribution would arise from the construction of the stations and the boring of the necessary tunnels, as well as from legal hurdles such as planning permission.

This distribution would incur negative public opinion and discourage tourism to Solent City in the intermediary period while the underground system was constructed.

After weighing up the advantages and disadvantages of constructing an underground system similar to that of the London underground, we have decided against it. The disruption its construction it would cause and the economic impact of its construction make it an infeasible option for Solent City.

SUMMARY OF SOLUTION

Trams and an underground train system have been ruled out for safety and economic grounds respectively. This has resulted in our selection of a cost-effective, low-carbon and safe intra-city system for our transport solution:

We have decided that it is necessary to impose a zero-emission zone across the entire city, with significant fees for all carbon-emitting vehicles. Furthermore, the Park and Ride system currently operating in Portsmouth and Southampton will be extended to encompass all of Solent City, and to also offer group and individual transport in and around the city. In order to do this, the existing electric buses will be accompanied by a fleet of autonomous cars that will act as a taxi service. This system will reduce road collision accidents, reduce traffic and significantly reduce the need for parking in the city centre. The implementation of this system will be mostly funded by a new transport tax for residents and ticket fees for tourists, which will give everyone unlimited access to free, clean and efficient transport within the city.

IMPACT ON INFRASTRUCTURE

The existing infrastructure of the cities of Portsmouth and Southampton would be incorporated into the infrastructure of Solent City. The transport solution we propose will not require a complete overhaul of road infrastructure in the region, because autonomous cars operate under the same conditions as existing road vehicles. However, our transport solution will reduce the need for parking in the city centre, and thus will allow a radical reimagining of the city's pedestrian areas.

STREETS

The pavements in Solent City could be made wider to make the city a more pedestrian and bike friendly place. The reduction in traffic as a result of using more autonomous vehicles, which would be able to detect congested areas and find alternate routes automatically, will mean that some lanes can be converted into pavement or bike lanes. This will reduce the amount of congestion for people on the paths and will mean that there will be more room for a possible bike scheme, which could be another possible option for carbon neutral transport. The narrower road area will also be a great space for visitors to come and see the interesting and varied streets.

SHOPS & BUSINESSES

The lack of car parks will increase the area available for business or tourist attractions, thus increasing the revenue coming in to the city council and making it possible for us to further explore other options to further reduce carbon and pollution emissions in Solent City. Shop owners would be encouraged to use recyclable materials and to use environmentally-friendly packaging in their products wherever possible. They would also be encouraged to use carbon-neutral delivery methods, such as trains (which produce less CO_2 per journey than a HGV) when delivering their goods, even outside of the area.

INCREASED GREEN SPACES

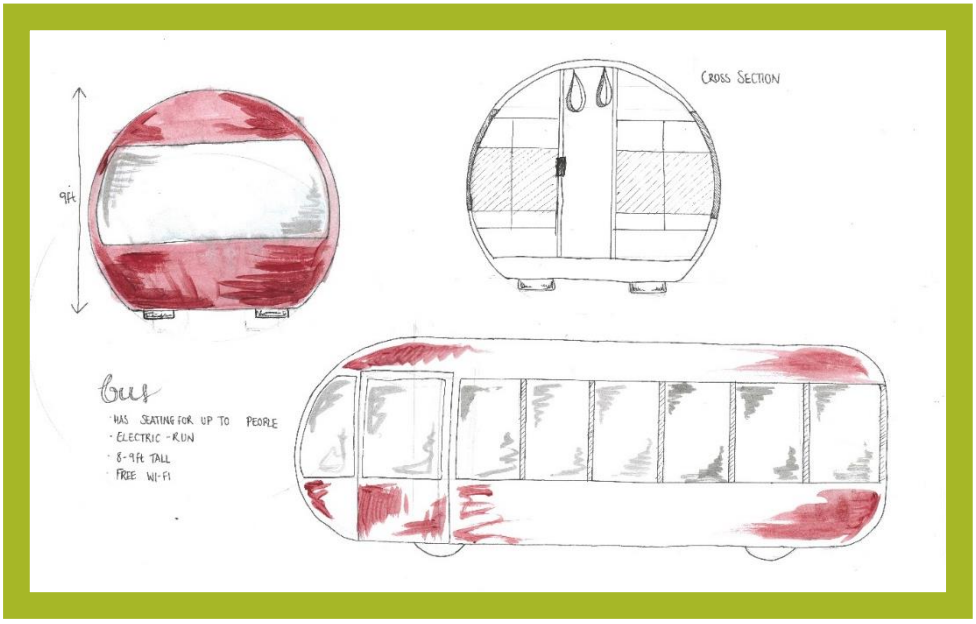
The lack of car parks will also increase the area available for potential redevelopment into parks or gardens, thereby increasing the coverage of Solent City with "green spaces" for local residents to enjoy.

BIKES

In addition to wider streets, there will also be regular 'bike parks' which could make a bike-share scheme much easier, but at present, the idea is still under consideration due to trials still being carried out in other areas in the UK - having shared bikes may cause a general lack of respect for them, and so many trials carried out found that there were many bikes left around on the streets which is an occupational and health hazard. Southampton already has its own bike-share system, called Yobike, which offers its 25,000 users a "seamless, hassle-free experience" - one can download an app to use its 1000 bikes for as little as £1 an hour. This scheme would be continued with minor improvements, such as adding drop-off stations around the city to reduce the risks of bikes simply being strewn across the floor.

BUSES

Much like regular buses in the UK, our bus system will provide access to all main areas in Solent City. There will also be a Park and Ride system, which will be available from car parks as an alternative to hiring an autonomous car. In Oxford, which is aiming for cleaner, greener streets, the buses operate though hybrid technology, and there are five Park and Ride car parks from the five main different directions into the city centre. This encourages people to park their car and catch the bus,



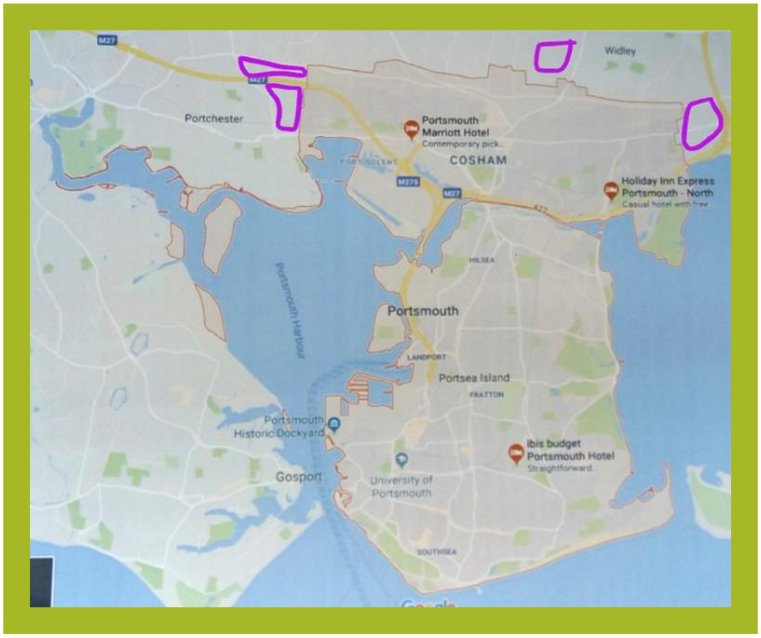
which is a far easier alternative to attempting to find a parking area in the very busy streets in Oxford. Since the introduction of this system in 1973, congestion has been greatly reduced, and due to the increasing volume of traffic on the roads since then, the car parks have been expanded greatly. Our system in Solent City would mimic the Park and Ride in Oxford but using completely electric buses instead of hybrid models.

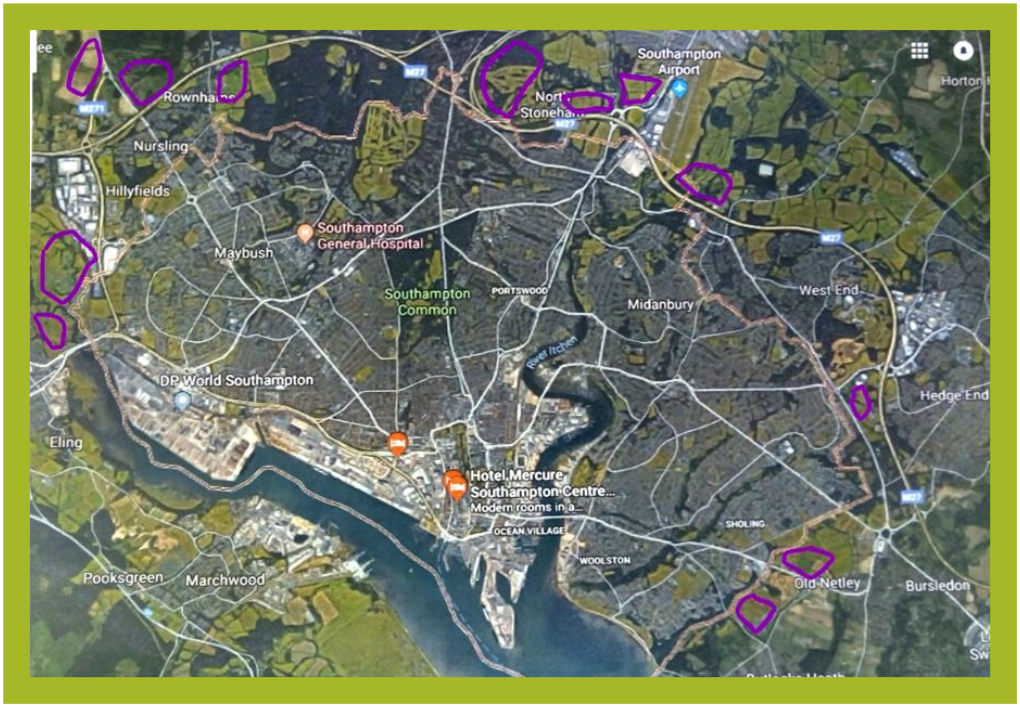
PRIVATE VEHICLE OWNERSHIP

Under our scheme, private vehicle ownership would be permitted, and residents would be encouraged to purchase electric vehicles. Residents who already own diesel or petrol cars would be informed before the introduction of the transport scheme that these vehicles will be not be permitted in the city centre. This warning to owners of petrol and diesel cars would be as soon as the scheme was finalised, with sufficient time to allow these cars to reach the end of their natural life before the scheme takes effect.

Private car dealerships would be advised to sell electric or hybrid cars within the Solent Area. It is understood that there is no way of forcing people to buy a completely new car, or get rid of their old one, so some diesel and petrol cars would be unavoidable. However, these cars would not be allowed in the city centre, providing an incentive to travel with buses, our autonomous car taxi service, and electric cars. Electric cars, including the autonomous cars (which will be available to buy) will be recommended on our website.

The maps below highlight possible areas in which to build Park and Ride car parks, shown in purple pen for Portsmouth and Southampton respectively. For obvious reasons, this may not be final locations of such services, as local residents would need to be consulted and planning permission obtained, in addition to checking for any localised environmental impacts that the building of the car park may have beforehand.





MORE CHARGE POINTS FOR ELECTRIC CARS

Electric cars are much less polluting than petrol or diesel cars and, as such, it is desirable to encourage the residents of Solent City to use electric cars rather than other alternatives. In order to make this an attractive option, the coverage of electric charge points would need to be drastically increased, so that electric car users can drive an electric car without having to meticulously plan where they recharge their car. Modern electric cars have sufficient charge to be a viable option in urban areas, as they can typically run 100-150 miles on a single charge. As Solent City will only be ~20 miles in length, this will be adequate for the average car user travelling in the city.

HOW CHARGE POINTS WORK

There are multiple types of charging points for electric cars. These different charging points are: rapid chargers, fast chargers and slow chargers. Each of these different chargers have their benefits and drawbacks, for example, rapid chargers take between 20 to 40 minutes to reach 80% power but are more expensive than alternatives; Tesla's Supercharger network takes less time to charge than conventional charge points, but are incompatible with non-Tesla models of electric vehicle.

DC chargers are tethered to DC cables which means that only certain types of cars with the correct lead would be able to use them. AC cables, in contrast, are carried in the car, and so can be used with any charger type (potentially with an adapter). This difference means that in order to make Solent City a welcoming place for different models of electric car, AC

chargers will have to be used. Adaptors to allow electric cars to charge if they use a DC charger exist, and so DC charged cars will still be able to charge their cars with AC cables.

With regard to fast chargers, all models on the market are AC and tend to take 3-5 hours to charge. Although Tesla chargers are the fastest charging on the market, they are only compatible with Tesla cars, and so using a Tesla model of charger would not help anyone who is bringing their own electric car into the city.

Type 2 (7-22kW) chargers are the most common fast chargers. These chargers can, if the right tether is used, have a charging time of 1-2 hours. The only downside to these chargers is that they are untethered, which would require the car to carry around a cable to allow the car to charge.

Slow chargers have the charging time of around 6-12 hours, with most models having broadly similar characteristics. The 3-pin cable is the most common plug, as it is identical to the one used for domestic appliances. As most electric vehicles come with a 3-pin plug to begin with, this model would be the best for slow charging.

LOCATION OF CHARGING POINTS

For the rapid charging points, some lampposts will be used as charging stations as they can be cheaper to install than other stations. The purpose of these emergency charging points will be to allow easy access to a charging facility if the car begins to run low on power. There have already been trials of these chargers in London, which showed their successful usage. These chargers will work by using smart cables to calculate the money needed and charging that figure to a mobile phone or computer. The smart cables cost approximately £50 and the installation of these chargers is about £1000 which is far cheaper than the usual cost for electric charging site which are about £6000.

Alongside these lamppost charging points will be electric charging points similar in style to those used to fuel petrol cars. In order to charge an electric car in a non-emergency scenario, the residents of Solent City will be able to charge at a charging station. These charging points will also be rapid, to allow as many people to charge the cars as possible.

There will also be charging points in the old petrol stations around the city. These will be fast chargers and will allow people to charge their cars whilst they do things around the city. These chargers will allow people to charge their cars to full battery. Finally, the autonomous car depots will be equipped with slow chargers, to allow the autonomous cars to fully charge overnight.

AUTONOMOUS CAR DEPOTS

When the autonomous cars are not in use, they will need to be parked and charged. As the average electric car can travel 100-150 miles on a single charge, they will require an alert that instructs them to return to their depot if their battery is running low. This will be most likely only once a day, depending on how busy the day has been for each particular car. Therefore, each car will continuously monitor its own charge levels - one car running out could have disastrous consequences as they are autonomous and may be stranded without human support. In order to prevent instances where this happens, the cars will be programmed to only accept trips they can make without losing charge, and if the likelihood of losing charge is high, they may take a short detour to the nearest charge point and ask their human occupants to plug them in (the humans would then take another car).

The autonomous car parks will also act as a cross-over car park, where motorists coming into the city can temporarily exchange their old petrol car for an autonomous electric car for journeys into the city. Compromising cost and space, these car parks will be multi-storey car parks that are above ground. These cross-over car parks will consist of two multi-story car parks - one for incoming cars, and one for outgoing cars.

The depots will have red and green lights over spaces to show whether they are free, and signs to show drivers how many spaces there are per floor of the multi-story car park. The inspiration from these ideas comes from the Westgate car park in Oxford, which has received many positive reviews for its cleanliness, use of technology and car charging spaces (it has 50 of these, which encourages - rather than warding off - electric car owners visiting Oxford). The second part multi-story car park will be very similar, but contain the city council's AI electric cars (see Autonomous cars title). This section will not be accessible to the general public, with autonomous cars instead driving up to a pre-defined area where travellers can catch a ride.

For a minimal charge, drivers and visitors will be able to get into the city using one of the AI autonomous cars, or alternately catch an electric bus for an even lower fee. Monthly and annual tickets will be available through the city's website for residents of the city at discounted rates. After each use, the autonomous car will be checked, with fines implemented if the user borrowing the cars leaves it in a less-than-optimum condition. This should deter litter and mess being left in the vehicles for the next user, therefore encouraging more people to use this system through good public opinion.

To account for peaks in electricity at certain points in the day, a trial period will take place, to see how locals and visitors alike react to the system, and to calculate how much electricity can be allowed for when the system will be in peak use and when the optimum charging times are.

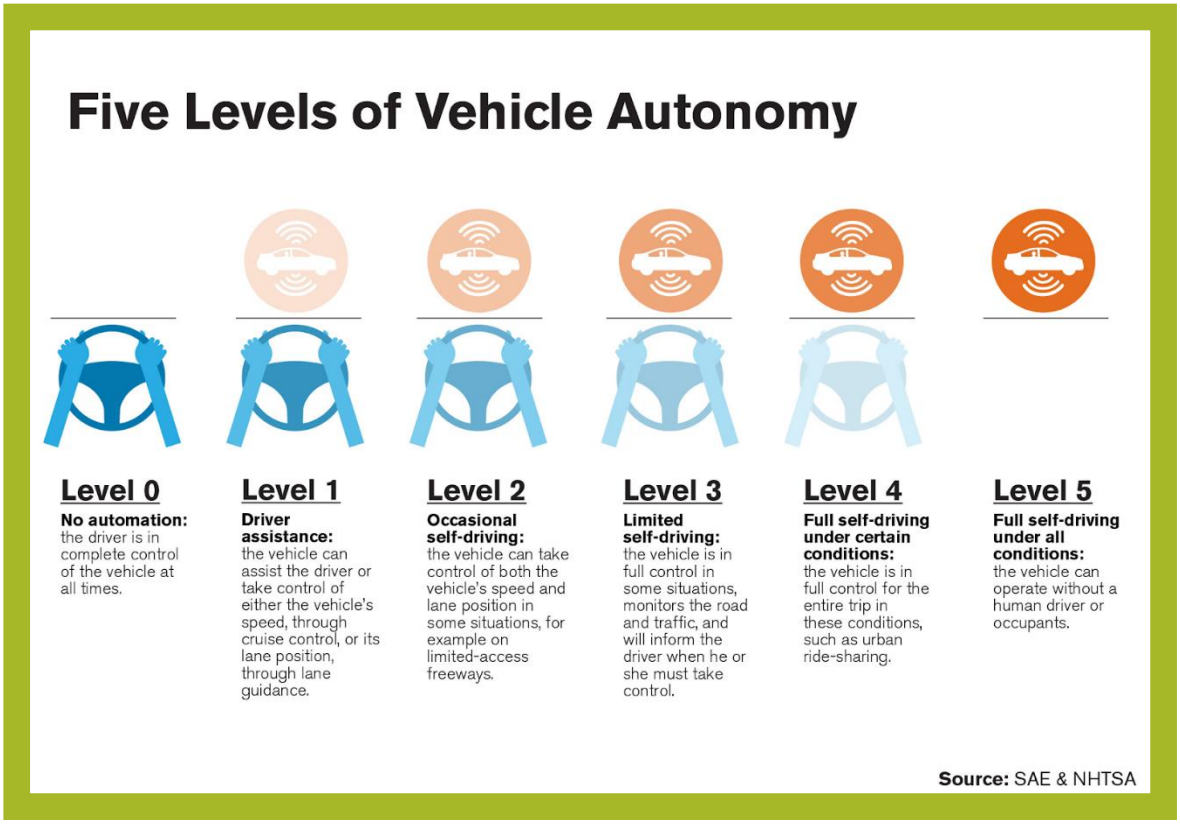
AUTONOMOUS VEHICLE SCHEME

The autonomous cars in our city will be:

- Electrically powered – the electricity used will be generated from our energy solution. Therefore, they won't be as polluting as petrol cars.
- Available in different sizes, to encourage families to visit the city and accommodate more varying groups of people in Solent City.
- Available to hire with an app, phoneline and "car stations" around the city.
- Decorated to make them more aesthetically pleasing so they can attract more visitors, thereby increasing income for the city.

HOW AN AUTONOMOUS CAR OPERATES

WHAT DOES AUTONOMOUS MEAN?



There are different levels of autonomy that a car can possess. This ranges from fully autonomous (or self-driving) cars that guide and control themselves without human intervention of any kind, to cars that can assist the driver in a minor capacity (e.g. cruise control). SAE have defined levels of autonomy (pictured above) that build towards full

autonomy, or "Level 5" autonomous vehicles. Currently, vehicles on the road possess up to "Level 2" autonomy, such as Tesla's Autopilot system.

However, autonomous cars are currently in development by most car manufacturers (including BMW, Toyota and Ford) as well as multinational corporations such as Google and Apple. Current technology has enabled some autonomous car researchers to reach "Level 3" autonomy, where a car can drive itself in some situations, but requires an active driver to take control in others.

WILL THEY BE AVAILABLE BEFORE 2027?

Companies such as Tesla have publicly stated that their autonomous cars will be available for consumer purchase by 2018. Other companies have more conservative estimates, for example BMW claiming they will have achieve full autonomy by 2025. With billions of pounds invested into research across the industry, it is very likely that these targets will be met.

Another obstacle to the introduction of autonomous cars is legislation to govern their usage. However, given that the technology will be available in the next 10 years, it is unthinkable that legislation will not follow suit in time to put autonomous cars on the road for 2027.

For the purposes of Solent City's intra-city transport system, the autonomous cars in use will only require "Level 4" autonomy - full self-driving without an active driver, in a known geographical area (their operational boundary). This level of autonomy will be easier to achieve than "Level 5" autonomy, and so it is certain that that the technology will be available within the next 10 years.

WHICH MODEL WILL BE USED

There are many different companies operating in the field of autonomous vehicles, and none have yet presented a "Level 4" autonomous vehicle for commercial sale. It is therefore impossible to say with certainty which company the cars will be sourced from. However, the general technical details should remain the same.

TECHNICAL DESCRIPTION OF THE OPERATION OF AN AUTONOMOUS CAR

HOW IT ADAPTS TO ITS ENVIRONMENT

Autonomous cars use a variety of sensors to detect and respond to their environment much more quickly and adeptly than a human driver could. These sensors will provide raw input data to the car's internal computer systems, from which complex algorithms can derive important data such as the distance to an obstacle, or the speed shown on a speed limit sign. From here, further complex algorithms are used to take the derived data and calculate the required action to take, e.g. applying the brakes if an obstacle is detected or reducing the force on the accelerator if a new speed limit is imposed.

THE CAR'S INPUT SENSORS

ULTRASONIC SENSORS

An ultrasonic sensor operates by sending out very high frequency sound waves. The sound waves used are above 20,000Hz and so are too high for humans to hear. However, the sensor can detect waves of this frequency, and by timing how long it takes for the echo of the sound to reflect back to it, the sensor can detect nearby objects. In order to send and detect sound waves, they have two main components; a speaker to generate the sound and a microphone to receive it.

HOW IT OPERATES

An ultrasonic speaker operates using two magnets. One of these magnets is permanent and fixed, while the other is a mobile electromagnet. As pulses of AC electricity pass through the coil of the electromagnet, its magnetic field reverses polarity very rapidly. Because of this, it is attracted to and repelled by from the permanent magnet very rapidly, and so vibrates back and forth. These vibrations are amplified by attaching the electromagnet to a cone. The frequency of the sound can be altered by using alternating the direction of current through the electromagnet more or less frequently as required. An ultrasonic speaker will be designed to operate at very high frequencies to generate ultrasonic pulses of sound.

A microphone acts similarly to a speaker, but in reverse. Incoming sound waves cause an electromagnet to vibrate in a coil of wire, and thus generate an alternating current in the wire that represents the presence of a sound, as well as its pitch and amplitude.

At regular intervals, the ultrasonic sensor will send out a pulse of ultrasonic sound. This sound wave will travel through the air until it impacts an object, at which point it will be reflected. Some sound will be reflected back towards the sensor and will be detected by the microphone in the sensor.

HOW MEANINGFUL DATA IS DERIVED FROM THE ULTRASONIC SENSORS

The time between sending and receiving a sound wave can be measured, and can be used to calculate the distance to the object sound is reflecting off.

The speed of sound is approximately 341 metres per second in air. Because this is a known and relatively constant fact, the equation *distance to object x 2 = speed of sound x time elapsed since sound was generated* can be used to calculate the distance a sound has travelled before reflecting off an object.

THE USES OF ULTRASONIC SENSORS

By using a number of ultrasonic sensors, the autonomous car can map its immediate surroundings to a high degree of precision. However, because of interference, an ultrasonic sensor is only useful in a short range. Furthermore, ultrasonic sensors cannot operate at high speeds, because if the speed of the car is too great, the car will gain a significant distance on the ultrasonic waves and the sensor will lose accuracy. Because of these characteristics, the ultrasonic sensor is ideally suited to low-speed short-range applications such as parking. Current models of car use such sensors to provide assisted parking functionality, ranging from emitting a beep when the car approaches an obstacle to parallel parking with limited human interference.

RADAR SENSORS

RADAR sensors operate on similar principles to ultrasonic sensors to detect how far away objects are by sending out signals, and measuring the time taken for the signals to return. However, radar sensors use high-frequency radio waves instead of ultrasonic waves, which allows them to also measure the speed of objects.

HOW THEY OPERATE

Radio waves are generated using a magnetron. A magnetron is a device containing a strong electromagnet that rotates periodically to emit electromagnetic radiation such as radio waves. Once a radio wave has been generated, an antenna directs it out away from the sensor. From here it travels at the speed of light until it impacts an object, at which point it reflects back towards the sensor.

The antenna used to transmit the radio waves also acts as a receiver. Once a pulse of radio waves has been transmitted, a piece of equipment called a duplexer is used to link the antenna to the receiving unit. The antenna then listens for a short period of time for any reflected radio signals. The duplexer then links the antenna to the magnetron once more, and the cycle is repeated.

HOW MEANINGFUL DATA IS DERIVED FROM RADAR SENSORS

The receiving unit detects incoming radio waves. The time that the radio waves are received is recorded and compared with the time that the waves were sent, to calculate the distance to the object that the radio waves reflected off. This data can be used to build a 2D map of objects around the sensor in a relatively long range.

Furthermore, the speed an object is travelling at relative to the sensor can be measured from the incoming radio waves. When a radio wave reflects off an object moving towards the sensor, the returning wave must travel a shorter distance and hence has a greater frequency than the known frequency of the outgoing wave. This difference in frequency is caused by the Doppler effect, and can be used to calculate the speed of the object that the radio waves reflected off.

THE USES OF RADAR SENSORS

The autonomous cars will use a multitude of RADAR sensors, and this will allow the car to continuously track the position and speed of nearby vehicles. It will also provide another method of detecting obstacles to the car's path, to increase the redundancy of obstacle detection systems within the car and hence the car's safety.

LIDAR SENSORS

LIDAR sensors have similar purposes and principles of operation to RADAR sensors, but operate using pulses of infrared laser light instead of radio waves to measure the distance to and speed of nearby objects.

HOW THEY OPERATE

A LIDAR sensor contains a laser light generator, which generates a very strong beam of monochromatic light in an infrared frequency. This laser beam is emitted from the sensor, reflects off nearby objects back towards the sensor and is registered by the receiving unit.

HOW MEANINGFUL DATA IS DERIVED FROM LIDAR SENSORS

Using identical principles as the RADAR sensor, a LIDAR sensor can calculate the distance to objects by measuring how long it takes the laser light to reflect back to the sensor. A microprocessor within the LIDAR sensor registers the incoming and outgoing laser pulses and can use this data to construct a 3D map of a nearby object to a high level of precision.

However, a LIDAR sensor differs from a RADAR sensor in how it calculates the speed of moving objects. It fires multiple pulses in quick succession, and uses the difference in distance between the sensor and the moving object to calculate the object's speed and acceleration. This process is extremely accurate, because the LIDAR sensor may send thousands of laser pulses at any given object per second.

THE USES OF LIDAR SENSORS

LIDAR uses infrared laser pulses, with a much greater frequency than radio waves - the increase in frequency results in a smaller wavelength, allowing much smaller objects to be detected and hence much more detailed 3D maps can be generated. LIDAR's extreme accuracy means that it is used predominantly to detect and identify obstacles near the car. The system is accurate enough to differentiate between pedestrians and cars, and even to notice whether a cyclist indicates to the left or right.

LIDAR VS RADAR

LIDAR is much more accurate and generates more detailed results than RADAR. However, the increased accuracy of LIDAR results in a significantly increased cost. Furthermore, RADAR systems have fewer moving parts than LIDAR systems (laser generation requires rotating parts), and so are more reliable and robust. RADAR systems are also much less affected by adverse weather conditions than LIDAR systems.

Autonomous cars require high levels of accuracy in mapping their surroundings, but also require reliability and low-cost solutions. Hence, autonomous cars tend to use a combination of LIDAR and RADAR sensors to achieve both requirements.

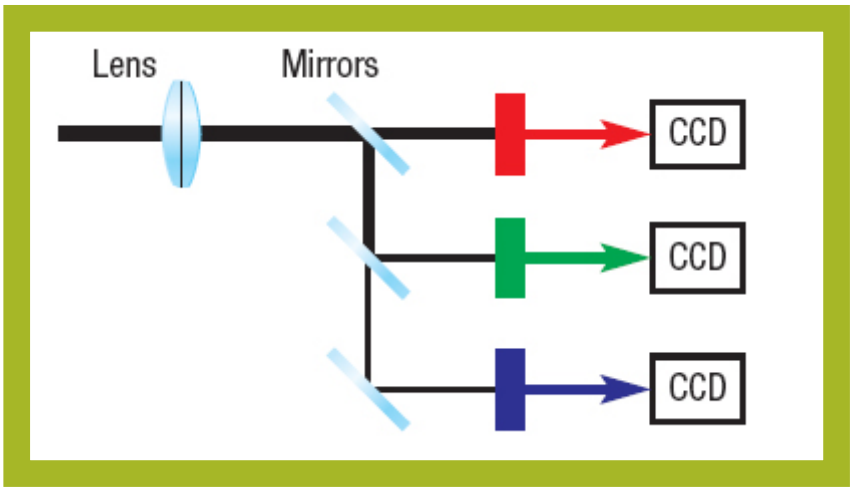
IMAGE SENSORS

Image sensors are video cameras that operate at a high frequency to produce a live stream of image data for the car to interpret.

HOW THEY OPERATE

An image sensor converts analogue light waves into a digital image. This process begins when light waves are focussed through a lens onto a light sensor. This light sensor is usually either a Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) and is made up of millions of transistors (one or more transistor per pixel). Each transistor converts the light intensity into a flow of electrons - a greater intensity of light results in a greater flow of electrons. The charge from each transistor is recorded by the image sensor in digital format. This data can then be compiled to produce a bitmap image.

In order to produce colour images, the light is directed through three filters before being measured by three transistors - one for red, one for green and one for blue as shown below.



This process is repeated at greater than 30 fps to generate a live stream of data for the computer systems in the autonomous car.

HOW MEANINGFUL DATA IS DERIVED FROM IMAGES

The numerous image sensors positioned around the autonomous car generate a live feed of data. However, this data is essentially meaningless to the autonomous car in its present state. Therefore, useful data must be derived from the raw data generated by the image sensors.

This process is carried out by image recognition software. The most effective algorithms at recognising images currently use neural networks. These structures consist of a set of linked "neurons", each with a given weight (i.e. their relative importance). The neural network is then "trained" on a large dataset of images, with useful data labelled. For

example, they may be trained on images of traffic lights with the position of the traffic lights and the current state of the lights labelled. Every new image that the neural network processes alters the weights of neurons in the network, adding weight to those that correspond to the desired image of a traffic light. Once the network has been trained on millions of images, it has been calibrated so that it is capable of recognising a desired feature of an image, e.g. whether or not there is a stop sign in the image.

Current image recognition software has an average success rate of 95%; this is expected to improve in the next 10 years for autonomous cars to be safe on the road.

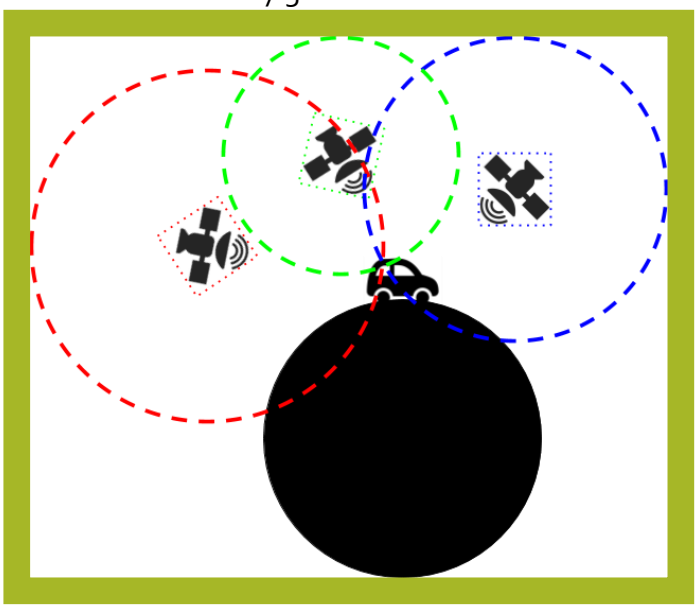
THE USES OF IMAGE SENSORS

Many different types of useful data can be derived from the data generated by an image sensor. This data can have uses including:

- Interpreting signs and traffic lights: the image sensors can operate in colour and hence can recognise fonts and colour. When inputted into a machine learning algorithm that has been trained on a large dataset of signs and their associated meanings, the image data from the image sensors can be translated into meaningful data such as recognising speed limits, give-way signs and traffic lights.
- Recognising lane markings: if some image sensors are directed downwards, the sensor can recognise the lane markings on a road and thereby calculate the distance from the edge of the lane (by using the sensor's known height and angle relative to the road). This will allow the autonomous car to remain central in its lane at all times.
- Recognising obstacles: although an image sensor's primary function is not to detect obstacles, it can be used to determine what type of obstacle the car is facing. Pedestrians would be difficult to distinguish from statues if the car was relying purely upon radar technology, and so another use of the image sensors is for obstacle recognition. This is achieved using a neural network trained on images of high importance obstacles such as pedestrians, cyclists and other vehicles.
- Providing redundancy: if other sensors in the autonomous car were to fail, the image sensors can be used for many other purposes. A key back-up function is the ability to detect obstacles and calculate the car's position relative to them; this functionality can be achieved by using stereo image sensors and applying parallax calculations to find the distance to objects.

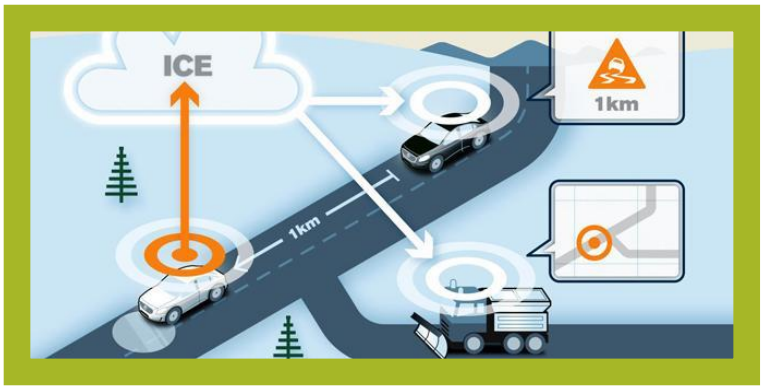
GPS SENSOR

A GPS sensor can be used to pinpoint the car's exact location at any given time. The Global Positioning System (GPS) consists of 30 satellites orbiting 20,000km from Earth. Each of these satellites transmits data at the speed of light (using microwave radiation), including its position and the current time at regular intervals. A GPS sensor on the autonomous car receives these signals from at least 3 satellites (as minimum of 4 are in line of sight at any given time). Because the speed of light is constant (in a given medium), the time difference between the satellite sending the signals and the GPS sensor receiving them can be used to work out how far the GPS sensor is from the satellite. Receiving signals from 3 satellites allows the GPS sensor to trilaterate its position (as shown).



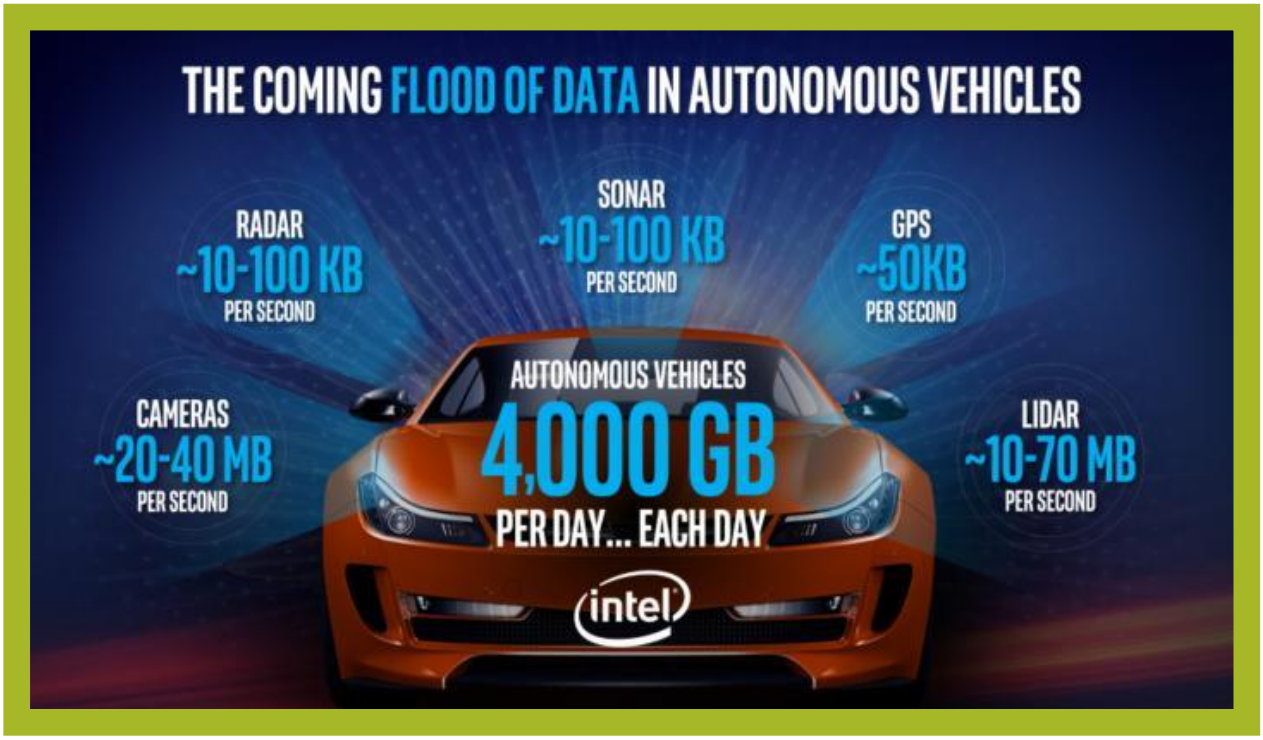
THE CLOUD

The autonomous cars used in Solent City will be WiFi-enabled, allowing them to communicate over the internet through the use of a router. This will allow them to send details of their journey centrally to servers over the internet. This information can then be processed to generate a real-time map of traffic, or a "dynamic electronic horizon" that is sent to all cars in Solent City, allowing them to sense far beyond the range of their other sensors.



Example data could be sent to a cloud server would be the car's location (using a GPS sensor), the car's final destination or even the weather conditions at the car's position. All of this data could be processed by internet servers to generate warnings or recommendations that are sent to specific cars in Solent City. For example, cars could be recommended to take a route of least traffic, or could be warned that certain roads are likely to be closed shortly because the weather conditions ahead.

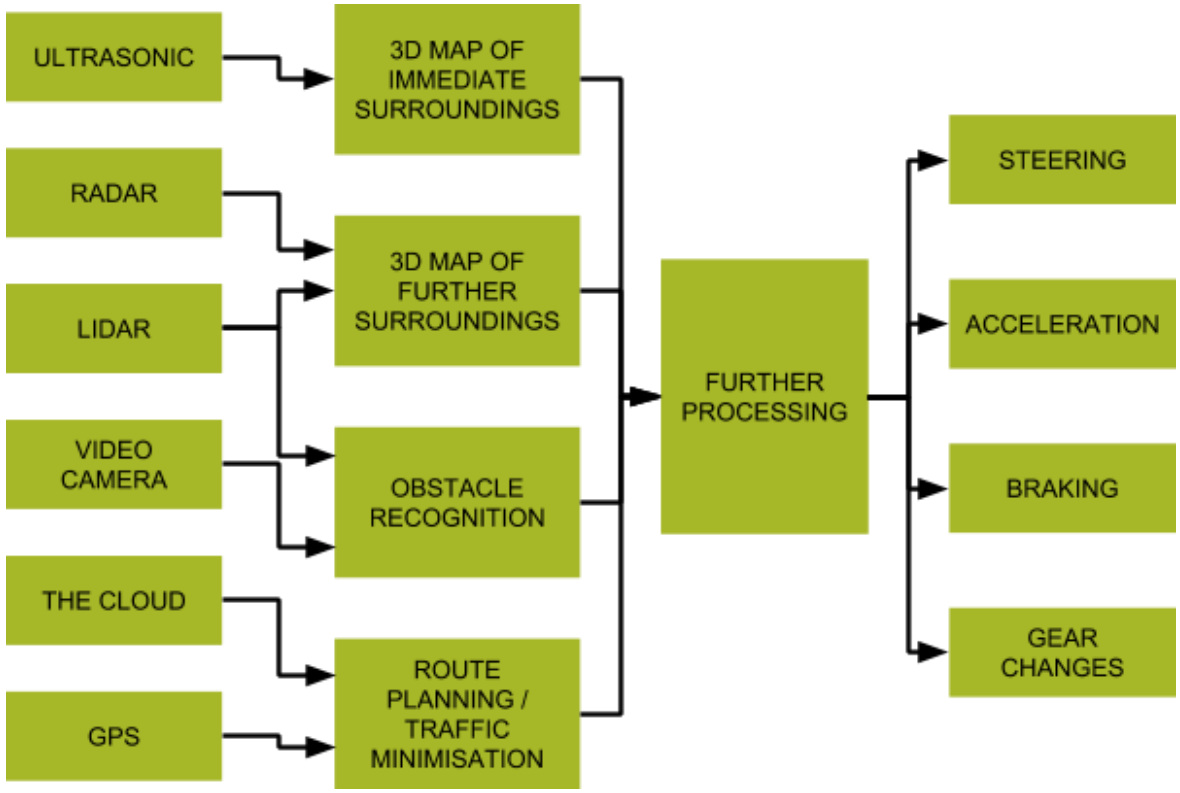
The true power of this extra sensor will only be realised once sufficient numbers of autonomous cars are on the road. With a limited number of cars, rough estimations can be made; with thousands or more cars, the wealth of data means that swarm intelligence can be used to build a comprehensive map of all roads in real-time. This processing will require extremely powerful servers and well-designed algorithms to cope with the enormous volume of data (estimated by intel to be 4000GB per day per car).



HOW THE CAR WILL NAVIGATE

The car will receive a wealth of information about its surroundings from the multitude of sensors all around the vehicle. This information is then processed to generate a 3D map of the car's surroundings, detecting and recognising obstacles in real time. This real-time map can be processed, along with data from the cloud and the car's GPS system to produce the speed and direction that the car should take. The algorithms involved in this processing are currently in development, and are incredibly sophisticated; companies in the field of autonomous driving have spent years developing these algorithms, with the end goal of a set of algorithms that can take the raw input data from a car's sensors, and convert this into a set of outputs that translate to the safe movement of the car in its intended direction.

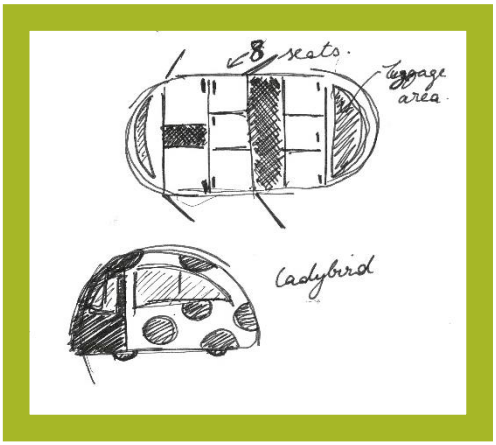
An autonomous car will have a number of outputs, but the most important are the acceleration, brake and the steering. An autonomous car will be automatic by nature, and so gear changes will be made automatically based on the RPM of the engine. The acceleration, brakes and steering will be all be controlled electronically, without the need for a mechanical pedal or wheel. Hence, the data outputted by the autonomous car's processor can easily be converted into real-life action, instructing the car to change direction or speed with ease.

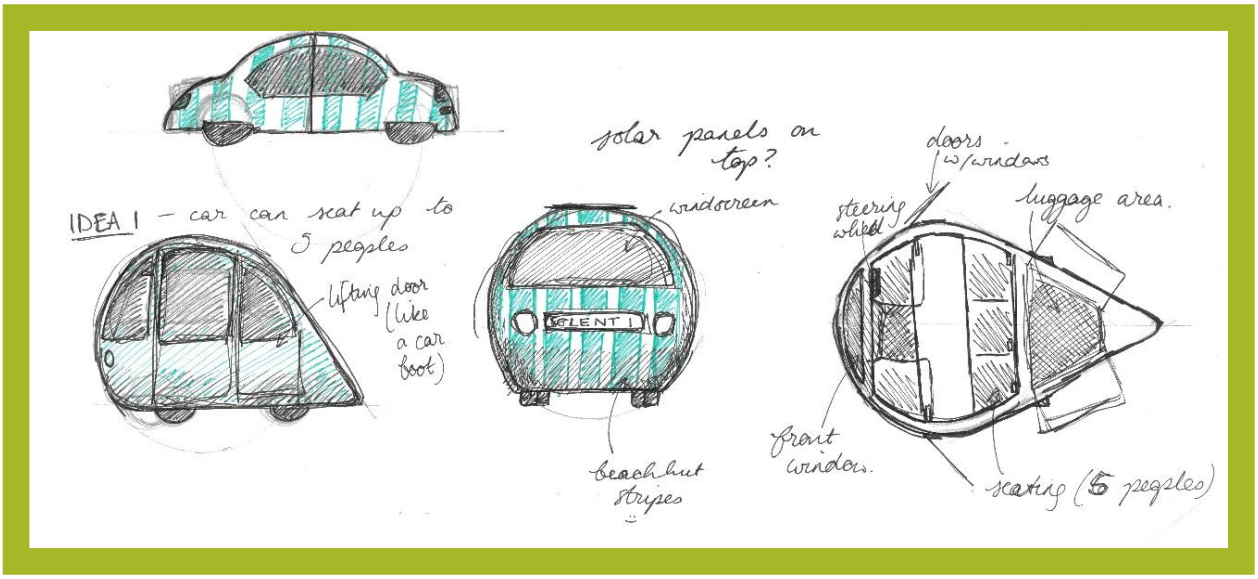


VEHICLE DESIGNS

As well as functioning as autonomous vehicles, the cars should be designed so that they encourage tourism and a sense of community in the city. One idea that we had that would further this aim was a competition for local schools to design some of the cars. Not only would this make the next generation prouder of the cars in their city, it would also simultaneously involve and educate the next generation of people who would be living there how the autonomous cars work. The children would also learn about the design of the transport system and the environmentally-friendly way that we plan to generate energy for the city, helping to reduce pollution and make the city carbon-neutral. This will also hopefully encourage the children to be much more aware of their environment and their impact on it, therefore helping to ensure that the future of Solent City remains green for as long as possible.

So far, we have made two designs for the autonomous cars and one design for buses. In the actual scheme, there will be few different designs for the cars, to provide different capacity vehicles for ease of access. One of these designs is for a car with 8 seats, for larger groups of people who may wish to travel together, for instance a family. The other main design for the cars will include one for a car with only 5 seats, while smaller designs will also be considered for smaller groups or people who may wish to travel in pairs.





Mainly for aesthetic reasons, the cars have been designed to be circular and bubble-like; this design should make them much more 'friendly' looking (to decrease the likelihood of

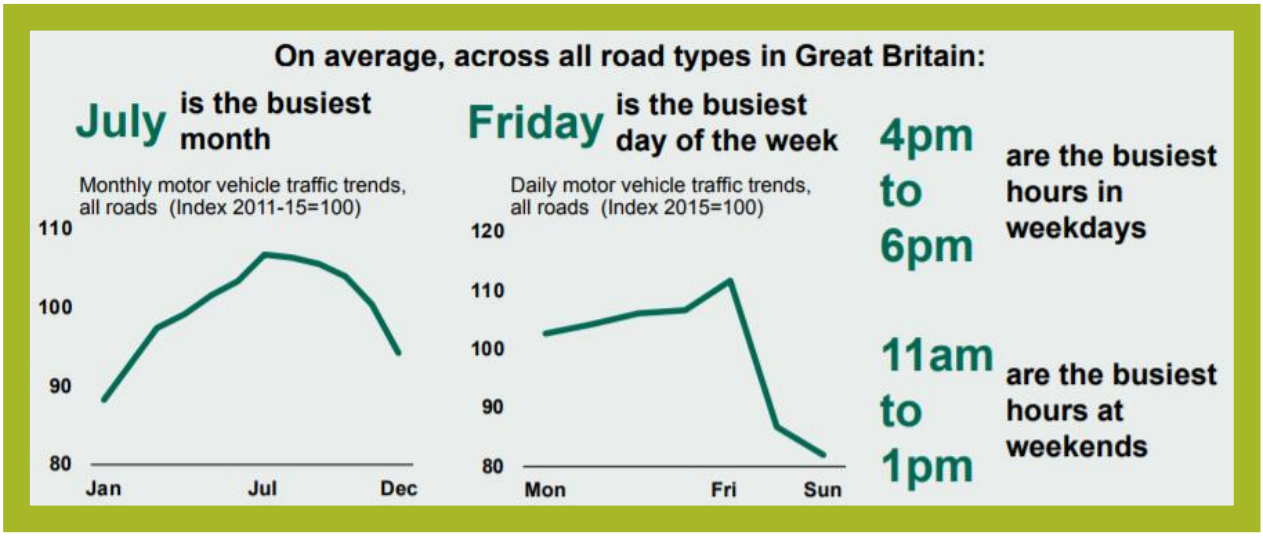
vandalism when there isn't a passenger in the car), as well as much more memorable, another modest way of encouraging tourism and visitors and boosting the city's social status. Practically, this will also make it much easier for visitors to view the city, as the cars will have larger, higher and wider windows. Likewise, to make the journey easier and to encourage visitors to use the city's shops et cetera, a small section at the back of the cars will be empty for luggage; a 'car boot' of sorts.

NUMBER OF CARS REQUIRED

In 2014, there were an average of 519 cars per 1000 people in the UK, meaning that the population of Solent City would be likely to own approximately 1.038 million cars between them. However, this statistic is unlikely to be representative of an urban population, because it takes into account rural households, where a car is essential for daily life, and so will be an overestimate of how many cars will be owned by residents of Solent City.

Currently, Portsmouth and Southampton both have average of around 0.4 cars per person. Yet if they were merged into one metropolitan area (i.e. Solent City) this figure would be expected to fall, as residents of larger cities tend to own fewer cars. Because of this, large cities such as Birmingham and Manchester are the most representative area with which to compare Solent City. Birmingham and Manchester have an average of 0.36 and 0.3 cars per person. Taking an average of these two figures gives an estimated 0.33 cars per person, or approximately 660,000 cars in a population the size of Solent City's.

Although there are likely to be around 660,000 cars in an urban area the size of Solent City, our transport system will not require this many cars. This is because a service where cars are always circulating would be greatly more efficient than the current private ownership model in use. Most cars spend vast portions (up to 95%) of the day parked, either on private property, in public or business car parks. Even in rush hour, when traffic is at its greatest, many 5-person cars carry just one passenger - a recent study by the European Environment Agency found that in the UK, a typical car holds an average of 1.58 passengers (including the driver). This figure has increased in recent years due to the influence of ride-sharing initiatives such as Uber and Lyft, but still remains far from optimal. Our transport system would be expected to increase the efficiency of car transport until it is on par with other shared transportation such as buses - the same study found that buses are typically 70% full. As result of this, fewer than 660,000 cars will be required to run our transport service.



The transport service in Solent City will eventually be expected to deal maximum traffic conditions. This point occurs on Fridays in July between 4-6pm (see above), where the total traffic on the road is at 250% of the average levels. In order to work out the number of commuters travelling at this time, the total distance travelled by vehicles must be considered. In 2015, cars in the UK travelled a total of 247.7 billion vehicle miles (a unit equivalent to one mile travelled by one vehicle). This equates to 28.3 million vehicle miles per hour. Given that at peak traffic times the traffic levels are 250% of the average, 70.8 million vehicle miles will be travelled per hour at this time. Scaling this down for Solent City's population of 2 million people gives a target of 2.17 million vehicle miles per hour. From before, an average of 1.58 passengers populate a car, and hence, our transport system will have to be capable of dealing with 3.43 million people miles per hour (one person travelling one mile every hour) at peak traffic times.

In Birmingham and Manchester, leaving work at 4pm on a Friday allows the driver to travel a maximum of between 39.3 miles (in Manchester) and 45.1 miles (Birmingham) in 60 minutes. However, the average speed on urban "A" roads is as low as 18.6 miles per hour. This pessimistic figure will provide a better estimate of speed for vehicles in rush hour traffic that can be adopted for further calculations. By dividing 3.43 million people miles per hour by an average rush hour speed of 18.6 miles per hour in Solent City, we arrive at the carrying requirements for Solent City's transport services: 184,400 people. This is a rough estimate, and until rigorous feasibility studies can be carried out on the road networks of Solent City, a more precise figure will be difficult to ascertain. In the absence of a better estimate, the autonomous car transport system in Solent City will be designed to carry 184,400 passengers at peak demand.

Assuming that the average car has around 4 seats (which most modern electric cars do), Solent City will require an estimated 46,100 autonomous vehicles to run a transport system.

IMPACT ON ENERGY PRODUCTION

Our transport solution is likely to result in significantly increased electricity requirements for Solent City relative to other UK cities, because of the large volume of electric cars that will require charging.

A survey of taxi drivers in 2016 found that the busiest taxi drivers drove 30,000 miles / year. Even using optimised routes chosen by autonomous cars, the cars would be expected to match this figure, because unlike human drivers, an autonomous vehicle would not require breaks (a legal requirement for humans). Assuming that all autonomous vehicles ran at this rate for the year, the fleet of 46,100 autonomous vehicles would travel a combined distance of 1.383 billion miles over a year.

By the time the fleet of autonomous vehicles are produced, battery technology will have developed significantly, and so it is reasonable to assume that the autonomous cars will have the fuel efficiency of an efficient electric car today. One of the most efficient cars on the market today, the Hyundai IONIQ Electric (pictured), can travel 100km (62.14 miles) on approximately 14 kWh of energy. If the fleet of electric vehicles in Solent City can match this efficiency (which is likely), then the total energy consumption of the autonomous vehicles in the city will be 312 GWh / year.

These increased energy requirements will not be a major issue, because they will mostly occur at night, and could be absorbed by base load power generators such as coal or nuclear power plants that are expensive to build but comparatively cheap to run (and hence should be run at full power continuously for optimum efficiency).

COSTING
THE COST OF CARS REQUIRED

A large proportion of the cost of this scheme will come from the cost of manufacturing or buying 41,600 electric autonomous cars.

An average modern car could be expected to travel 200,000 miles before becoming more expensive to maintain than is economically viable. With this figure, the cars in Solent City would last an estimated 7 years before requiring replacement.

A 4-seater electric car can range in price from £12,000 to around £30,000. In order for the cars in Solent City to be cost-effective, they should compromise cost and durability. Hence, they are likely to cost in the middle of this bracket, at an estimated £20,000 each.

The additional cost for an autonomous car in comparison to a non-autonomous car is predicted to be between £5200 and £7400 ($7,000 - $10,000) in 2025, and will drop steadily to around £2200 ($3,000) by 2035. While expensive, this cost is not unreasonably high. It is also very likely that significant discounts could be obtained from companies such as Google or Apple if the cars were ordered in bulk, because of the significant positive publicity they would receive from the cars' use.

In addition, the car's maintenance costs must be taken into consideration. Although a low-maintenance model of car would be chosen, the cost of maintaining autonomous driving systems is also costly, and so a high figure of £5,000 over the lifetime of the car can be used as a crude estimate. In reality, this figure is highly dependent on a number of different factors (e.g. accident rates), and so cannot be true representation of the actual cost.

Summing these three values, we arrive at a rough figure for the cars in Solent City:

~£5,000 + ~£5,000 + ~£20,000 ≈ £30,000 per car every 7 years, or £4,300/year/car

Multiplying this figure by the number of cars in the scheme gives a total cost:

£4,300/year/car × 41,600 cars ≈ ***£178.9 million / year***

Insurance for driverless cars is an uncertain area; however, as the majority of cars in Solent City will be autonomous under this scheme, insuring the cars will be considerably less expensive than otherwise, as any accidents are likely to just involve autonomous vehicles (or be not the fault of the car). With a sharp reduction in accidents, insurance will become less of an issue for cars in the future. As no concrete figures are available for the cost of insuring driverless cars, it will be assumed than any damage to the cars (or other the property of other drivers) is covered by the average maintenance costs.

COST OF ELECTRICITY

In 2014, electricity supplied to the transport industry cost an average of 8.385p per kWh. At this rate, the total cost of the 312 GWh per year required for the scheme would be just **£26.2 million / year**.

INFRASTRUCTURE COSTS

The infrastructure required to run this scheme will have capital costs attached, which must be calculated to give a final cost for the scheme.

MULTI-STOREY CAR PARKS

The main infrastructure costs associated with the scheme will be the cost of building the multi-storey car parks (MSCPs) needed to store and charge the autonomous vehicles. The cost per car parking space has been estimated at £7,500 (by Parking Consultants Ltd.), and so the total capital cost of building MSCPs is likely to be:

41,600 × £7,500 = **£312,000,000.**

An approximation of this value can also be calculated by multiplying the minimum car parking space dimensions (11.52m²) by the number of cars in the scheme (41,600) by the cost of building a MSCP per m² of internal area (£640/m²).

CHARGING POINTS

Each charging point in the MSCP will cost around £6000, so the chargers in the MSCP will add approximately £276,600,000 to the cost of the MSCP.

Furthermore, the petrol stations in the city will need to be replaced with electric charging points. There are 28 petrol stations in the area around Solent City, and the average petrol station contains approximately 9 docks. If they were replaced with charging ports costing £6000, then that would cost £1,512,000 in addition. However, the implementation of the autonomous vehicle scheme will drastically reduce the number of drivers on the roads, and so this value will be as much as 50% lower; an estimated £750,000.

The proposed lamppost chargers will start off as a scheme with 50 dotted around an area, with the view to increase this number if they were successful. These chargers cost about £1000 so to start off with, they would cost about £50,000.

These values sum to a total cost of **£277,400,000**.

GREEN SPACES

Lastly, the cost of replacing car parking spaces around the city with informal green spaces is estimated at £6,740/hectare. It is estimated that there are as many as 11.3 million parking

spaces in the UK; in Solent City, this would translate to 346,000 spaces, or 300 hectares extra space in the city. Hence, the total cost of converting the space into informal parks would be around **£2,000,000**.

TOTAL INFRASTRUCTURE COSTS

Summing the values obtained for each infrastructure section gives a total infrastructure cost:

£312,000,000 + £274,400,000 + £2,000,000 = **£591.4 million**

TOTAL COST

The capital costs of this scheme are estimated to be: **£591.4 million**.

The operating costs of the scheme can be calculated as estimated to be:

£178.9 million / year + *£26.2 million / year* = **£205.1 million / year**.

This high cost reflects the fast rate at which heavily used autonomous cars will need to be replaced. Although this figure appears very expensive at first glance, it is actually relatively cost-effective.

The average person in the UK is estimated to spend £168,880 in car-related costs over their lifetime. If all 2 million people in Solent City spent this money on car-related cost over their lifetime, this would amount to £337.88 billion spent. Dividing this by an average life-expectance of 80 gives a cost of £4.22 billion spent on cars every year.

Our transport scheme will therefore dramatically cut the costs that motorists face, as the average resident in Solent City will no longer need a car when our system is fully implemented. Even if they face higher premiums for the occasional out-of-city journey, they will still be better off economically under the system we propose.

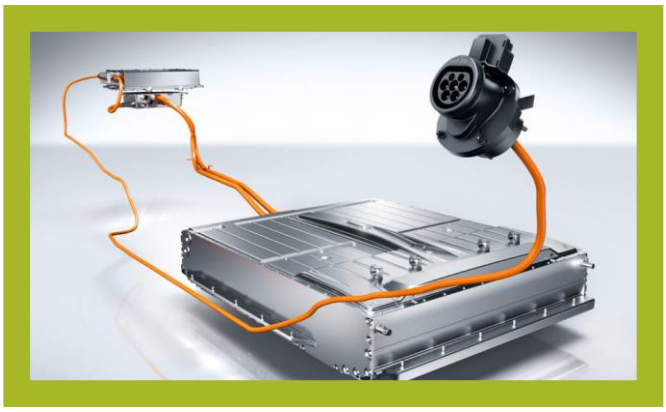
FUNDING

The scheme would largely be funded by transport tax paid by citizens, with a small fee to use the transport system, similar to many Park and Ride car parks (see above). As petrol wouldn't have to be paid for (due to the cars being electric), this would be cheaper in the long run for residents of the city, who would only really need a maximum of one car per household because of the accessibility of using the public transport system. It would also prevention large amounts of air pollution in the atmosphere and so eliminate the need for further action down the road, thereby saving Solent City money in the long term; money which could be used to increase visitor volume to the city, increasing income for businesses and the local authorities.

CARBON COST

Although the cars themselves will not generate carbon dioxide during their operation, their construction and disposal will both release carbon dioxide emissions on par with standard electric cars. For example, the carbon cost of manufacturing an electric car has been estimated at 8.8 tonnes of CO_2 greater than a petrol car (mostly due to carbon emissions involved in manufacturing a large battery).

A report from the low carbon vehicle partnership estimates the total CO_2 generated by an electric vehicle to be 18 tonnes. The additional computer equipment and sensors in Solent City's autonomous vehicles will not have enough mass to significantly alter the estimation of CO_2 emissions from the electric vehicles.



As 41,600 electric vehicles will need to be produced, and over the lifetime of each they will cause 18 tonnes of CO_2 to be emitted, the total CO_2 emissions from the cars will be 748,800 tonnes every 7 years (when the cars must be replaced), or **107,000 tonnes/year**.

IMPLEMENTATION SCHEDULE

Such a radical change to the transport systems in Solent City could not be implemented overnight; nor could it be implemented in a single phase. The residents of Solent City will need to become accustomed to the system for it to become a widespread success. Furthermore, the residents are unlikely to abandon their privately-owned cars until they can see the success of the scheme over a number of years, and their cars reach the end of their natural lifespan. In order to allow the residents of Solent City time to adjust to the new, and to dynamically respond to any issues, it will be implemented in five phases:

PHASE I (1 YEAR)

This phase will begin with an initial feasibility study into the scheme, considering factors such as the cost of new infrastructure and public support for the scheme. Assuming that the necessary funding can be acquired, the different sections of the project will then be opened to tender - this process will allow companies such as Google and BMW to bid for the right to supply the autonomous cars and associated infrastructure for Solent City.

The type of public procurement process used will be a restricted tender, where pre-selected businesses are invited to submit a tender for the contract, while any business may request to participate. The process will begin with the publication of the contract notice, after which businesses have 37 days to request participation. A minimum of five candidates will then be selected, who will then have 40 days to submit a tender. At the end of this process, the best applicant will be awarded the contract.

This process will ensure that leading companies in the field of autonomous driving have the opportunity to compete for the highly specialised contracts required to run our transportation service.

Once the tender process is complete, one or more businesses will own the contracts to supply Solent City with the fleet of autonomous vehicles and infrastructure required to make the transport initiative a reality.

PHASE II (6 MONTHS - 2 YEARS)

This phase will consist of a number of trials of the transportation system, beginning with a trial of 100 or fewer cars that are geographically restricted to the city centre. This trial will be carried out during off-peak traffic times, so that contact with other drivers is minimised until strictly necessary. This will allow small technical issues that will inevitably arise to be solved on a small scale, rather than requiring the total recall of a large fleet of autonomous vehicles.

During phase II, the trials would increase in size from approximately 50 cars to 1000 cars, assuming the success of each consecutive trial. Phase II will act as a final feasibility study

before the larger-scale commitment of money and other resources to the project. Phase II would be expected to last from 6 months to 2 years.

Upon the success of phase II, the contract-holders will begin the large-scale manufacture of the autonomous vehicles that will be used in Solent City, as well as the infrastructure specific to the use of autonomous vehicles, including the autonomous car depots. During phase II, the aforementioned contract holders in phase I will be expected to begin the widespread expansion of electric charging points in Solent City - these will be required regardless of whether or not autonomous vehicles are used in the city, as an increase in electric vehicles is projected over the coming decades.

PHASE III (3-5 YEARS)

Assuming the success of phase II, phase III will extend the operation of the autonomous cars vastly. During this phase, the autonomous cars in the city will act as an extension to the Park and Ride system of buses already in place in the city. The public will be able to rely on the autonomous cars should they wish; however, the widespread use of private cars will be expected to continue during phase III.

The phase would be expected to last for 3-5 years. Throughout this period, regular public surveys will be conducted on topics such as usage of the cars and the level of acceptance of the system. This will allow improvements to be made to the system before the final phase of its implementation and will also serve to keep the public aware of current events regarding the transport system (another way of keeping public opinion about the city transport positive). During this phase, the system will gradually increase from operating at 5-10% of its final level to about 25% of its final level - accordingly, around 10,000 autonomous cars will be on the road by the end of phase III.

PHASE IV (5-15 YEARS)

Phase IV will be the final phase of the transportation system before the system is completed. During this time, the operation of the transport system will be increased to 100%. However, this phase could take up to 15 years as the number of autonomous cars in the city will be tailored to the requirements of the residents. If the residents wholeheartedly support the scheme, then phase IV would introduce all of the 46,100 autonomous cars within 5 years. If the residents support the scheme but continue to use private vehicles, then phase IV could take a considerably longer period of time to implement, and may never reach the projected operational level.

PHASE V (FULL DEPLOYMENT)

In this phase, all of the required autonomous cars will be operational and the focus will shift to the maintenance of the system. Over time, components of the system will degrade and lose efficiency, and these must be replaced. For example, the cars in the system will

gradually be replaced with superior and cheaper models as the autonomous car industry progresses in the coming decades.

SUMMARY

In summary, the implementation schedule for the autonomous cars is as shown:

TRANSPORT BY SEA

INTRODUCTION

As per the brief, transportation by sea must be provided for the people of Solent City. In order to achieve this, we have divided naval transport into two sections; short-range and long-range transport. These vessels are fundamentally different, and as such, have different issues to deal with.

SHORT-RANGE NAVAL TRANSPORT

In order to keep the city as carbon neutral as possible, we have made the decision to use electric boats for short trips, such as the 16-mile crossing to the Isle of Wight. This should significantly decrease the amount of pollution being produced as there are as many as 200 ferry crossings each day according to the island's official tourism website, which can mean approximately 73,000 ferry trips a year. The existing ferry services will be replaced with electric ferries when their operational lifespan ends. Current battery technology is sufficient to sustain a ferry for these relatively short journeys.

LONG-RANGE NAVAL TRANSPORT

A cargo ship travelling at 24 knots can be expected to consume about 225 tons of bunker fuel per day. Given that one tonne of bunker fuel can release as much as 43.3 GJ of energy, a cargo ship may consume almost 10,000 GJ, or 12 MWh of energy. A cargo ship can be expected to be at sea for months at a time; batteries with capacity greater than 100 MWh are currently not small enough to be considered a viable option for powering a cargo ship. Even with the prospect of renewable energy sources charging the battery while the ship moves, the extra weight added by such an unfeasibly large battery makes battery powered cargo ships a technological and economic impossibility, at least in the near future. For this reason, we have decided to keep powering the city's cargo ships with more traditional fuel sources.

However, a shift towards Liquefied Natural Gas could be implemented, since it is a cost-effective way of complying with IMO regulations as of 2020 that prohibit the use of fuels

with a high sulphur content, such as bunker fuels. Speed limits would also be put in place, since slower vessels produce less pollution.

ALTERNATIVE FUELS

Bunker fuel is highly polluting, and stored electricity in batteries is currently not a viable source of energy for long voyages. Because of the inherent disadvantages of the current system of fuelling long-range naval transport vessels, we considered a number of alternative fuel sources.

BIOFUELS

The largest issue with biofuels is the large amount of land required to grow the crops to convert to fuel. Farming land for biofuels will inevitably result in destroying large populations of naturally growing plants; this will disrupt habitats and ecosystems, and can stop large amounts of nutrients going into the soil which can cause the death of the crops that are being grown. The resulting monocultures grown for biofuels would naturally decrease biodiversity in the ecosystem, thereby decreasing the ability of the ecosystem to deal with new threats such as disease and foreign predators, as well as causing havoc for creatures like bees that depend on a wide variety of plants. Bees are vital for the continuation of our ecosystems and are being threatened by colony collapse disorder, which an increase in monocultures can only worsen.

Another argument against biofuels is that they have a reduced energy density in comparison to fuel oil and bunker fuel, and so a greater volume of fuel would need to be transported for every journey. An increase in the mass of fuel being carried by a cargo ship results in a decrease in the mass of cargo it can carry, thereby making biofuels commercially unviable in an industry that relies upon low-cost transportation.

HYDROGEN

Hydrogen would, in theory, be a good option for powering boats, because when hydrogen combusts the only product formed is water, rather than the carbon dioxide released by the combustion of fuel oil. However, the water produced can cause problems for the environment; water would form as a vapour, and water vapour is a major greenhouse gas which has been shown to amplify increases in temperature from carbon dioxide in a

positive feedback loop. This approach would therefore mean having to modify the design of ship engines to accommodate hydrogen fuel cells while still producing pollution, which would result in an increase in cost without a significant environmental benefit.

WIND

Using a cargo ship powered by wind turbines onboard the ship would be a very ineffective solution, because the 3.6 MW that the average offshore wind turbines produce means that four turbines would be needed to meet the 12 MWh required by cargo ships. Having four wind turbines on board a ship would greatly reduce the amount of cargo that it would be able to carry. As a result, wind turbines would not be a viable option for powering cargo ships.

SOLAR

Solar power, (see Wind and solar power stations), has the tendency to leach cadmium into the environment. Cadmium can lead to lung haemorrhages, kidney damage and cancer. The main risk is when cadmium is exposed to water so using them to power boats could cause more problems than it solves. In addition, large batteries would be required to store solar energy for the night-time, and this would reduce the amount of cargo that the boats could carry. This is infeasible, as discussed above.

FUEL CHOICE

As shown above, alternative fuel sources to existing hydrocarbon fuel would not be viable due to their inefficiency. This means that existing fuels will have to be used in long-range naval transport. These fuels are quite polluting, which means that these emissions would have to be offset elsewhere.

This decision means that the existing boats could be used for long-range travel, which will decrease the cost of naval transport significantly. For example, a small cargo ship costs approximately £25,000,000. Solent City contains one of the "world's leading ports" (according to the Southampton VTS). This means that unnecessarily replacing all of the ships that use the port, or at least replacing their engines, would be economically crippling. In comparison, offsetting the carbon emissions caused by these ships would be cheap.

CARBON EMISSIONS FROM SEA TRAVEL

As a result of this decision, the emissions from large sea vessels will need to be offset. In one year, the port of Southampton handles 36.7 million tonnes of cargo, and 1.7 million cruise passengers. An upper bound for the amount of CO_2 emitted by a cargo ship is 40g / tonne / mile. The edge of UK water is 12 nautical miles from the shore. Hence, ships entering and leaving Southampton travel 24 nautical miles in total, and the amount of CO_2 emitted by these ships is:

36.7 million tonnes CO_2 / year x 40g / tonne / mile x 24 nautical miles (27.6 miles) =

40.5 million tonnes of CO_2 / year

Cruise ships with a capacity of 5,000 are estimated to emit as much CO_2 pollution as 83,678 petrol cars:

~100g CO_2 / km x 83,678 cars x 24 nautical miles = 371.9 tonnes / journey.

As a cruise ship of this size can take around 5,000 passengers, there must be:

1.7 million / 5,000 = 340 journeys / year

This results in **126,400 tonnes of CO_2 / year** from cruise ships.

The sum of these two values is the gross CO_2 output of large ships from Southampton port:

40.6 million tonnes of CO_2 / year.

Portsmouth also handles passengers and cargo, but its port is much smaller than Southampton's. As reliable figures for its yearly operation cannot be ascertained it will be assumed that it is 50 % the size of Southampton's port, and so **60.9 million tonnes of CO_2** are emitted by large ships near the city every year.

AIR TRAVEL

INTRODUCTION

Over the last few decades, air travel has become an important part of life for many people in the Solent City area. It is therefore imperative that suitable solutions should be found to grant the Solent City residents satisfactory access to air travel.

POTENTIAL ALTERNATIVES TO CURRENT SYSTEMS

In this section, a number of alternatives to current commercial aeroplanes are considered, which all claim to address the either the issue of flight length or aviation-related pollution.

SUPERSONIC AIRCRAFT

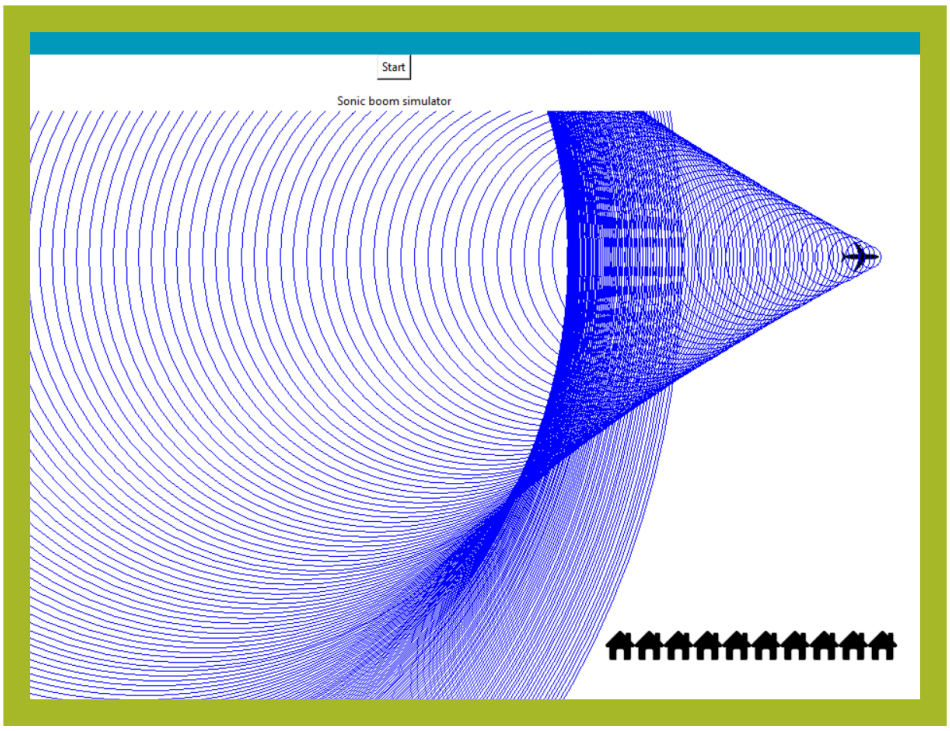
Supersonic aeroplanes offer the prospect of drastically reduced flight times because they travel much faster than traditional subsonic aeroplanes, at speeds greater than Mach 1 (the speed of sound). Such aircraft can cut hours off transatlantic journey times, and so can help travellers to avoid jet lag upon arrival. Companies such as Aerion Supersonic are currently developing modern supersonic aircraft for use across the globe. However, supersonic aircraft have a number of major disadvantages that have historically prevented the widespread adoption of supersonic aircraft in the place of traditional, subsonic aeroplanes.

Chief among these limitations are the prohibitive development costs of researching and creating a supersonic aircraft. Concorde, the first and only British commercial supersonic passenger aircraft, cost £1.134 billion to develop in the 1970s (almost £10 billion in today's money), which is significantly more than a subsonic plane costs to develop. This additional cost arises from the difficulty with dealing with the heat that travelling at increased speed generates. Furthermore, because supersonic flight requires a slenderer fuselage than in a traditional aircraft, cabin space is restricted. This in turn damages further damages the profitability of supersonic aircraft. Because of these factors, a conventional aeroplane is much more cost-effective per passenger per nautical mile than a supersonic aeroplane, which hinders the widespread use of supersonic aircraft - a conventional transatlantic flight would cost around 1500 USD in comparison to the 11000 USD (inflation adjusted) for a flight on Concorde.

Perhaps the most damning feature of supersonic aircraft is its sonic boom. When an aircraft approaches Mach 1, the sound waves that it emits group together into a single shock wave that propagates outwards from the aircraft at the speed of sound. This shock wave is extremely loud, and can damage fragile structures as well as causing distress to observers on the ground. Furthermore, travelling at greater altitude does not significantly decrease the magnitude of the sonic boom, and so the problem cannot be avoided in this manner. Because of this, international aeronautical regulations prohibit supersonic travel over land,

and so supersonic flight paths would be restricted to transatlantic and transpacific routes. Although companies involved in the design of supersonic aircraft are attempting to limit the impact of a sonic boom, until they can design a supersonic aeroplane with a silent sonic boom, current regulations will place severe restrictions on the use of supersonic aircraft.

In order to visualise why a sonic boom occurs, the following simulation has been created. The blue lines represent sound waves propagating out from the aircraft as it travels. In the simulation, the aircraft accelerates and breaks the sound barrier. The consequence of this is a densely packed shock wave that will impact the houses (bottom-right) shortly after the aeroplane passes their position. This simulation shows the difficulty of minimising the effect of a sonic boom - in order to reach speeds greater than Mach 1, the speed of sound must be passed, and so sound waves will inevitably bunch together.



As a result of the legal and economic factors discussed above, we will not be using or investing in supersonic aircraft for air travel to and from Solent City.

CARBON-NEUTRAL AIRCRAFT

We looked at the two different options for the development of carbon neutral aeroplanes, but ultimately decided against recommending carbon-neutral aeroplanes, as both types had many problems associated with them:

HYDROGEN POWERED AEROPLANES

These aeroplanes use hydrogen fuel instead of the hydrocarbon fuel used in most aeroplanes today. This means that when the fuel is burnt as part of an oxidation reaction,

water vapour is released into the atmosphere instead of carbon dioxide. However, although less potent than carbon dioxide, water vapour is nonetheless a greenhouse gas, and can exacerbate the effects of global warming when released into the atmosphere.

Although the production of hydrogen can be achieved in a number of ways, none are environmentally and economically sustainable. Steam reforming releases carbon dioxide into the atmosphere as it requires the use of fossil fuels; biomass gasification could require large-scale deforestation to generate enough hydrogen to power a fleet of aeroplanes; and, extracting hydrogen via the electrolysis of water requires large amounts of electricity, which adds significantly to the economic cost of a hydrogen powered aeroplane.

Furthermore, an aeroplane powered by hydrogen would require a large amount of space for the liquid hydrogen fuel, as it requires four times the volume for the same amount of energy as a normal jet-fuel powered aeroplane. In addition, hydrogen is extremely flammable, and liquid hydrogen has been known to explode extremely violently. The safety mechanisms to stop this add further expense to the aircraft.

BIOFUEL POWERED AEROPLANES

Biofuel powered aeroplanes burn organic matter to produce energy in a similar way to the use of fossil-based fuels. Although burning biofuels releases carbon dioxide into the atmosphere, the net CO_2 emissions would be zero, as organic material absorb CO_2 from the atmosphere as they grow. However, in order to power all the aeroplanes in the area, large-scale deforestation would be required (as the use of waste organic material would not be sufficient). While biofuel could be a method of powering aeroplanes without resorting to net CO_2 emissions, it is impossible for us to use because of the deforestation aspect.

SPACE FLIGHT

Companies such as SpaceX and Virgin have recently set goals to deliver intercity air transport using space flight technology. These programs will operate by flying to the edge of the atmosphere and back down again, and could cut travel times from London to Sydney down to from 24 hours to 2 hours.

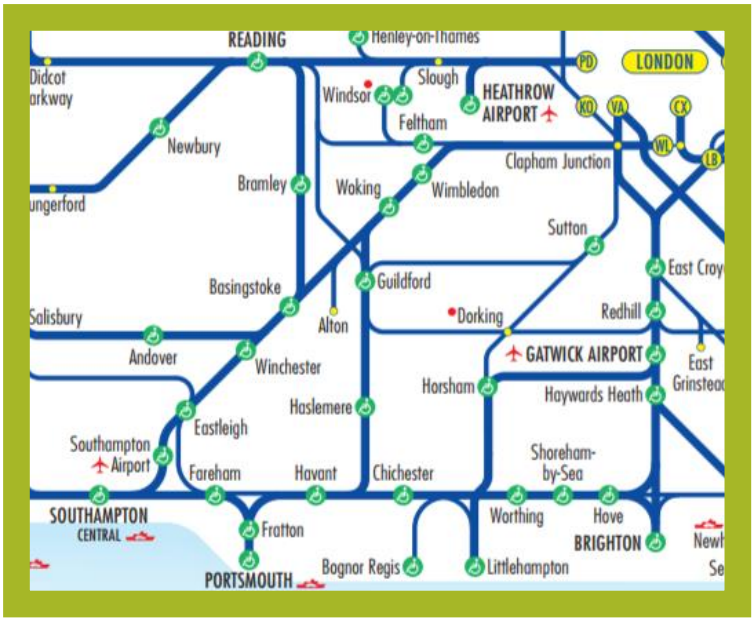
However, this technology is currently not available, and recent estimates of 15-20 years until it becomes a commercial reality mean that it will not be available for use in Solent City.

AIRCRAFT CHOICE

As shown above, there are currently few, if any, viable alternatives to current aeroplanes in use today. Each method of air travel is not feasible for a number of reasons, chief among them technological difficulty and economic viability. Because of this, we will be using traditional aircraft for our air transport solution.

AIRPORT CHOICE

The Solent Airport is a very small airport that is usually only used for private planes much smaller than aeroplanes required to service a population of 2 million people. This is the only airport in the Solent area, as Southampton airport is 0.3 miles outside of the Solent City boundaries.



Because of this, our options for providing air travel to the city consist of building our own airport, or arranging transport to and from other airports such as Southampton, Heathrow or Gatwick Airport. While we considered designing an airport for the city, the cost involved, in both money and energy, would be enormous and wouldn't necessarily have significant benefits, because of the large number of large-scale airports in the surrounding area. We could very easily extend the autonomous car service to cover the short distance to Southampton Airport, while adequate train links to Heathrow Airport and Gatwick Airport are already in existence (see image).

SOUTHAMPTON AIRPORT

Southampton airport is committed to being environmentally friendly, so it would not have a significant negative impact on the carbon neutrality of our city. The vast majority of the airport is lit by LED lights, which are the most efficient lighting solution currently available; there is free parking for bikes and cycling routes on their website to encourage cycling to the airport; they recycle the majority of their waste, and use the rest as an energy source by burning it and then use the soot produced in processes such as creating road surfaces. There does not seem to be a lot that can be done to improve how environmentally friendly Southampton Airport is, besides encouraging them to use comparatively environmentally

friendly aeroplanes where they can - it is understood, however, that the majority of the planes coming in and out of the airport are not owned by the airport, but rather travel companies such as EasyJet and Flybe.

SOLUTION

As a result of these considerations, our autonomous car service will be extended to include transport to and from Southampton Airport. Alternatively, residents of Solent City wishing to travel by air can take a train directly from either Southampton or Portsmouth railway station to either Gatwick or Heathrow, Britain's two largest airports. This journey takes from 2 to 3 hours, while the journey from Southampton to Southampton Airport is just 6 minutes by train. This range of options for air travel into Solent City provides acceptable air transport solution without further intervention, although the CO_2 emissions this will produce will need to be offset elsewhere.

PREFERRED AEROPLANE TYPE

If we were going to construct our own airport and government-owned airline, we would use the Airbus A320neo family of aeroplanes. These aeroplanes have a 124-220 passenger capacity, making them a very good choice for an airport designed mainly for passenger use. This family of aeroplanes is also compatible with the new PW1100G-JM engine, which drastically reduces fuel consumption, operating costs, CO_2 emissions and noise pollution. This engine is still not perfect, but after careful assessment of the other options we decided that this is the best available.

Since the aeroplanes used are largely out of our control, we would instead highly recommend and actively promote the use of these planes to businesses that operate in the area. We would do this via a government website, that would also have other advice for energy saving both for businesses and individuals.

CARBON EMISSIONS FROM AIR TRAVEL

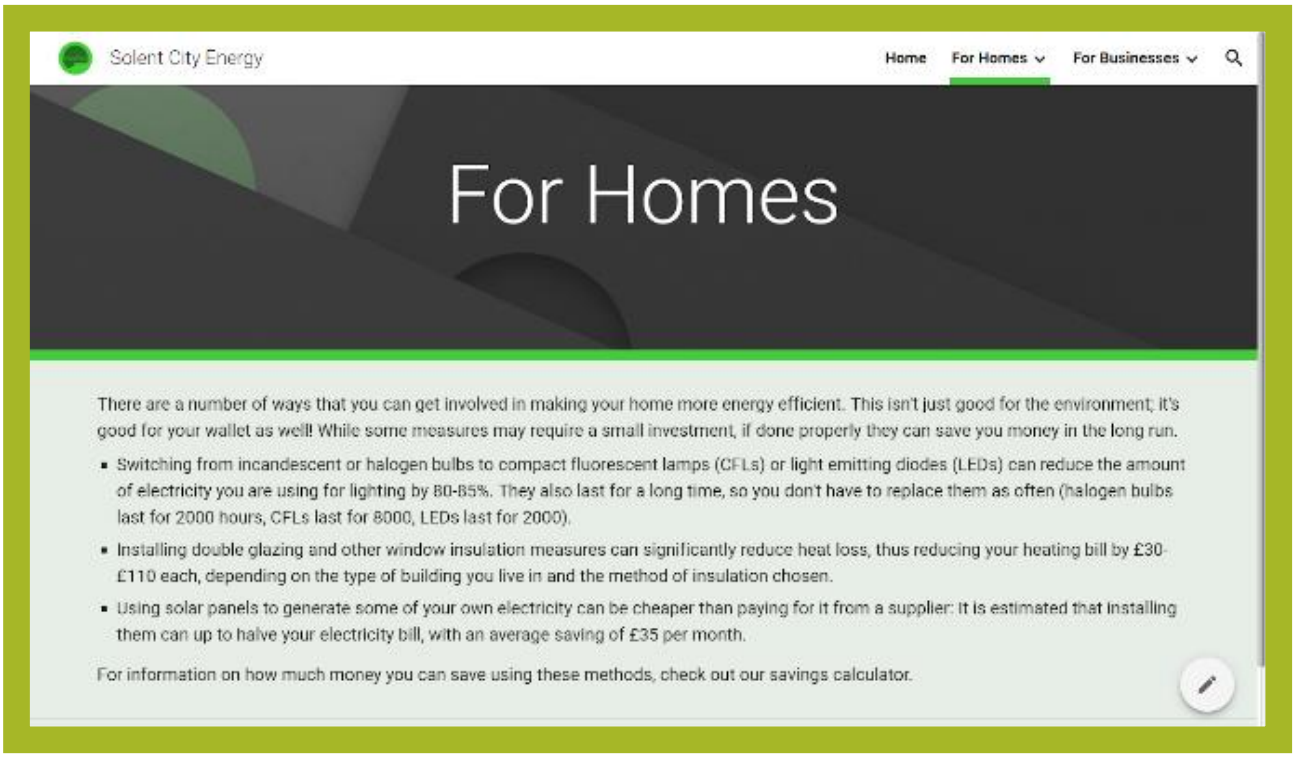
Air travel is notoriously polluting; however, as discussed above, this pollution is essentially unavoidable. One estimate of the level of CO_2 pollution would take the total distance travelled by UK airlines in a year, and multiply it by the 500g CO_2 produced by a plane per km. Statista estimates this distance to be 1889 million km, and so the UK aviation industry produced about 944.5 million tonnes of CO_2 in a year. Solent City would account for **28.9 million tonnes** of this CO_2 production per year.

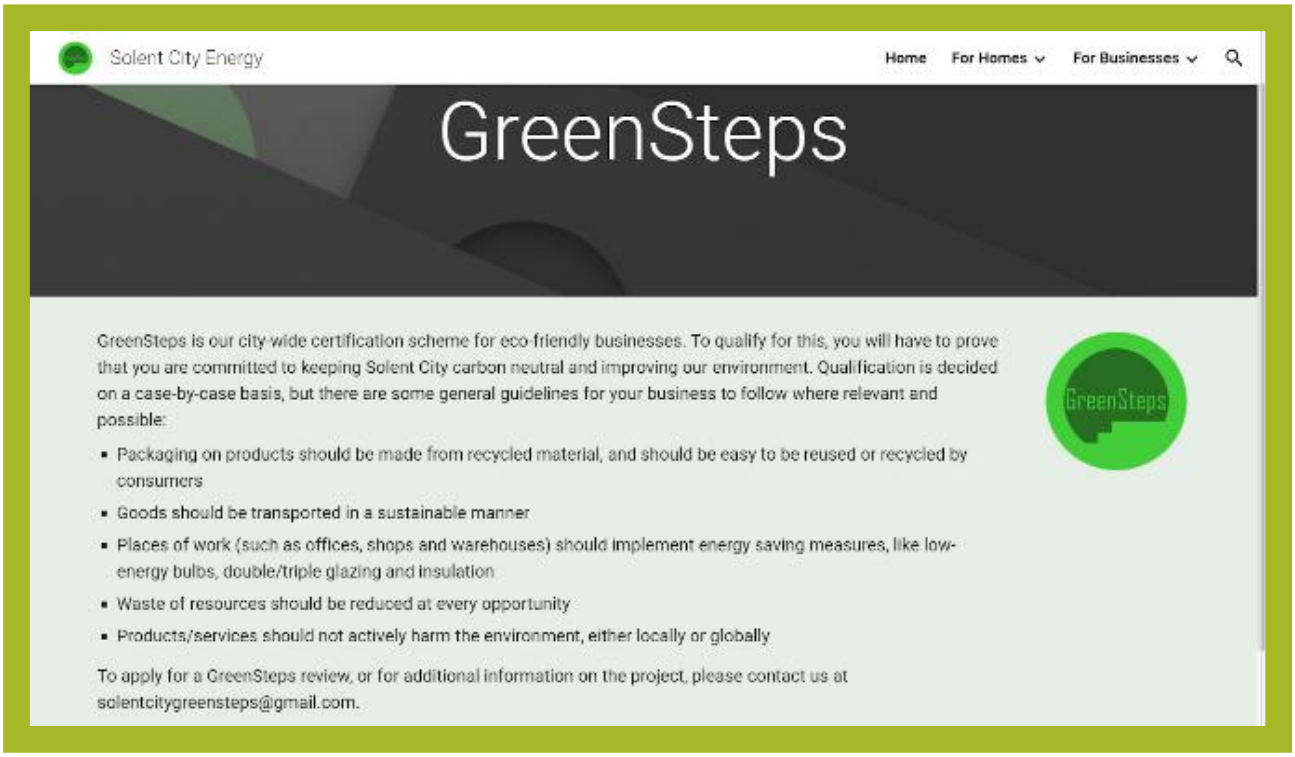
ENERGY SAVINGS

ACCESS TO INFORMATION

A factor that can lead to a lack of uptake for energy saving measures is a lack of trusted information available to the general public. To rectify this, we would have a government website that listed the different improvements that people could make to their homes and places of work to make them more energy efficient. It would include a rough estimate of how much it could cost people, as well as how much electricity (and money) would be saved over time - there could be a savings calculator where people could put in information about their house and then page would tell them how much they electricity and money they could save by putting in place different measures. A reputable source of clear, directly relevant information would contribute significantly to public awareness of ways that they personally can improve their energy efficiency and the ways that it benefits them; this would be likely to lead to an increase in these energy methods being used in Solent City.

We have produced a prototype of our energy website, to showcase the concept:





GREENSTEPS CERTIFICATION

As seen in our website prototype, we would introduce a scheme for businesses in the Solent area to indicate to consumers that the company was operating in an environmentally friendly manner. Businesses could apply for certification, and it would be granted on a case-by-case basis after a review of the company (general guidelines are shown in the above screenshots of our website plan). The project would be called 'GreenSteps' and would encourage companies to be more eco-friendly, while also prompting consumers to make more active choices about the services they use. It would be similar to ISO certification, but naturally much smaller in scope (at least initially), and particularly focussed on impact on the environment.

ENERGY SAVING TECHNOLOGY

HEATING AND COOLING

INTRODUCTION

Many houses in Britain are heated by natural gas, which releases carbon dioxide and is a fossil fuel. There are, however, many alternative methods to heat houses. An average home in a mild climate requires between 5000kWh and 30,000kWh yearly for heating. If the natural gas was methane, which is often used, this amount of energy would produce between 977.6kg and 5865.8kg of CO_2 a year, per house. As there are around 870,000 homes in the Solent City, this would result in between 850 thousand and 5.1 million tonnes of CO_2 per year, and an energy requirement of, at most, 26.1 TWh per year.

Houses will also require a cooling mechanism. British homes don't usually require any form of air conditioning due to the climate, and so insulating the homes would keep them cool enough in the summer months. This insulation will also help to prevent the loss of heat in colder months.

Offices also require a temperature regulation system, which may need to be different to the method using in houses, due to their size.

HOUSES

There are many ways in which to heat and cool houses without using natural gas or producing as much CO2 as traditional methods. Some of the many methods are discussed below:

INSULATION

Making sure that houses in the Solent Area are well insulated will make sure that less heat is lost to the environment and will reduce the costs of heating. This will also ensure that the house stays cool in the summer months, reducing the costs of air conditioning and ventilation systems, where they are used. This will mean that the citizens of Solent City will spend less money on heating and cooling and will also mean that less energy will be required to regulate the temperature of domestic buildings.

ELECTRIC BOILERS

Electric boilers are a greener alternative to gas boilers, providing that the electricity produced is generated using a green system. They work using an element similar to electric kettles, and are cheap to install, energy efficient and compact enough to be put in small spaces. However, these systems can struggle with heating large houses or large amounts of water, as they are so small.

An average 9-kilowatt model usually costs around £1,800. Energy from this model costs about 15p per kilowatt.

HEAT PUMPS

Heat pumps work by taking heat from the surroundings (usually from underground or the air) and passing it over a refrigerant liquid. This liquid evaporates, turning into a gas, which is then compressed, increasing both the temperature and pressure. The gas is now a suitable temperature to heat a home. Heat pumps are very low maintenance, easy to install and don't use much electricity, but many can only heat to a temperature of about 40°C. This makes them very good for underfloor heating but not particularly good for producing hot water, or for use as a central heating system.

SOLAR THERMAL PANELS

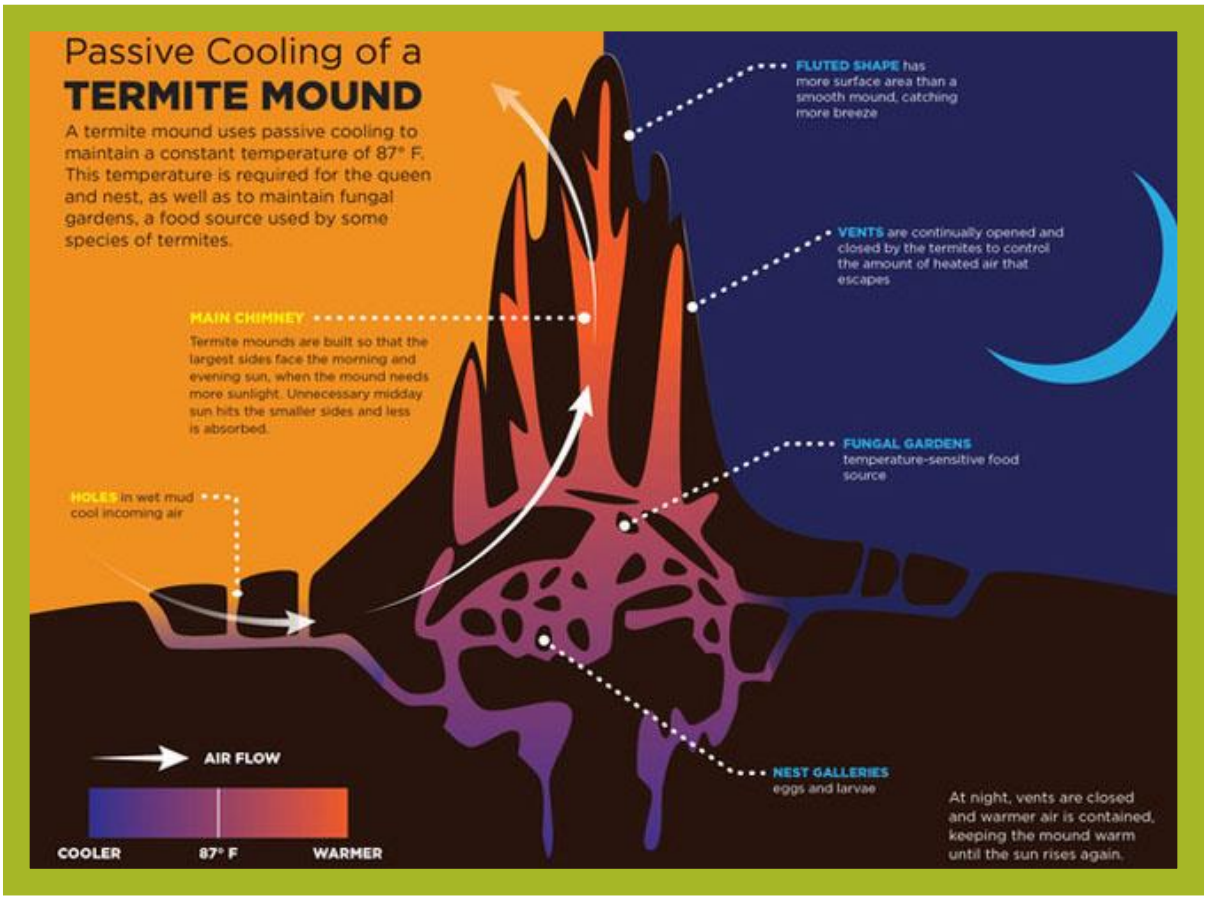
Solar thermal panels use sunlight to convert light energy into heat energy. They can produce between 10% and 90% of people's hot water, and they are around 50% efficient, which is three times more efficient than solar electric panels. Solar thermal panels can be used as central heating, but only when the house is designed for it. This would mean that many of the existing houses in the Solent Area would have to be rebuilt if we wished to use this method. This would be incredibly expensive, and as there are many other options, it would also be a waste of time. These solar panels are also made using cadmium, a toxic substance that can leach into the environment. Some research is being done into making solar panels that do not contain cadmium, but the progress is limited, so it must be assumed that this technology would not be available within the next ten years.

OFFICES

Office buildings, which are typically much larger than the average home, require a way of ventilating air throughout the building, to both heat and cool themselves. One way of doing this is by using biomimicry; modelling our buildings on organic-made structures in the natural world which use minimal energy to achieve constant temperatures.

TERMITE MOUNDS

Termite mounds have exceptional ventilation capabilities. Termites use the power of the sun to circulate air around their mounds; during the day, air warms, rising into smaller tubes, cooling and then sinking into the larger ones. At night, the air in the small tubes cools faster than the air in the large, central tubes. This makes air flow through the mound, and as the cooler air sinks, the warmer air rises.



This, or at least a similar system, could be adapted and used to ventilate office blocks within Solent City. This approach has been tried and tested in countries with a hot climate, like Australia and Zimbabwe, but, as England has a mild climate, and the difference in temperature between day and night is not as large as in these hotter countries, the approach would most likely be unsuccessful.

ANT NESTS

Unlike termite mounds, ant nests rely on the wind to ventilate themselves. This method would be more likely to work within the mild, windy climate of Britain. Ants build turrets which direct air into their tunnels, and the air is then spread through the whole nest by these tunnels. Carbon dioxide (which is released by the ants during respiration) is forced through the tunnels, and out into the environment, in the process being replaced by fresh, oxygenated, air.

Newer office blocks could use this structure to ventilate the building with minimal energy use. There would, however, have to be energy-using mechanisms to open and close the vents, as on a cold day the wind could easily cool the building down to below the legal working temperature of 19°C.

This method will be used in new office buildings, as it decreases the amount of energy needing to be produced, allowing more energy to be used for other systems.

OLDER OFFICES

Older offices do not have the structure required to incorporate the ant nest method of ventilation. These offices will use the existing vents and air conditions systems (pictured), operated with electricity, and use electric boilers as heaters.

LIGHTING

BUILDINGS

A small change that can make a huge difference to the power consumption of our city is making CFLs (or LEDs where suitable) mandatory in all buildings where possible, and restricting the sales of inefficient bulbs. Using CFLs can reduce power consumption through lighting by approximately 80%. While EU regulations have banned the import of both halogen and incandescent bulbs, many shops still have stockpiles of the older and less efficient bulbs, so regulation may still be necessary to ensure that Solent City is using the right lighting sources.

Traditional incandescent bulbs produce light by passing electricity through a thin wire, causing it to heat up, then release energy in the form of visible light (photons); this is an extremely inefficient process, with approximately only 10% of the electricity being converted into light. In a CFL, electricity is passed through a tube that contains argon and a small amount of mercury, causing the molecules to emit energy in the form of ultraviolet radiation which then in turn causes the fluorescent phosphor coating to emit visible light; this process has a much higher degree of efficiency, as it does not generate as much heat.

While tungsten bulbs have numerous disadvantages, their versatility and quality of light can make them indispensable for creative industries such as photography, theatre and filmmaking. Their high CRI abilities also mean that they are used in clothes shops, so that consumers will have an accurate picture of the colour of the items they are purchasing. This means that banning these bulbs altogether will not persuade certain businesses to switch to more efficient bulbs and may instead mean that they simply buy their bulbs from outside the city, potentially harming the local economy. For this reason, we will not completely ban inefficient bulbs, but will still ensure that they are strictly regulated to prevent unnecessary usage.

STREETS

While a system of lighting our streets without the need for electricity seems appealing (streetlights use 25-100 watts and are on for approximately 4275 hours per year), the information available indicates that this will not be a reality within the next 10 years. There are a number of ways that researchers are working towards this goal, but as of yet all of them have severe limitations and disadvantages:

The genetics of trees can be modified with DNA from certain bioluminescent creatures to allow them to glow. However, the majority of these creatures glow with fluorescent proteins that are only active when the relevant molecules are excited by UV light, so trees with these proteins would only glow in the day.

The compound luciferin, found to be the source of the light given off by fireflies, can be infused into trees, but it is prohibitively expensive (approximately £142 per gram) and a lot of it would need to be bought over time to maintain the luminescence.

Gold nanoparticles can be added to plants so that they emit light - this light can also increase the rate of photosynthesis in the plant, thereby decreasing carbon dioxide levels. However, gold nanoparticles are expensive and a lot of them would have to be bought since they only last within the plant for 2-8 months.

Bioluminescent bacteria can be held in plastic capsules to provide a small but useful amount of light, but they are very expensive to make and at present only last for about three days.

While one or more of these methods may be viable in the future, at present the best we can reasonably do is use bulbs that are as efficient as possible and ensure that the lights are only on when necessary, through the use of LDRs or timers.

DECISIONS

Electric boilers will be recommended to the citizens of Solent City, as will proper insulation of houses/offices and energy efficient bulbs. This decision has been made because an electric boiler (or multiple for large buildings) are able to heat the entirety of a building, including central heating and water, without leaching toxic heavy metals into the environment. Insulation and efficient bulbs will also be recommended on the GreenSteps website, as they reduce home/business owners' heating and lighting costs respectively, whilst also reducing the amount of energy we need to produce.

For unconstructed office blocks, the ant nest model will highly recommended, as it conserves heat and therefore saves electricity. Electric ventilation will be used in offices that have already been constructed but will not be recommended for new buildings.

In the worst-case scenario, all of the houses in Solent City will use gas-powered boilers and inefficient bulbs. This would result in CO_2 emissions of **5.1 million tonnes per year** for the heating (since the bulbs would be powered by clean electricity they would not produce CO_2). Realistically, the number would be less, but this figure will be used to ensure that we offset enough CO_2.

ENERGY SOLUTIONS

INTRODUCTION

To support the use of the autonomous electric cars, as well as to keep the plan for Solent City carbon neutral, there will have to be a carbon neutral energy supply. This energy supply will need to be able to produce enough energy to supply the city, assuming that peak demand is required at all times. There are many different ways to supply carbon-neutral energy, but there are advantages and disadvantages of each of these methods.

CALCULATION OF ENERGY REQUIREMENTS

The total energy generation and supply for the UK in 2015 is broken down in the table below:

	2015 *TWh*	Percentage change on a year earlier
Electricity		
Generated from		
Coal	76.3	-24.3
Nuclear	70.3	+10.3
Gas	99.8	-1.2
Renewables	83.3	+28.9
Total	337.7	-0.4
Supplied to		
Industry	92.1	-1.3
Domestic	108.8	-0.1
Other final consumers	103.1	+1.9
All	304.0	+0.2

Given that the population of the UK in mid-2015 was 65,110,000 people, we can calculate the percentage of people who reside in Solent City in comparison to the UK:

2 million people / 65.11 million people = 3.072 % (4 s.f.) of the total UK population resides in Solent City.

From the table, in 2015 304.0 TWh of electricity was supplied to consumers in the UK. Using this figure, we can calculate Solent City's electricity requirements if they were proportional to those of the UK in 2015:

3.072% of 304.0 TWh = 9.339 TWh (4 s.f.) of energy required by Solent City per year.

However, the transport scheme put into place will increase this requirement, because transport fuel usage will be shifted from hydrocarbons to electricity.

The use of autonomous electric vehicles in the city will result in an increase of energy consumption of 312 GWh/year (see Autonomous vehicle scheme - Impact of energy

production). There will also be an increase in electric vehicles generally in the city. A crude estimate would suggest that there will be approximately the same number of autonomous cars as non-autonomous, and so the increase in electric consumption from the transport industry could be as high as 624 GWh/year.

While energy saving methods are likely to decrease the consumption of electricity, we will not be including these potential decreases in our calculations because we can't guarantee that people will follow our recommendations and the phasing in of efficient bulbs may take some time. To ensure that we don't underestimate our power requirements, we will work on the worst-case-scenario assumption that none of these measures are implemented in places where they weren't previously, meaning that the electricity consumption will remain the same.

This means that the city's energy solution must be capable of generating approximately 9.963 TWh per year. This is equivalent to having the following power capacity: 9.963 TWh / (365 x 24h) = 1.137 GW.

SELECTION OF PRIMARY ENERGY SOURCE

In order to supply Solent City with a continuous supply of energy, an energy supply method (or a combination of different methods) must be first selected. For the purposes of Solent City, we decided that a nuclear fission reactor would be the best choice of primary energy source. However, in reaching this conclusion, a number of alternate power generation methods were considered:

FOSSIL FUEL POWER STATIONS

The usage of a fossil fuel powered power station was initially considered. Recent advances in gas-powered power stations have resulted in a decrease in carbon dioxide emissions and an increase in energy production relative to other fossil-fuel power stations including coal and oil. Furthermore, gas power stations are among the quickest to construct, and recent discoveries of shale gas have made gas powered stations an economic option for the UK. However, despite emission reductions, the power station would still release a vast quantity of carbon dioxide; this quantity would be incredibly expensive to offset with current carbon capture technology. Hence, the use of a fossil-fuel power station and maintaining carbon neutrality would be prohibitively economically and technologically expensive.

BIOFUEL POWER STATIONS

The use of a biofuel power station was also considered. Biofuel power stations release up to 85% less carbon dioxide than fossil-fuel powered power stations - as consequence carbon neutrality can be achieved more easily (as the biofuel absorbs as much carbon dioxide when it is growing as it releases when burned). However, in order to avoid large-scale

deforestation and other environmental damages associated with growing the biomass for such a power plant, current biomass power stations utilise waste biomass to produce energy. One such plant, in Little Falls, Minnesota, operates utilising corn cobs and corn stover as a feedstock. This feedstock is converted into n-butanol through the use of genetically engineered Clostridium bacteria, which can then be burned to produce energy. This process is sustainable, because the feedstock, corn, can be produced indefinitely to meet demand.

However, this process is very expensive, due in part to the large quantity of waste required to produce significant amounts of energy, so would not be economically viable for powering an entire city.

WIND AND SOLAR POWER STATIONS

Both wind and solar power are renewable, free and clean sources of energy. However, there are a number of major drawbacks that prevent them from being suitable for Solent City and led us towards our decision to use nuclear power.

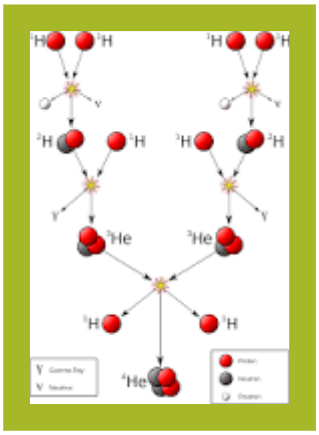
To start with, neither wind nor solar can be easily used to reliably generate enough energy to become the primary supply source in the area. Although wind power has excellent efficiency (of around 45%), the largest offshore wind farm in the world, the London Array, can only generate 630 MW of power. Onshore wind farms can generate greater power, but require a large amount of land. For example, the Beidaqiao wind farm in China is capable of generating 201 MW of power, but takes up 30 km^2, an area four and a half times the size of Gibraltar. In order to generate enough energy to power Solent City, the wind farm would need to be at least 5 times as large; however, Solent City itself is only 215 km^2, and so such a large wind farm is infeasible and impractical.

Solar power has a similar issue. While solar power can be a good source of energy in areas with a high level of sunlight, weather reports from the last seven years indicate Solent City is not optimally located for this; during the winter months, the hours of sunlight can drop as low as two per day. Given that solar panels can convert at maximum 22% of available energy into useful electricity, a solar farm to power the entirety of Solent City throughout the year would require a large amount of land that could be better utilised for agricultural purposes or housing.

Another factor that influenced our decision against wind farms was that they cause disturbances to the surrounding area. For example, wind farms produce noise pollution at a level of around 50-60 decibels, or approximately the volume of a loud conversation, and the blades can be a danger to creatures such as birds and bats. Furthermore, solar panels and wind turbines are often considered unsightly and ugly, which could drive people away from living in Solent City, thus reducing income and magnitude of visitors.

However, these problems do not mean that these energy sources have no place in our plans for Solent City. The Rampion Wind Farm (under construction and due to be finished in 2018) and other smaller wind farms in and around the Solent area could be used in the event of our other energy production methods failing. The existing solar and wind farms already plugged into the National Grid and supplying the Portsmouth area (e.g. Lovedean Solar Farm) would also continue to be used to supply energy to Solent City as secondary energy sources. Also, we would run programmes to convince people to invest on solar panels on their own roofs, to provide renewable energy for their houses, and reduce our need to produce as much electricity.

NUCLEAR FUSION



Nuclear fusion offers the potential for renewable, clean energy that can be produced efficiently and on-demand. Energy harnessed from a nuclear fusion power station will be is acquired by fusing two 'light' atoms together in a nuclear fusion reaction and using the resultant energy in the standard methods of power production (heating water to use in a steam turbine).

The process required to cause a fusion reaction would utilise hydrogen gas (as it is the lightest atom known), and subject it to exceedingly high temperatures and pressures. This process requires materials and equipment able to withstand these conditions to contain the reaction safely.

The hydrogen atoms themselves must be under immense pressure in order to fuse. As a result of this, they form a state known as plasma (an ionised gas). This plasma circulates inside the reactor, and the hydrogen atoms within it fuse to form a new nucleus. This process releases vast quantities of energy, because the new nucleus has less mass than the sum of the two fused nuclei. The reduction in mass corresponds to a gain in energy, as predicted by Einstein's famous equation $E = mc^2$.

The most promising of the potential hydrogen fusion reactions is the fusion of deuterium and tritium isotopes, due to its high ratio of energy release relative to the conditions required to make them fuse. The reaction yields about 17.6 MeV (with a loss of 0.4% of total mass after reaction) of energy. However, this energy yield must be balanced against the energy required generate the conditions conducive to reaction. For nuclear fusion take place, temperatures of over 100 million kelvin and pressures of 2.05 atmospheres must be achieved (and maintained). Current attempts to build a nuclear fusion reactor, such as the Joint European Torus in Culham, UK, can only generate 70% of the power it needs to operate, and so are not viable power generation options yet.

Another difficulty with nuclear fusion is the fuel used. Although there is a relative abundance of deuterium fuel in the oceans, tritium must be either bred from lithium, which is a further use of energy, or collected from the upper atmosphere (where it exists in sparse concentrations).

As a result of these technological and practical issues, fusion energy is still several decades off becoming viable power generation option.

NUCLEAR FISSION

Nuclear power is generated by causing a controlled nuclear fission reaction, usually with the fuel source uranium, and capturing the energy released by the reaction in the form of electrical energy. This method of power generation has a number of advantages that would potentially make it a good choice for Solent City.

Firstly, the generation of power via nuclear fission does not intrinsically release carbon dioxide into the atmosphere. Therefore, nuclear power stations can be theoretically carbon-neutral, provided there are no miscellaneous carbon costs from activities related to the generation of nuclear power (for example, if the uranium was transported to the power station using petrol or diesel vehicles).

Furthermore, the fuel source, uranium, has 3 million times the energy density of coal. In practical terms, 1 kg of uranium can be used to generate as much energy (45,000 kWh) as 14,000 kg of coal; because of this, transporting the fuel to the reactor is less of an issue, and the process is much more efficient. Although the UK has limited uranium reserves, many of its allies (including the US, Canada and Australia) have in the region of 270- 2400 thousand tons of uranium each and already sell uranium to the UK, and so fuel supply wouldn't be an issue for the lifetime of the nuclear reaction (which would be less than 100 years).

In addition, the economic cost of energy generated by nuclear fission is competitive with that of energy generated by coal, the major source of energy globally. The main cost of producing energy by nuclear fission comes not from the fuel, which is relatively inexpensive, but from the construction and decommission costs of the site.

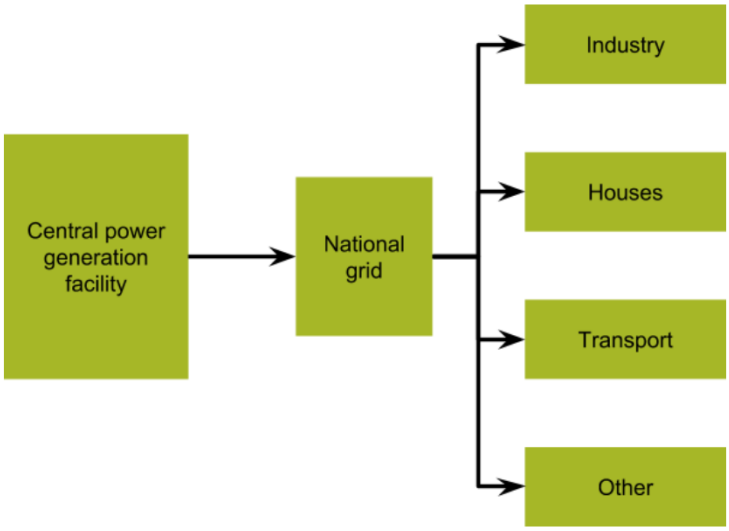
There is, of course, the problem of the nuclear waste generated as a by-product of the nuclear reaction. There are already methods of disposing of nuclear waste in the UK, but the addition of an extra nuclear power station would require further measures to dispose of the waste safely and securely. However, this problem is not insurmountable and the benefits (lack of carbon dioxide released into the atmosphere, very cost effective, fuel is abundant) outweigh the downside of having to dispose of nuclear waste.

Because of these reasons, we have chosen to meet the majority of the power requirements for Solent City with a nuclear fission reactor.

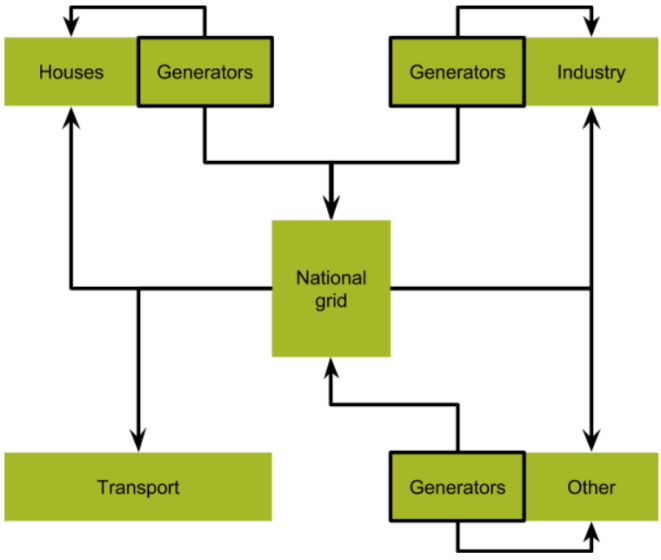
CENTRALISED VS DISTRIBUTED POWER GENERATION MODELS

Centralised power generation implements the concept of using one (or possibly more for larger areas) source of energy that supplies the entire area, such as a large-scale wind or solar farm, a nuclear fission plant or a coal-fired power station. In contrast, the distributed power generation model relies on a grid of interconnected, distributed energy resources that can generate an arguably more robust supply of energy to either a local community in a microgrid or a wider area as part of the national grid.

CENTRALISED POWER GENERATION MODEL



DISTRIBUTED POWER GENERATION MODEL



EFFICIENCY

A distributed power generation system has the potential for large increases in efficiency relative to a single power plant. Power plants tend to be located close to necessary natural resources (typically away from population centres and close to either a fuel source or a coolant such as water). While this can provide advantages such as improved air quality and space in a city, it does necessitate the transmission of generated electricity from source to consumer. Despite the steps take to limit the losses in the transmission process, there is a typical loss of power in the range of 8-15% in the form of heat energy (due to the resistance of the cables); a distributed power system would circumvent this issue by locating energy generation resources much closer to the consumer. However, the economic advantages of being close to the energy supply (coal, for example) far outweigh the costs of this loss of energy in transmission, as the fuel does not need to be transported large distances, via fuel-guzzling and expensive transport systems like planes and boats.

Both models could be managed to operate at optimum efficiency through the use of smart grid systems. Such systems monitor consumption and generation in real-time and tailor the supply and distribution of energy so that the minimum amount of energy is wasted.

A centralised power plant has advantages in efficiency arising from the bulk generation of power (e.g. lower energy expended maintaining the system). A distributed power system has the advantage of minimal loss of energy from transmitting the energy, but needs high levels of maintenance, costing citizens large amounts of money.

ECONOMIC IMPACTS

The implementation of a centralised power generation model can significantly stimulate the economy in the area. For example, when a nuclear power plant is under construction, it can generate as many as 3,500 jobs, with approximately 1000 of those maintained in some capacity after the construction is finished. This model can therefore deliver stable income at a higher than average level for a significant number of people. Furthermore, the company operating the power plant must pay tax to the government, and this can generate millions of pounds for the local community.

As an indirect result of the investment in a centralised power plant, there is greater investment in the local economy, and an indirect increase in tax revenue of as much as £20 million that can be reinvested into the local community in the form of improved infrastructure, healthcare and schools. Furthermore, the increase in highly paid workers contributes to an increase in spending in the local area that can support beneficiaries such as grocery stores, restaurants and other small businesses in the service industry. The total positive economic impact of building a centralised power plant has been estimated at between 160-470 million USD (£113-332 million).

In contrast, a distributed energy generation model does not require the same level of economic investment as a centralised energy generation model (besides the increased overhead cost of extending the existing cabling network in the area), and so doesn't have the same benefits on a wider economic scale. However, it does provide a number of economic advantages. These include a decrease in financial risk when implementing a number power generation system, and the associated cost benefits of increased efficiency discussed above. Furthermore, some distributed energy resources have reached grid parity, when they become less expensive for the consumer than buying energy from the national grid (mostly a centralised power generation model). For many rural energy consumers, where the grid supply is more expensive than using their own generator, distributed energy resources are already a reality.

The number of jobs that are created in an area when a centralised system is put into place, and the tax revenue that helps to support the community; indirectly boosting small businesses, and providing jobs for citizens, would benefit the city far more than a system that mainly benefits a rural area.

STORAGE

A distributed power system has greater issues surrounding the storage of energy than a centralised system has. Distributed energy resources can take many forms, including solar and wind powered generators. As such generators are highly dependent on environmental factors, energy must be stored for use when the environmental conditions are not suitable for energy generation. This may require a large capital investment into energy storage solutions, which could add to the negative economic impact of implementing a distributed energy generation model. Although solutions such as using car batteries to store surplus energy have been suggested, such concepts would still require significant economic investment to become a reality.

The centralised power generation system is able to tailor the supply to the demand with greater ease than a distributed system. Storage would not be as much of a problem because of this. This allows them to avoid the problems associated with modern energy storage systems.

ROBUSTNESS AND RELIABILITY

A distributed energy supply operating over a large area is considerably more robust than a centralised energy supply. This is because a significant proportion of distributed energy resources must fail in order to have a noticeable impact on the energy supply, while only the main centralised generator must fail for a centralised energy supply to fail. In addition, the failure of cabling transmitting energy from source to receiver is much less significant in a distributed network of transmission than if the central cables connecting the power plant

to the national grid fail in a centralised transmission network. However, we will implement methods of keeping emergency services operational, and will have power reserves for those who would be classed as vulnerable, to ensure that the impact of a failure would be relatively minimal.

In both instances, the energy required to power the emergency services would be met and delivered, in the event of a power failure. Therefore, the robustness of the whole system does not matter enormously, as any problems that may occur would be fixed quickly. The national grid provides an additional layer of redundancy, so that should the main system of energy generation fail, there is still a supply of energy to the city from the other redundancy systems, provided the cabling remains functional.

REGULATION

The centralised model for generating power is much easier to regulate, since it places the government and government regulated companies in control of generation and distribution of power instead of individual citizens. This means that high standards of safety and security can be implemented throughout the entirety of our power system, without having to rely on individuals to comply with regulations which would risk corners being cut to save time or money in the short term. The centralised system also allows for more efficient management, as it is all located in one area.

OUR CHOICE

We have decided to use the centralised model for energy generation. It has many advantages over the distributed system, especially given that we are powering an entire city: it is more beneficial to a city economy, it is able to respond to differing power demands more easily and it is easier to regulate and manage.

However, the biggest factor that influenced our decision was that the centralised system is the one that fits best with our plans to generate the majority of the power for Solent City with a nuclear power station. A nuclear power station, by definition, is part of a centralised energy system, since it would have to generate electricity for a large area to be economically viable. The distributed energy system works better for wind and solar power, which we have already discounted for a variety of reasons.

NUCLEAR POWER

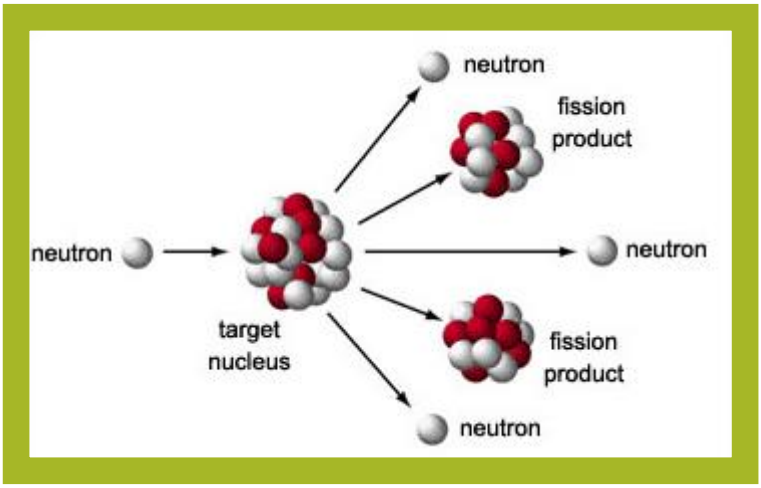
We have decided to generate the majority of Solent City's energy using a nuclear power station; to achieve this, there are a number of factors that will have to be considered.

INTRODUCTION

In a nuclear power station, energy is released via the splitting of atoms (nuclear fission) belonging to certain elements (fuel). This energy is then used to heat the coolant, thereby generating a gas that rises to turn a turbine. The turbine is connected to a generator that converts the kinetic energy from the turbine into electricity, which can be stepped up to a higher voltage and added to the grid. The process is maintained by moderators such as control rods.

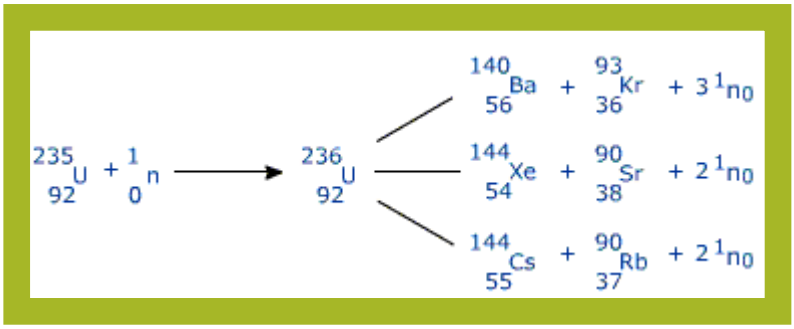
BASIC CONCEPTS IN NUCLEAR FISSION

The energy produced from a nuclear fission power plant is obtained from the splitting of transuranic atomic nuclei. This process begins when a neutron is absorbed by the nucleus of a heavy atom. This atom then splits into fission products and releases neutrons and energy. The neutrons released are known as "fast" neutrons because of their high incident velocity (around 3% of the speed of light). In contrast, neutrons in thermal equilibrium with their surrounding (and hence are considerably slower) are known as "thermal" or "slow" neutrons.



In order to generate energy continually, a chain reaction must be sustained. For this to occur, the neutrons released in the fission reaction must collide and react with other atoms in the fuel. However, not every collision between a neutron and an atomic nucleus results in fission. Some collisions cause transmutation to another element. For example, when uranium-238 captures a neutron it can sometimes transmute to plutonium-239 instead of undergoing fission. Which process occurs depends on the energy of the neutron involved in the collision.

An example reaction and its associated fission products:



The fuel used in a nuclear reactor is based on the element uranium, which exists naturally in the form of two isotopes, uranium-235 (0.72% of natural uranium) and uranium-238 (99.28% of natural uranium). These two isotopes have different nuclear properties, and so react differently when impacted by a neutron of different energy. In practice, this means that uranium-235 is more likely to undergo fission with low-energy neutrons (< 1 eV), while uranium-238 is more likely to undergo fission with high-energy neutrons (> 5 MeV).

However, this creates a problem when attempting to sustain a chain reaction. When either isotope undergoes fission, it releases neutrons with energy in the range 1 MeV - 2 MeV; neutrons of this energy cannot react and cause a sustainable fission reaction with either isotope of uranium at their natural concentrations (i.e. 0.72% U235 and 99.28% U238). Because of this, too few neutrons cause fission reactions and the reaction falters.

This issue can be overcome in one of two ways. Traditional reactors use a moderator to slow down the neutrons emitted from fission reactions so that they reach thermal equilibrium with their surroundings, and hence have suitable energy to cause fission more frequently in uranium-235. Depending on the neutron absorption rate of the moderator, it may be necessary to enrich the uranium fuel (i.e. increase the proportion of U235) to release enough neutrons to sustain a reaction. Reactors using this method are known as thermal reactors.

Fast reactors, on the other hand, utilise unmoderated fast neutrons emitted from fission reactions to sustain a fission reaction. This method works by using a highly enriched core of uranium and plutonium to start a fission reaction, and surrounding this core with non-enriched uranium. The neutrons emitted from the core are fast neutrons, and so are very likely to collide with uranium-238; however, at their energy levels uranium-238 is fertile rather than fissile. This means that the uranium-238 transmutes to plutonium-239, which is fissile in a fast reactor, and can be used to replace the uranium-235 used to start the reaction or removed and reprocessed for use as fuel elsewhere. This method can produce more plutonium fuel than it consumes, and reactors that do so are known as "fast breeder" reactors.

INITIAL CONSIDERATIONS

GENERATIONS OF REACTOR

Nuclear reactors are typically classified by generation, for example generation I, II, III or III+. Each generation represents an evolutionary development of the previous, and as such, later generations tend to be more efficient and technologically advanced. Current reactor technology has enabled the construction of generation III+ reactors, but generation IV reactors are in development. A number of generation IV reactors are due for construction in the 2020s, with further developments in the 2030s and 2040s. Given the rapid pace of reactor development, the reactor chosen for Solent City should be a generation III+ or higher to prevent the technology it used from becoming obsolete in its operational lifespan.

TYPE OF REACTOR

As discussed above (see Basic concepts in nuclear fission), there are two main types of nuclear reactor: thermal reactors and fast reactors.

In the past, thermal reactors have been used, and hence have been developed, much more extensively than fast reactors. This was mostly because fast reactors require greater enrichment levels (3 times or more) to provide a suitable proportion of fissile atoms to start up a chain reaction, and enriching fuel to this level is considerably more expensive. Despite this, over 400 reactor-years of experience have been accumulated that can be used to develop fast reactors.

Thermal reactors typically use water (either light or heavy) as a coolant, whereas fast reactors typically use liquid metal coolants such as liquid sodium or lead because of their low neutron absorption properties. Coolants of this kind are considerably more expensive than using water, and can be highly reactive with air and water (as in the case of sodium) which can be a safety risk. They can also require additional care in terms of piping and materials they come into contact with, potentially increasing the cost of the fast reactor.

However, liquid metal coolants are much better than water at transferring heat, and because of this, the coolant circulation system in a fast reactor is capable of removing heat from a reactor even in extreme accident scenarios. Furthermore, the use of metal coolants means that the fuel in a fast reactor can consist of metal uranium rather than uranium oxides (as the metallic fuel is chemically compatible with the liquid metal coolant). The high thermal conductivity of metal fuel, combined with the use of liquid metal coolant, means that in the event of an accident, the reactor can simply shut down without exceeding temperature limits in the reactor in a meltdown scenario. This significantly enhances the safety of fast reactors.

Fast reactors run their fission reactions at a faster rate than thermal reactors, as thermal reactors contain a moderator that acts as a buffer for neutrons between the fission stages of emission and absorption. Because of this, if the reactor begins to malfunction, or the conditions in the reactor change unpredictably, the reaction can deteriorate more quickly. Consequently, a fast reactor must be supervised even more carefully than a traditional reactor, because any change could spiral out of control more quickly than normal. With modern computer systems, the reactor can theoretically be kept in a state of equilibrium through the use of negative feedback loops.

An additional safety concern is the fast reactor coolant. Whereas bubbles in the traditional coolant (water) cause a decrease in temperature, bubbles in the liquid metal coolant of a fast reactor cause an increase in temperature (due to the poorer thermal conductivity of gas relative to liquid). This can cause a positive feedback loop, where increased temperature causes increased gaseous bubbles in the coolant. This effect must be carefully controlled in a fast reactor, while it is of no concern in a traditional reactor.

The main advantage of fast reactors is their high level of efficiency. Because fast reactors can be used to breed new fuel, they can utilise a far greater proportion of the potential energy from nuclear fission (approximately 200 times more) than traditional thermal reactors. Importantly, fast reactors are also able to destroy the nuclear waste with the longest half-life, converting it to waste that decays to background radiation levels in centuries rather than hundreds of thousands of years. This ability of fast reactors is particularly attractive, because they can run on the waste of thermal reactors, thereby significantly reducing the amount of high-level waste in the UK. The UK government currently has no publicised plan for dealing with high-level waste other than storing it indefinitely, so this property makes the fast reactor a much more sustainable design than the thermal reactor.

POLITICAL AND SOCIAL IMPLICATIONS OF BUILDING DIFFERENT TYPES OF NUCLEAR REACTOR

In the next few decades, it is likely that fast reactor technology will boom, due in part to a decline in the availability of uranium, but also a need to decrease the vast stockpiles of waste radioactive plutonium around the globe (particularly in Russia and the US because of their extensive nuclear weapons programmes). Indeed, from the 6 designs being developed by an international task force aiming to design new, generation IV reactors for the coming decades, 4 utilise fast reactor technology. If the UK doesn't invest in fast reactor technology soon, it may become dependent on foreign nations to provide its energy and the disposal of its waste nuclear material. This outcome is especially undesirable, given that Russia is currently the world leader in fast reactor technology, having just built its BN-800 reactor (880 MW capacity) and with plans for further development. The creation of a fast reactor

would therefore be a valuable pilot project and would be likely to attract investment into the UK nuclear industry while broadening the UK's own depth of nuclear expertise.

Public trust in the safety of nuclear technology was dented following the Fukushima disaster of 2011. Furthermore, public support for the construction of further nuclear reactors has fallen after the spiralling costs and publicity disaster of Hinkley Point C; the project will require significant government subsidies and has been delayed by almost a decade. While these economic and safety concerns would also surround a fast reactor, a fast reactor project could realistically be presented to the public as the safe disposal of nuclear waste while simultaneously generating clean energy. Because of this, such a project would be more likely to garner public support, and hence the UK government is more likely to support the construction of a fast reactor than a traditional reactor. Despite these concerns, the public broadly still support the creation of additional nuclear reactors in principle, and so significant public opposition would not be expected if a new nuclear reactor was to be created. Therefore, we will be using a fast reactor.

FUEL TYPES

All nuclear reactors require fuel in the form of unstable transuranic elements. The decay of radionuclides is the powering force behind a nuclear reactor, and hence the fuel used must be chosen with care.

URANIUM

Uranium is the basic fuel used by (almost) all nuclear reactors. Uranium ore is a relatively common substance on Earth and can be found in varying concentrations all over the world. In 2015, there were 5,718,400 tons known to be recoverable (i.e. can be mined – see picture - for less than 130 US Dollar / kg), which will last about 90 years at the current rate of nuclear fuel usage (63,000 tU/year). It is believed that this amount is only a fraction of the amount present on Earth and that new supplies will be discovered to replenish those used. A 1000 MWe nuclear reactor only requires around 27 tonnes of fresh fuel each year - typical nuclear reactors do not operate beyond 70 years, and hence the total fuel requirement for the plant would be less than 2000 tonnes. This preliminary calculation shows that the supply of uranium can be relied upon to meet the needs of Solent City for the foreseeable future, and certainly for the life of a standard nuclear plant.

PLUTONIUM

Plutonium is an initial fuel source used by some nuclear reactors, but is progressively "bred" by most reactors as neutrons impact uranium atoms, causing them to transmute into plutonium isotopes. All plutonium isotopes undergo fission with fast neutrons, but only Pu-239 and Pu-241 undergo fission with "slow", or thermal neutrons; for this reason, fast reactors utilise plutonium much more than thermal reactors.

Only three isotopes of plutonium (out of 15) have half-lives greater than 7,000 years. As a result, plutonium does not exist naturally in the Earth's crust, and has decayed into other actinides. Plutonium is manufactured for use in a nuclear reactor through the transmutation of uranium-238 atoms. This occurs when U238 atoms capture a neutron, and then rapidly emit two electrons and two anti-neutrinos to transmute into Pu239. This is the process carried out by a fast reactor to breed plutonium fuel. The fuel can be made specially by bombarding uranium-238 with neutrons, or can be extracted from nuclear waste.

THORIUM

Thorium has been touted as a potential successor to uranium as the main fuel source of nuclear power. It is three to four times more abundant in nature than uranium, produces a lesser volume of radioactive debris when used in a nuclear reactor and has a greater energy density than uranium. Furthermore, thorium is considered a safer alternative to uranium because it has increased chemical stability and resistance to radioactivity. However, the use of the fuel is largely untested, with a few reactors in China and India (where the fuel is abundant) providing the majority of global experience using thorium. In addition, thorium fuel is harder and more expensive to prepare than uranium fuel, as the process required to prepare it utilises greater temperatures. Lastly, thorium lacks the excellent neutron economy required for many uranium reactors, especially fast reactors. For these reasons, thorium reactors are not widespread, and it would not be advisable to build a thorium based nuclear reactor for Solent City.

DECISION

Because of the reasons listed above, in particular the ability to burn long-lived radionuclides and its passive safety features, we have decided to build a fast nuclear reactor over a thermal nuclear reactor. This type of reactor has been around as long as the thermal reactor but has been historically underdeveloped. As a result, there are only a handful of functional fast reactor designs that have reached the construction stage. For fuel, the nuclear reactor will not use thorium, and will instead use a blend of uranium and plutonium (the fuel of choice for fast reactors).

EVALUATION OF REACTOR DESIGNS

There are several reactor designs under consideration today. Each has its benefits and disadvantages, while not all are commercial designs; in the past, many fast reactors have been developed to further fast reactor research in their respective countries rather than generate energy per say.

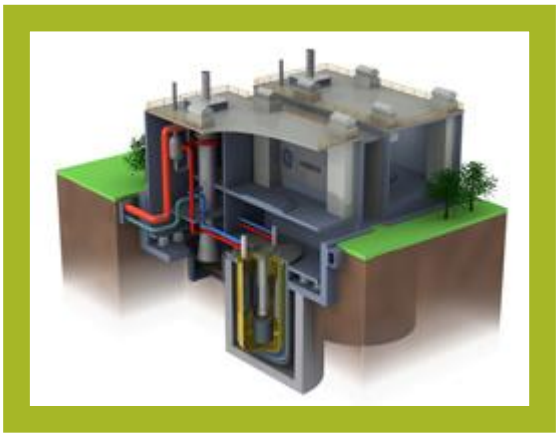
Fast reactors are typically classified by their coolant: gas, lead or sodium. To date, no gas cooled fast reactors have been built, with the main focus of international research on sodium-cooled reactors. Although lead-cooled reactors have been constructed, these are fewer in number and generally lower in capacity than sodium-cooled reactors.

Of the existing modern fast reactor designs, only a few are commercial models, with an operational capacity exceeding 600 MW. These include BN-1200 (~1200MW) and PRISM (~300MW per unit, multiple units). Other designs, such as the German Dual-Fluid Reactor and BREST-1200 are currently in development, but require significant improvements before construction begins.

BN-1200

BN-1200 is a Russian sodium-cooled fast breeder reactor design, based heavily upon the earlier BN-800 fast reactor (~800MW). The reactor will have an electric output of 1220MW, and a breeding ratio of 1.2-1.35 for mixed uranium-plutonium fuel - this means that for every kg of fuel used in the reactor, 1.2-1.35 kg of fuel are produced. The project aims to meet generation IV safety limits, and is also intended to be more economically attractive than its predecessor. The design is currently on hold while design improvements take place, with no decision to begin construction until 2019.

PRISM



PRISM (Power Reactor Innovative Small Module) is a sodium-cooled integral fast reactor design owned by GE Hitachi. The design is based on the EBR-II (Experimental Breeder Reactor) design, which operated for 30 years, but with ten times the capacity. A single PRISM module has a capacity of 311MW, while two PRISM modules combine to power a 622MW generator. This design can also be scaled upwards, for example by combining two generators to reach a capacity of 1244MW. PRISM modules are an attempt at building a generation IV reactor, with the intention of closing the nuclear fuel cycle. PRISM has multiple configurations, but when it is recycling spent nuclear fuel it has a breeding ratio less than 1, and hence consumes all of the plutonium fuel it is given without producing surplus. Despite this, PRISM can still unlock vastly more energy from uranium fuel than a thermal reactor, because most of the fertile uranium fuel is converted into fissile plutonium for consumption. PRISM is hence classed as a "fast burner" reactor rather than a "breeder" reactor.

The PRISM design has reached maturity thanks to investment from the US government and GE Hitachi, and so wouldn't need significant improvements to operate successfully. Furthermore, this option has already been considered as a credible way to dispose of waste plutonium by the UK Government, with feasibility studies having taken place and been accepted. Additionally, the PRISM design has support from the Institution of Mechanical Engineers.

DECISION

Although BN-1200 has a greater capacity than PRISM, it is an incomplete design, with significant alterations required before its deployment; it is also a Russian design, and may not be shared willingly with the UK government. In comparison, PRISM is a mature design, and has already been considered as a feasible solution to the plutonium waste issue in the UK. As both reactors aim to close the nuclear fuel cycle and look towards Generation IV safety goals, there is little else between the designs. As a result, we will build a series of four PRISM modules, with a total capacity of 1244 MW.

HOW PRISM OPERATES

OVERVIEW

The reactor core is situated in a pool of liquid sodium coolant (see diagram below). The heat from the core increases the temperature of the primary sodium through the process of nuclear fission. This hot sodium is cycled around the reactor core through the use of a pump, which pumps cold primary sodium upwards past the core. This forces the hot sodium over the edge of its container and it falls down towards the cold sodium to be pumped once more.

During this cycle, the hot primary sodium is exposed to pipes containing the secondary sodium. Heat is transferred from the primary to the secondary sodium through the heat exchanger, and the secondary sodium is pumped around to the steam generator. The steam generator utilises the thermal energy in the secondary liquid sodium to boil water and create steam. This water is pumped through the steam generator, where it turns a turbine and then condenses back into liquid water with the aid of the condenser. The rotating turbine turns a generator, which converts rotational energy into electrical energy. This generator is connected to the national grid (via a transformer), and the electrical energy generated by the nuclear power station can hence be transferred out to the national grid, and from there, to the everyday consumer of electricity.

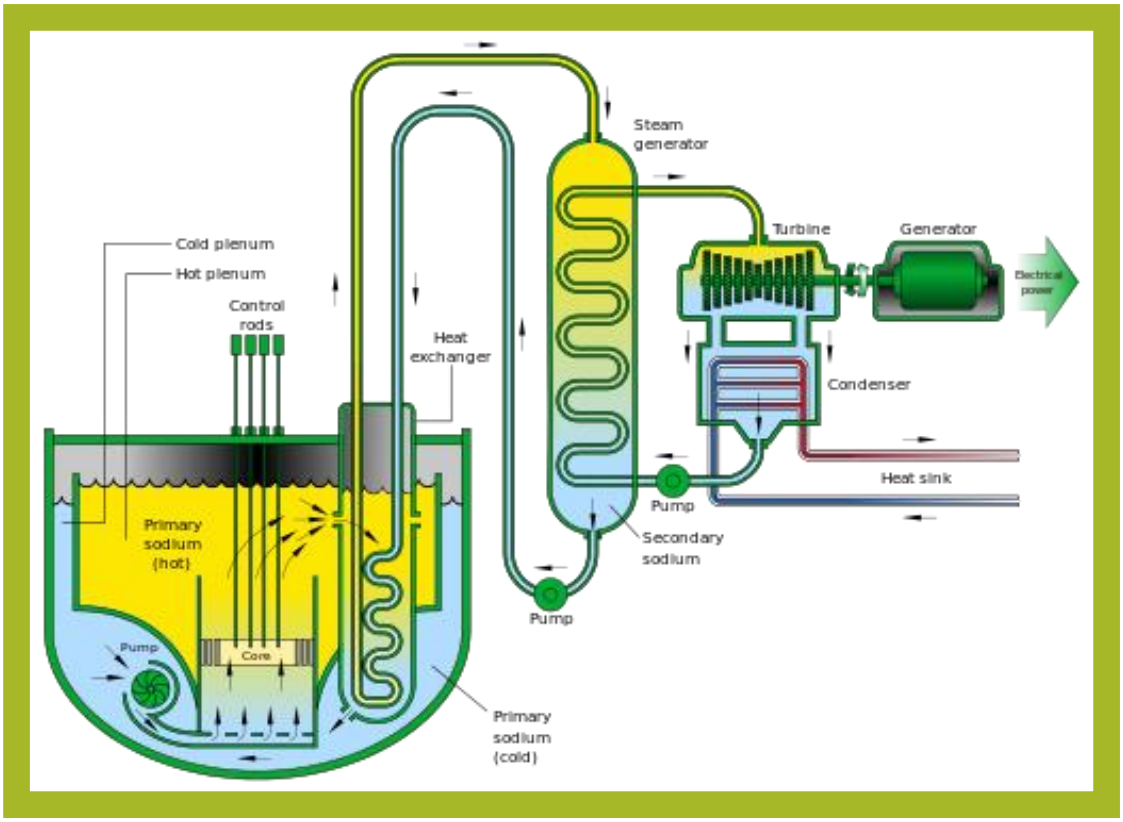


TABLE OF PARAMETERS

Overall Plant	
Electrical output	1244MW
Thermal Efficiency	37%
Number of power blocks (per plant)	2
Number of reactor modules (per plant)	4
Power block	
Number of reactor modules (per block)	2
Net electrical output	622MW
Number of steam generators	2
Steam generator type	Helical coil
Steam cycle	Superheated steam
Turbine type	3600 rpm, tandem compound, four flow
Turbine throttle conditions	14.7 MPa (2135 psia) / 452°C (846°F)
Main steam flow	2738 Mg/h (6.024×10^6 lb/h)
Feedwater temperature	216°C (420°F)
Reactor module	
Thermal power	840MW
Electrical output	311MW
Primary sodium inlet / outlet temperature	360°C (846°F) / 499°C (930°F)
Primary sodium flow rate	5.4m³/s (86,000 gpm)
Intermediate sodium inlet / outlet temperature	326°C (619°F) / 477°C (890°F)
Intermediate sodium flow rate	5.1m³/s (80,180 gpm)

FUEL

The fuel used in a PRISM reactor can depend upon its configuration; PRISM reactors can be configured to recycle waste actinides, to consume weapons grade plutonium, to breed new plutonium fuel or to breakeven (produce as much fuel as it consumes). Which configuration is used depends on the purpose of the PRISM reactor – the main practical difference between each configuration is the composition of the reactor core, i.e. the fuel rods used and its position in the core. For the purpose of Solent City, the PRISM reactor will be configured to recycle the UK's waste plutonium (which is reactor grade, and not weapons grade). In the future, when the waste plutonium has been consumed, Solent City's PRISM

reactors may be converted to the "breakeven" configuration to produce their own fuel indefinitely. However, for this section, it is assumed that the PRISM reactors in Solent City are operating to consume waste reactor grade plutonium.

FUEL TYPE

PRISM reactors require a blend of metallic uranium, plutonium and zirconium to begin, and then progressively produce plutonium fuel for use in the reactor core (although slightly less than the original amount of fuel inputted). This metallic fuel is used because it is chemically compatible with the liquid sodium. Although the metallic fuel is less capable of withstanding high temperatures than oxide fuel, this safety risk is dealt with passively, because the liquid sodium has excellent thermal conductivity, and hence temperatures cannot exceed operational limits.

The uranium in the fuel is approximately 20% uranium-235, and is hence very highly enriched. The U235 in the fuel is fissile material, and is used in the fission reaction. The remaining U238 is fertile material, and so is gradually transmuted into Pu239, a fissile material that then undergoes fission.

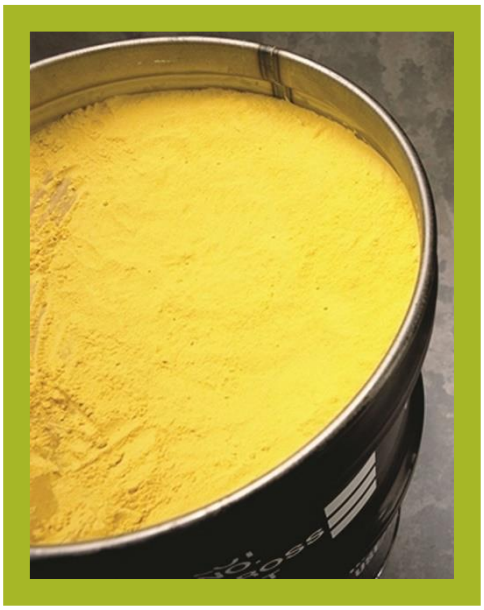
The plutonium in the fuel alloy is used as fission material for consumption. In this way, waste plutonium can be converted into less harmful nuclear waste products.

Zirconium is not a transuranic element, and so does not undergo fission in the reactor core. Instead, zirconium is included in the allow to increase the thermal conductivity of the fuel, thereby allowing more heat to transfer out of the fuel for use in the reactor. Zirconium's presence in the alloy also increases the dimensional stability of the fuel (the fuel's ability to retain its original dimensions), an important consideration in a nuclear reactor core.

FUEL PREPARATION PROCESS

URANIUM ENRICHMENT

In order to use uranium as part of the fuel in a PRISM reactor, the uranium ore taken from the ground must first go through a multi-step enrichment process. In fact, modern mines use a method called situ leaching to extract a solution of dissolved uranium, thereby avoiding producing large amounts of waste rock. This solution, once pumped to the surface, must be filtered. The uranium is then separated by ion exchange and precipitated from the solution. The precipitate is then filtered once more, and dried to make a uranium oxide concentrate known as "yellowcake".



Once the "yellowcake" (see image) has been produced, the uranium must be "enriched". This is because natural uranium is typically found with a proportion of the uranium-235 isotope at 0.72%; for a fast nuclear reactor, the uranium fuel must be highly enriched (HEU), and should have about 20% uranium-235. This process requires the uranium to be in gaseous form, so the uranium oxide (UO_2) is first converted into uranium hexafluoride (UF6) by combining it with anhydrous hydrogen fluoride and fluorine gas in a series of chemical reactions. The enrichment process then takes place, using centrifuges to separate the uranium-235 from the uranium-238 based on the small difference in weight between the two isotopes. In a centrifuge, heavier materials move tangentially towards the edge of the container, and hence the slightly heavier 238UF6 can be separated from the lighter 235UF6. However, the difference in mass between 235UF6 and 238UF6 is only 0.852%, and so the centrifuge process is repeated multiple times with thousands of vertical centrifuges to maximise the efficiency of the overall process. This process continues until the required enrichment level is reached. Although laser techniques to enrich uranium are in development, they are unlikely to reach commercial maturity in the next 10 years, and so the dominance of the gas centrifuge method looks set to continue.

Once the enriched uranium hexafluoride has been produced, it is converted to uranium tetrafluoride (UF_4) through a reaction with hydrogen gas in a vertical tube-type reactor. This UF_4 is then converted into metallic uranium through the Ames process (thermal reduction of UF_4 using magnesium or aluminium powder) for use as part of the fuel alloy.

PLUTONIUM PREPARATION

Nuclear fuel, once it has been processed by a standard LWR is composed of 96% fissionable elements. A simple electrometallurgical process can be used to retrieve these elements and separate them from the waste products. Waste plutonium that has been separated in this way currently resides in Sellafield in powder form and could be directly used as part of fuel alloy.

ZIRCONIUM PREPARATION

Zirconium is an element found naturally in the Earth's crust. It is typically found and extracted from the silicate mineral zirconium silicate. Its most important mineral form is the substance zircon, found in igneous rock and retrieved by collecting and purifying the sand produced when igneous rock erodes. From here, the zircon is purified and reduced with a spiral concentrator and a reducing agent to produce pure zirconium.

FINAL FUEL PREPARATION

In order to make the required alloy, uranium powder is downblended with plutonium powder and turned into a metal alloy with zirconium (through heating the metals). This metal alloy is then fabricated into fuel rods in a fuel fabrication facility. There are several existing fuel fabrication facilities in the UK, such as Springfield's Fuels Limited. However, it is likely that a new facility would have to be created to produce fuel rods and assemblies for the PRISM reactor.

Different reactors require varying numbers of fuel rods and assemblies. For example, a pressurized water reactor may use between 121-193 fuel assemblies, each consisting of 179-264 fuel rods, while a boiling water reactor may use 350-800 fuel assemblies per reactor with 91-96 fuel rods per assembly. A PRISM reactor module set to consume waste plutonium requires 391 fuel assemblies, resulting in an active core height of 66.0cm.

CORE CONFIGURATION

The core is configured with a number of fuel assemblies to produce the optimal amount of energy in a controlled fission reaction. Alongside the fuel rods are a series of other assemblies including reflector assemblies (which reflect stray neutrons back towards the fission reaction), control rods (see Control Rods) and ultimate shutdown cavities (see Ultimate Shutdown System). The diagram below illustrates a typical core configuration for a PRISM reactor module.

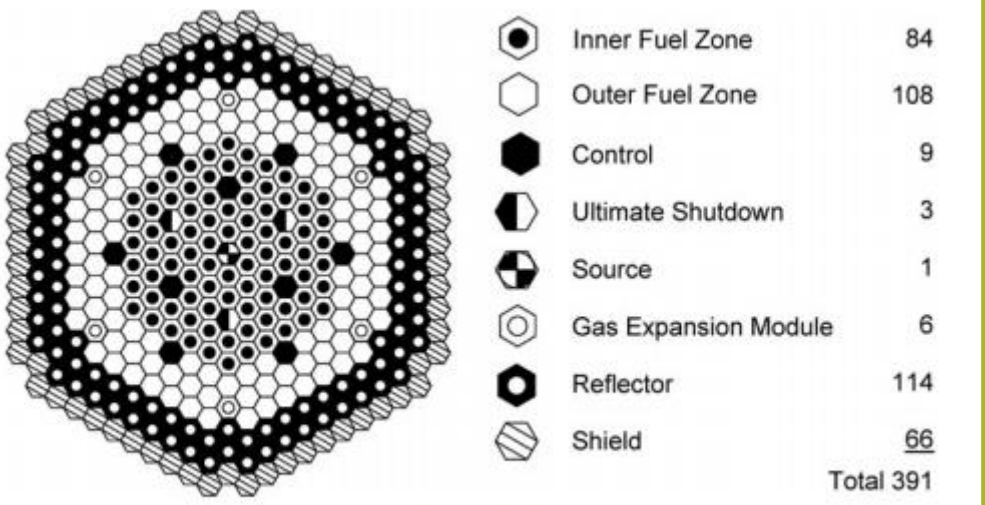


Fig. 8. Fuel assembly layout for UNF recycle core.

REACTOR REFUELLING

The fuel within a PRISM reactor core is gradually consumed, and hence becomes depleted over time. Spent must be removed and processed, and the reactor restocked with new fuel bundles every 12 months. This interval can be greater, although not when waste plutonium is being consumed in a fast burner configuration (rather than a breeder configuration).

A leak tight connection is made with the reactor core, and the reactor fuel assemblies are extracted into an ex-vessel transfer machine (EVTM). The EVTM transfers the spent fuel and assemblies in the reactor out of the reactor core and places the new assemblies and fuel into the core. The transferred fuel is then inspected and dealt with (see High-level waste).

SAFETY FEATURES

PASSIVE SAFETY

PRISM was designed in such a way that the design is intrinsically safe, because safety design features rely on the laws of physics "instead of human, electronic or mechanical intervention" (GE Hitachi). Theoretically, there should never be cause to intervene in the reactor due to safety concerns, because the reactor has a system of strong negative-feedback loops that will always keep the reactor within safety limits. For example, the incredible ability of liquid sodium to dissipate excess heat without damaging the reactor provides a form of passive safety, as it relies on the properties of matter instead of mechanical intervention. However, as safety regulations require, PRISM also features several active measures to prevent nuclear disasters.

CONTROL RODS

Control rods play a vital role in maintaining a safe nuclear reactor. They can be made of boron, cadmium, hafnium, indium or other materials that have cross sections suitable for the absorption of neutrons, as this is their function within the reactor. They absorb neutrons released during fission to prevent them from causing fission in other molecules in a chain reaction which can quickly get out of control, potentially producing a highly destructive quantity of energy. The rods can be moved in and out of the reactor core to vary the proportion of neutrons absorbed, so that the amount of power generated is easily regulated. As well as preventing a run-away chain reaction, this also allows for the amount of electricity generated to be varied according to demand during the day. The neutron spectrum of the reactor will have to be considered when choosing the elements to compose the control rods.

While they can be very expensive upfront (boron, a popular choice for control rods, can cost over 11000 USD per kilogram), control rods can last a very long time (estimates suggest as high as 30 years), provided they are protected from physical damage while in the reactor.

In the event of an emergency, the reactor core can be "SCRAMed", by inserting all control rods into the core simultaneously to shut the reactor down in under 200ms. PRISM's passive safety mechanisms make this scenario unlikely, but the control rods nonetheless act as a fail-safe to shut down the reactor in an emergency scenario.

FUEL SAFETY FEATURES

The metallic fuel used in a PRISM reactor uses the principles of passive safety to react safely to temperature changes in the core. If the fuel's temperature rises, the metallic fuel expands and decreases in density. This has the effect of slowing the fission reaction, resulting in a slowdown and the safe termination of the reactor.

ULTIMATE SHUTDOWN SYSTEM

In the event that the insertion of the control rods fails to shut down the reactor, PRISM features a unique method of stopping the reactor. The Ultimate Shutdown System consists of dropping neutron-absorbing spheres containing enriched boron-10 (in the form of boron carbide) into the reactor core. These spheres absorb the excess neutrons in the reactor to quickly cause the fission reaction to terminate.

COOLANT

The coolant of a reactor is the substance used to remove the heat that is generated from the reactor core, so that the heat can be converted into electrical energy. For a PRISM reactor, liquid sodium is used. Liquid sodium has very high thermal conductivity, and so is an excellent choice of coolant, especially given that the condition of a fast reactor can change must more rapidly than a thermal reactor. The ability to dissipate excess heat much faster than it can be produced aids the safety of a PRISM reactor.

Liquid sodium also has several other properties which make it an ideal coolant. It has a very small absorption cross-section, so doesn't absorb too many neutrons, thereby limiting the fission reaction unintentionally. It is also minimally negatively affected by high levels of radiation, which is important since it will be exposed to intense radiation while in the reactor. Sodium is liquid between the temperatures of 980C and 8820C. It can therefore be used as a coolant in a wide temperature range, mitigating the risk of it solidifying or evaporating (both potentially dangerous scenarios). Furthermore, liquid sodium is not prohibitively expensive, so can be used in a commercial reactor.

However, liquid sodium is not without its disadvantages. Liquid sodium is highly reactive with water and air, which can make it a dangerous substance to work with. Oxygen impurities in liquid sodium as low as several parts per million can result in sodium exhibiting corrosive properties. Container materials must therefore be chosen with care, to prevent potentially damaging coolant leaks. The first fast reactors suffered greatly from this issue, with regular leaks and even sodium fires during their operational lifespan. PRISM mitigates this risk through the use of a sodium leak detection system that warns of sodium-to-air leaks, and the use of stainless steel pipes that are resistant to corrosion.

CONTAINMENT BUILDING

A nuclear reactor must be built to the highest safety specifications to prevent a meltdown similar to the Chernobyl or Fukushima disasters. In order to prevent the release of radioactive material into the surrounding area, a reactor will employ a "defence in depth" strategy, consisting of a number of layered barriers to radioactive release. In the event that radioactive material escapes the fuel cladding and the primary coolant boundary, the containment building acts as the final barrier to radioactive release.

Such a structure must be able to withstand extreme temperature, pressure and radiation in order to contain a nuclear meltdown. A typical containment building must be able to contain highly pressurised radioactive gas, and so must be able to withstand a maximum pressure in the range of 275 to 550 kPa (2.7 to 5.4 atmospheres of pressure). PRISM's containment unit is constructed from stainless steel, and completely surrounds the entire reactor vessel. It is designed to be completely leak-proof and is large enough to contain all of the primary sodium, keeping the core, stored spent fuel and heat exchanger covered in coolant.

REACTOR VESSEL AUXILIARY COOLING SYSTEM

The reactor vessel auxiliary cooling system provides ultimate passive, and inherently safe, cooling of the reactor. It is always "on" because it utilizes natural circulation of sodium coolant that constantly removes a small amount of heat (<0.5 MWth) from the reactor modules. For decay heat removal, natural circulation of primary sodium coolant carries heat from the core to the reactor vessel. As containment vessel temperature increases, heat transfer to the atmospheric air increases, thus averting dangerous temperature rises.

OTHER KEY COMPONENTS

STEAM GENERATOR

The function of the steam generator is to use the heat provided by the secondary liquid sodium to generate superheated steam. Each individual reactor will have its own associated steam generator system (SGS). The SGS is vertically oriented, and consists mainly of a helical coil, as well as pumps and isolation valves. Two SGSs are connected together in a single power block to feed a 622MW turbine-generator.

PUMPS

In order to keep the primary and secondary coolant loops moving, PRISM has several submerged electromagnetic (EM) pumps that move the liquid sodium. These pumps have no moving parts, because they utilise the magnetic properties of sodium and create a magnetic field at a right angle to the intended direction of movement. When an electric current is passed through the pump, the liquid is moved by the pump.

The lack of moving parts increases the robustness of the pumps, ensuring that pumps do not break (which would be problematic, as their positioning makes them difficult to reach to fix).

HEAT EXCHANGER

The heat exchanger in a PRISM module has the purpose of transferring heat between the primary and secondary coolant loops, which are separated by a solid pipe. This is achieved by maximising the surface area of the heat exchanger, so that more heat is conducted from the primary sodium to the secondary sodium.

WASTE STORAGE AND DISPOSAL

A nuclear fission plant produces radioactive waste. This waste is usually classified into three distinct classes in terms of its radioactivity and radioactive life: high-level waste (HLW), intermediate-level waste (ILW) and low-level waste (LLW).

HIGH-LEVEL WASTE

High-level waste is found in the reactor core itself and consists mostly of spent fuel rods. As a result, it is usually in liquid form when removed from the reactor. A liquid form is not desirable, however, because liquids take up a larger volume than solids and space for nuclear waste disposal is at a premium. Furthermore, the final form of the waste should have low solubility, to reduce the risk of waste contaminating groundwater in the future.

A process called vitrification is used to treat the HLW, so that the liquid waste becomes an amorphous borosilicate, to store the waste safely. This process generates a molten product by heating the HLW and mixing it with crushed glass; this product can be put into a container until the waste has cooled and decreased in radioactivity. These containers hold approximately 150 litres of waste, and can be made of a variety of materials, but austenitic stainless steel is the current UK choice. HLW is transported to the Sellafield site in Cumbria for vitrification and storage, where it is stored for 50 years in underwater tanks until it has its radioactivity has decreased. Currently, HLW is stored indefinitely at Sellafield.

INTERMEDIATE LEVEL WASTE

Intermediate level waste (ILW) is typically produced in the form of contaminated materials from around the reactor, including metal fuel cladding and resins. This waste emits less radiation that HLW, and as such, the heat it generates is not significant enough to warrant special design requirements to contain it. However, ILW is radioactive enough to require some shielding

LOW LEVEL WASTE

Low level waste (LLW) comprises 90% of the volume of nuclear waste, but only 1% of the radioactivity. It typically is created when low level contamination of objects such as filters, paper or clothes takes place. It has sufficiently low radioactivity that it does not require shielding to handle it. LLW is often compacted or incinerated to reduce its volume before disposal.

FINAL STAGES IN DEALING WITH WASTE

LLW and short lived ILW can be disposed of in a land-based disposal site, as its radioactivity is low enough to be non-harmful. In the UK, this takes place in the LLW Repository at Drigg in Cumbria. This site is operated by UK Nuclear Waste Management on behalf of the

Nuclear Decommissioning Authority, and would be able to contain any LLW or short lived ILW produced by a PRISM reactor.

For longer lived ILW and HLW, land-based disposal is not a viable option, because although this waste is much smaller in volume (< 10% of all nuclear waste), it contains radionuclides with long half-lives and high-radioactivity. The international consensus is that geological disposal is the best method of dealing with this waste, and the UK government's long-term plan follows this advice. Geological disposal consists of sealing containers of nuclear permanently underground where the radioactivity of the containers can decrease to safe levels over millennia.

PRISM aids the disposal of HLW, because it uses existing HLW as fuel and the final waste products taken from a PRISM reactor are smaller in volume and half-life than the input waste. Because of this, PRISM will actively reduce the volume of HLW in the UK, and as such, does not require additional measures to deal with any HLW waste it produces.

ELECTRICITY PRODUCTION AND DISTRIBUTION

A nuclear reactor core and its associated safety features maintains a fission reaction that produces heat and boils water to turn a turbine. However, the rotational motion of the turbine must be converted into electricity, and distributed across Solent City for the reactor core to have a useful purpose. This is achieved with a number of components:

GENERATORS

A generator's function is to convert mechanical energy into electrical energy. A generator found in a power station will convert the rotational energy of a turbine into AC electricity to be distributed via the national grid.

Generators operate using the principle of electromagnetic induction, where an electromotive force (emf) is induced in an electric circuit by moving a magnetic field around it. In practice, the magnetic field is moved by rotating either a magnet in a coil of wire, or a coil of wire in a magnet. The magnitude of the emf produced can be increased in a number of ways:

- Increasing the strength of the magnet.
- Increasing the frequency of rotation of the magnet/coil.
- Increasing the number of coils in the wire.

In accordance with these considerations, the generator used in a power station will utilise a very strong magnet with many coils in its associated wire. The high currents generated in a power station mean that it is more advantageous to fix the coil of wire and rotate the associated magnet relative to the coil.

Most large generators do not use a permanent magnet, but a field coil, which is a coil of wire wrapped around an iron core that acts as an electromagnet. However, a field coil can only act as an electromagnet when supplied with a constant electric current.

Hence, in order for the generator to function, the field coil must be supplied with electric energy. This is not an issue when the generator is running, as a small portion of the electricity generated can be diverted for this purpose. However, when starting the generator, a component called an "exciter" must be used to generate a small electric current in the field coil.

Most modern generators use a technique called "self-excitation" to achieve this. This technique works by utilising the residual magnetism in the iron core of the field coil. The generator is started without a connected load (so that no power is drained from the system), and so the initial weak magnetic field in the field coil's iron core induces a weak voltage in the coil of wire. This voltage then increases the current in the field coil (by electromagnetic induction) and vice versa until the generator is at its required voltage. If

the residual magnetism of the field coil's iron core is insufficient, a process called "field flashing" can be used to kick-start the generator; this process uses an alternative source to inject current into the field coil such as a battery.

A generator in a nuclear power station must be synchronised with the national grid, to prevent catastrophic damage to the generator. In order to do this, the electricity produced must have the same frequency, voltage and phase as mains electricity in the UK. Because of this, a generator will must generate an alternating current with a frequency of 50 Hz, and produce 3-phase electric power (where three independent circuits produce electricity at a 120-degree phase difference). Furthermore, the voltage of electricity produced must be either 275 kV or 400 kV (depending on the location of the power station in the UK). Although the generator itself produces electricity at a voltage of 20-22 V, this electricity will be transformed to a higher voltage that matches the national grid at a later stage (through the use of a transformer).

TRANSFORMERS

The electricity generated by a generator is a different voltage to the electricity transmitted by the National Grid, which is different again to the voltage of electricity used in domestic properties. These changes in voltage are facilitated by transformers, the devices used to change the voltage of electricity.

A transformer uses properties of electricity to alter its voltage. When an alternating current flows through a wire, it generates a fluctuating magnetic field around it. Similarly, when a wire is placed in a fluctuating magnetic field, it experiences an alternating current. These properties can be used to transmit electricity across empty space.

A transformer changes the voltage of electricity by transmitting the electricity between two coils of wire, both wrapped around an iron core. In order to increase, or "step-up", the voltage, the secondary wire has more coils than the primary wire - this results in an increased voltage as more electrons experience the force of the electric field between the two wires. In order to reduce, or "step-down", the voltage, the opposite is true.

Transformers in a power station have relatively high efficiency; despite this, they generate large quantities of excess heat, and therefore require intensive cooling.

POWER LINES

Power lines are rated by their voltage, with the largest power lines (275 kV and 400 kV) owned by the National Grid. Many smaller power lines of varying voltage ratings connect to almost every house in the UK, allowing power to be drawn by consumers across the country. Power lines generate magnetic and electric fields because they carry high-voltage electricity; as a result of this, larger power lines must be located away from human

population to prevent dangers such as electrocution, while all power lines are shielded by plastic coverings.

Power lines are not 100% efficient at transmitting power; some energy is lost in the form of heat. This is because the current of electrons in the wires used to transmit power frequently collide with the metal ions in the wire; the kinetic energy of these collisions is converted into heat energy, which escapes the wire as infrared radiation. However, the energy loss from this process is dependent on the current of electricity in the wire - a greater current results in an increased flow of electrons and hence more energy loss. Because of this, power lines are rated at extremely low currents and extremely high voltages to minimise energy loss.

Modern day systems implement a "smart grid" that optimises the power output by directing power resources to where they are needed and increasing power output at peak times to meet demand. These systems can be run using custom-written algorithms to minimise the energy loss from the grid, and to maximise the production of energy when it is needed most.

Such optimisation schemes can involve the storage of power for use at a later date. For example, pumped storage reservoirs such as Dinorwig Power Station, Wales, can store energy by pumping water from a lower level to a higher level, and can release this energy when required. A "smart grid" will optimise the use of such facilities, so that when power demand is low, baseload power generation (energy from power stations that run continuously) is stored, and when power demand is high, this energy is released and converted into extra power for the national grid. This optimisation will all be carried out autonomously using devices such as electricity meters and digital software.

COSTING

CAPITAL COST OF BUILDING THE PLANT

The cost of nuclear power plants has risen sharply in the last decade, from an estimated average of $2 billion - $4 billion to a high of $9 billion. This is especially significant for the economics of nuclear power, as the capital costs of a nuclear power station (including accrued interest from loans) is estimated at 65-85% of the total cost. The majority of this cost comes from engineering, procurement and construction costs (80%), while a lesser cost is attributed to "various contingencies" and owners' costs required to make the project commercially successful.

Current estimates are mostly based on thermal reactors, and so could be unrepresentative of the PRISM reactor that will be built. However, cost estimates of nuclear plants that haven't been built are very difficult to calculate, and can be dictated by social forces that cannot be accounted for (delays in construction etc). Since PRISM has a broadly similar design to existing thermal reactors (and may even be cheaper due to reduced pumps and coolant loops), it will be assumed that PRISM is a thermal reactor for the basis of this cost estimate.

There have been extensive studies into the cost of nuclear reactors over the last few decades, and many conclude that the cost of building new reactors are chronically underestimated. This may not be particularly surprising, however, given that each day of delay can cost the project as much as $1.2 million. There are many economic risks involved in the construction of a nuclear power station, which would be subject to a review before construction.

The IEA-NEA Nuclear Energy Roadmap 2015 estimates the EU's average overnight costs* for building a nuclear reactor at $5,500/kW. This is not dissimilar to Synapse Energy Ltd.'s estimate of $5,500/kW to $8,100/kW, and also tallies with overnight cost estimations of $4896/kW to $5067/kW for a European reactor by OECD-NEA & IEA.

These estimations can be used to estimate the overnight cost of building a nuclear reactor of a given capacity. As the UK has limited experience with nuclear reactor technology in comparison to other countries included in the report (i.e. France & South Korea), and PRISM reactors have not been constructed before, a conservative figure of $6000/kW, or £4280/kW, will be used.

Given that Solent City's PRISM reactor will have a capacity of 1244 MWe, it can be calculated that the estimated overnight cost of building the reactor will be £5.32 billion.

Analysis by researchers at Imperial University suggests that the increase in cost due to loans and financial delays will be around 11%; factoring this in calculations gives an estimated cost of **£5.91 billion** for the PRISM reactor.

The cost of building a PRISM reactor for Solent City is likely to be reduced somewhat by the modular design of the reactor. Because the reactor consists of 4 near-identical reactor modules, both design and implementation costs will be lower than otherwise. However, it is difficult to ascertain a figure for the impact of this effect, because very few modular reactors have been built in the past.

**When dealing with large projects such as building a nuclear power plant, the project tends to take many years to complete, during which currency fluctuations affect total cost of the project. In order to standardise costs relative to a particular currency rate, an "overnight" cost is used, as if the plant was built overnight.*

OPERATING COSTS

THE COST OF FUEL

The cost of uranium can be hard to predict, because it can fluctuate dramatically and has done so particularly over the last 12 years. For example, in 2007 the price rose to a maximum of 140 US Dollars per lb, but then dropped to a level of roughly 40 USD/lb over the next few years. This can make estimating the cost of maintaining a nuclear reactor inaccurate, as the cost of uranium can be up to a third of the cost of the total nuclear fuel cycle. There are a number of models that have been used to make predictions about future prices, with varying degrees of success; the model with the highest degree of accuracy, according to a report from August 2017, has been an ARIMA (Autoregressive Integrated Moving Average) model which had a margin of error of 5.4% in predicting the uranium price for 2015.

However, it is unknown how accurate and reliable this model will be with a great deal of extrapolation - the price of uranium is heavily dependent on the demand in the energy industry, and this is very difficult to predict over long periods of time. It is likely that as the supply of uranium decreases, the cost of uranium will increase leading to a general trend towards higher prices, especially given that more nuclear reactors are scheduled for construction over the coming decades to meet the ever-increasing global demand for energy.

Ultimately, because the fuel costs due to uranium are insignificant in comparison to the capital costs of building a nuclear reactor, and because the price of uranium is subject to large fluctuations due to unpredictable events such as the Fukushima disaster, the estimates of cost are not overly important. Because of this, the cost of fuel will not be

considered individually, and instead will be considered as part of the overall operating costs.

TOTAL OPERATING COSTS

The operating costs for a power station come under two main categories: fixed cost and variable cost. Fixed cost includes costs such as waste management and operating coolant systems, while variable costs include factors such as fuel and energy usage. According to the Nuclear Energy Institute, fixed costs were at an average of $11.8/MWh, while variable costs for a nuclear reactor were at $7.9/MWh. This gives a total of $19.7/MWh for the operating costs, which is £14.09/MWh.

To produce the estimated 10.9 TWh per year (365 days x 24 hours x 1244 MW capacity) will cost **£153.6 million / year**.

COST-EFFECTIVENESS AND FUNDING

Recent nuclear power stations such as Hinkley Point C have required significant government subsidies in order to make them commercially viable. PRISM is likely to require some government aid, although on a lesser scale than Hinkley Point C.

Over its operational lifespan of 60 years, the PRISM reactor is estimated to produce 10.9 TWh of electrical energy per year; this means that over its lifespan it will produce 653.8 TWh of electrical energy. In order to break even as a commercial venture, PRISM will need to earn back its capital costs and offset its operating costs. Its operating costs for generating 653.8 TWh at £14.09/MWh would add £9.21 billion to the capital cost of £5.91 billion, giving a total cost of £15.12 billion for the plant over its 60-year lifespan.

In order to earn back £15.12 billion, this electricity should be sold at *£15.12 billion /6538ooooooookWh*, or 2.3p/kWh. This is lower that the market value for electricity in the UK of ~2.8p/kWh, so the project should not require additional government support (beyond the regulatory and waste-management support already provided).

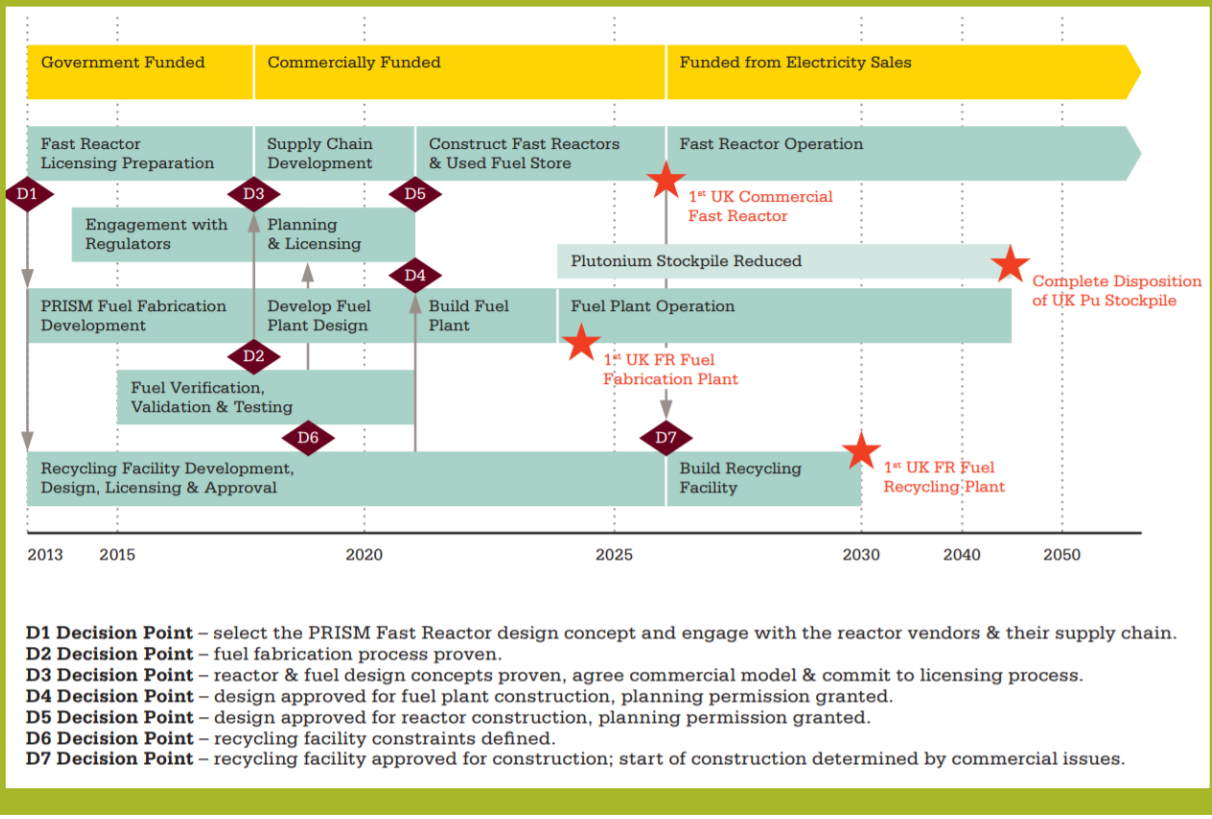
Because the PRISM reactor is predicted to be cost-effective, and to eventually make a profit, the project will be funded mostly by the government. This will allow any profits to be reinvested into Solent City's transport systems. After the reactor is built, its continued operation will be funded by electricity sales.

If PRISM sold electricity at 2.8p/kWh for its entire lifespan, it would earn **£18.31 billion** in electricity sales, and so make a profit of **£3.19 billion**.

IMPLEMENTATION SCHEDULE

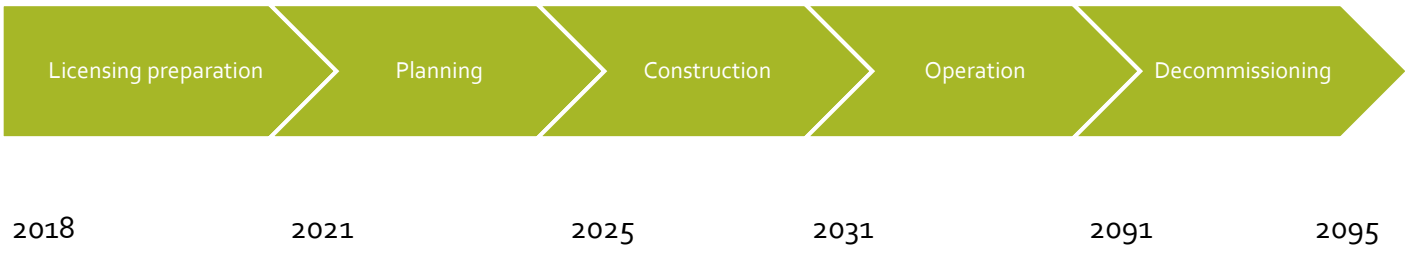
When implementing the construction of the PRISM nuclear power station, we will follow the guidelines set out by the Institution of Mechanical Engineers.

These guidelines include the construction of a recycling facility to facilitate the recycling and ultimate consumption of plutonium waste, as well as the funding sources at different points.



D1 Decision Point – select the PRISM Fast Reactor design concept and engage with the reactor vendors & their supply chain.
D2 Decision Point – fuel fabrication process proven.
D3 Decision Point – reactor & fuel design concepts proven, agree commercial model & commit to licensing process.
D4 Decision Point – design approved for fuel plant construction, planning permission granted.
D5 Decision Point – design approved for reactor construction, planning permission granted.
D6 Decision Point – recycling facility constraints defined.
D7 Decision Point – recycling facility approved for construction; start of construction determined by commercial issues.

However, this implementation schedule is designed for a PRISM reactor of half the capacity of Solent City's planned reactor (622MWe). It also dates from 2013, and so will need to be updated to be accurate for this project. The UK government estimates a nuclear project of this size will take 5 years to plan and 6 years to construct. Given that a majority of the design planning has already taken place, we have altered this ratio to 4 years planning to 6 years constructing. As a result, our implementation schedule will be as follows:

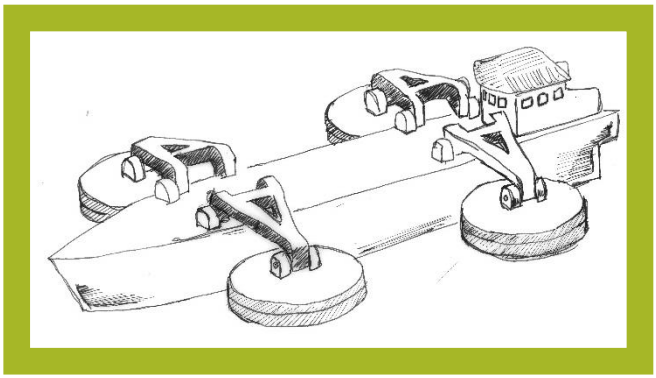


MOBILE WAVE CRAWLERS

INTRODUCTION

Mobile Wave Crawlers are a proposed way of harnessing wave energy. They operate using buoys attached to hinged arms, which are attached to generators on the side of a 50m-long boat. The boats have a wave detector system, which allow the distance between the buoys and the boat to be changed depending on the direction of the wave. This means that they will be able to harness more energy than some other methods of water power that are stationary. The estimated cost of these boats is 11 pence per kWh, which is much better than similar offshore stations that suffer from a lack of mobility and costly underwater pipes.

These boats won't be used to produce all, or even a large proportion of the power for Solent City. This is because the sheer number of boats required to produce this much power would disrupt fishing, marine life and the coastal economy. Instead, they will be used to supplement our main energy source by producing on-demand electricity that can be added to the grid whenever it is necessary. They will also act as an emergency energy source, as they can produce 20% of the total energy requirement, should our main energy systems fail. The boats can be towed out by bigger ships and left for 20 hours to gain enough energy to supply their 20MWh batteries. They will then be towed back inland and drop off their charged batteries, before heading back out to sea with new, drained batteries.



BENEFITS OF MOBILE WAVE CRAWLERS

Wave power is a clean and renewable source of energy. After the construction of the system to harness the energy, the generation of electricity is essentially free and does not require the burning of fossil fuels. The maintenance of these devices is also fairly cheap, so wave power seems to be a very cost-effective and environmentally-friendly system of generating electricity.

However, there are also a number of issues with traditional wave power stations. The transference of electricity from the station out at sea back to the land can pose a huge

problem that has been tackled until now with highly expensive undersea cables that can damage the delicate balance of our aquatic ecosystem and cost over 500000 USD. This is clearly not an efficient solution, since it significantly reduces the environmental and monetary benefits of this energy source. Also, there can be a high risk of damage in extreme weather conditions, which have certainly been known to occur in the areas of sea surrounding the Solent area.

These issues can be negated via our proposed method: we are going to use special boats as our stations instead of fixed structures. This change means that the need for costly undersea cables can be completely eliminated, since the energy generated is stored in batteries that can be brought back to land and added to the grid when needed (i.e. times of high demand such as midday). Furthermore, if there are rough weather conditions out at sea the boats can be brought back in to keep them safe from erosion so they can last longer and don't have to be quite as sturdy as normal wave power stations, which reduces the cost of constructing and maintaining them.

SHIP CONSTRUCTION

It is possible to convert old boats into mobile wave stations, rather than making them from scratch, to save on construction costs. This method would find a good use for boats that would potentially otherwise be burned because of difficulties inherent in separating the plastic from the fibreglass in modern boat materials. However, this would likely mean that the boats produced wouldn't be as durable as newer ones, which is a major concern since they are intended to produce our emergency supply of energy.

In addition, the Mobile Wave Crawlers are significantly larger than the average boat. This is because of the size of the batteries that have to be aboard the boat to make it worth the time and money invested in it. Furthermore, there have been developments in separating fibreglass from plastic in recent years, so it will soon become easier to recycle materials used in end-of-life boats. The cost of a second-hand boat would also be very high, as it would have to be converted from its original use. This could make it more expensive in the long run, especially considering that the second-hand boats wouldn't last as long as new boats and wouldn't be as durable. This would be especially dangerous, as we are using these boats as an emergency power supply in the event of a power outage; for this reason, second-hand boats will not be used.

PROTOTYPING

In order to prove that this concept will work as a functional source of wave energy, we created a prototype model:

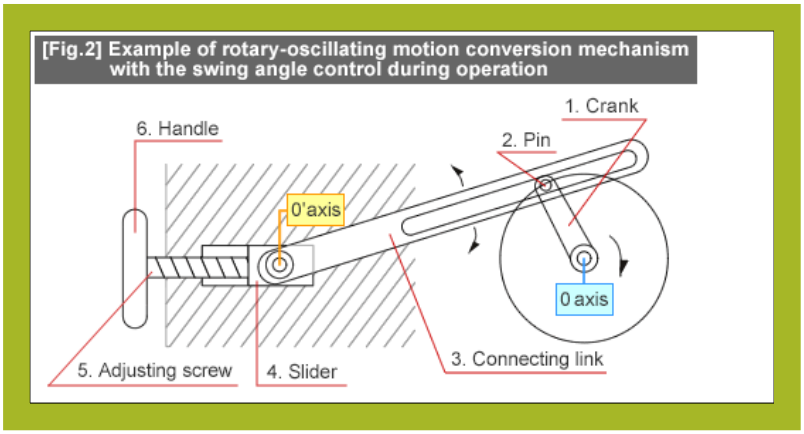
The prototype operated with a float on the end of a wooden arm that rose when waves broke against it. The rising and falling action of the arm caused a gear to be spun by the curved edge of the arm. This gear was attached to a dynamo, which would then turn and generate a voltage and current (albeit a small current).

This prototype has therefore shown that Mobile Wave Crawlers would be a working method of harvesting energy from waves.

ENERGY PRODUCTION

The boats would each be fitted with six generators, connected to pivoting float arms. Each float arm would have a buoy on the end that could be lowered into the water.

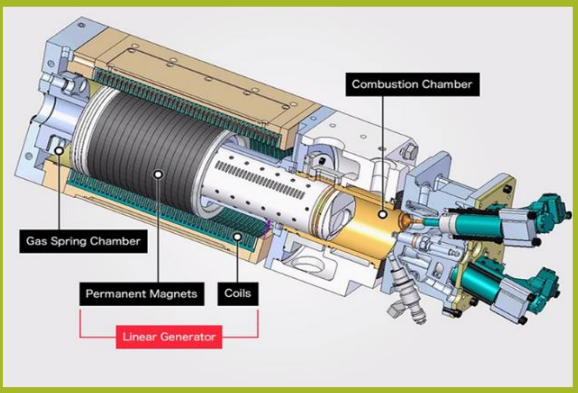
When the boat is in the right location, the buoys are lowered into the water and, as waves pass by the boat and the buoys are moved up and down, the generation of electricity begins.



There are two proposed methods for using this design to generate electricity:

METHOD 1 - LINEAR MOTION

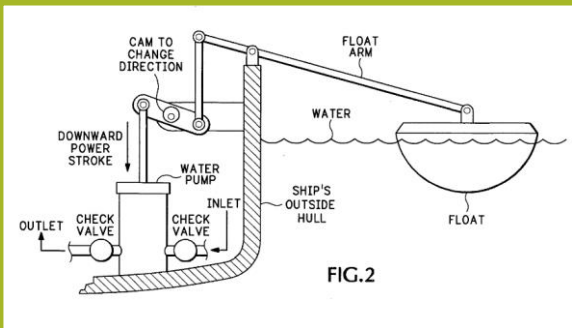
This first method is perhaps more direct: the movement of the buoys causes the arms to swing up and down (oscillating), then the movement is changed from oscillatory to reciprocating, so that the system can drive linear electromagnetic generators inside the boat.



Linear electromagnetic generators work in a slightly different way to standard generators (see Generators for more details). The majority of generators use rotary motion to move a magnet through a coil to induce a potential difference in the wire and therefore generate electricity; linear generators accomplish the same thing, but use a linear or reciprocating motion instead of a rotary one

METHOD 2 – HYDRAULIC PISTONS

Another possible mechanism is using hydraulic pistons to generate high pressure in a hydraulic fluid, which would be sent to drive a hydraulic motor connected to a generator. Once again, a cam, crank or some other mechanism would have to be used to convert the oscillations of the float arm to a reciprocating motion to be usable.



DECISION

We have decided to use the first method of generation (reciprocating motion driving a linear electromagnetic generator), since it does not require hydraulic fluid. We will therefore need six linear electromagnetic generators, six float arms, six buoys and six cams to build each one of our boats into mobile wave stations.

OPTIMISATION OF POWER OUTPUT

The boat maximises the power it can generate by using a wave detector system to adjust the position of the boat to match the highest wave amplitudes.

ENERGY STORAGE

The electricity generated by the Mobile Wave Crawlers will be stored in batteries to be brought back to the shore, so the power can be added to the grid.

The Mobile Wave Crawlers being used for backup power will not be connected directly to the power grid, as a result a means of transporting the power generated is required. The general idea discerned was to have oversized batteries on-board the boats which can then be removed, replaced and the batteries transported to places which will require emergency power in the event of a power failure.

The inspiration for this idea came from the Tesla Powerwall, which is essentially a battery built into a person's home; It is used to store the energy from a household generator for later use.

However, Tesla's design is not a design that can be removed and transported as required. As such we have made modifications to the design to allow for the movement of the batteries, as well as to allow them to store the amount of power generated by the boats.

COMPONENTS

The Tesla Powerwall batteries are lithium-ion which allows them to be rechargeable and have a high energy density. They also have a low rate of self-discharge, which means that the batteries can be stored until they are needed without them losing a large proportion of the stored charge. For these reasons, we have decided to use lithium-ion technology in our batteries.

Due to the delicacy of some of the components of the batteries it will require temperature regulation while in use to prevent under/overheating and the resulting damage that comes from it. As the batteries will be onboard a boat they will need a method of cooling/heating that will last 20 hours without a need to be connected to an external source on land. As a result of these requirements, water-cooling technology will be used to ensure the battery doesn't under/overheat while in use. This will involve an internal liquid cooling and heating system and would allow for efficient temperature control within the battery. A dual coolant and refrigerant loop system would help ensure continued performance despite the conditions it may experience in the changing seasons.

SPECIFICATIONS

The boats themselves generate approximately 20 MWh over 20 hours before returning to transfer energy to the grid when it is needed. As a result, the batteries will need to be much bigger than the specifications for the Powerwall 2 as it is only capable of storing 13.5 kWh. The Powerwall 2 measures 1.12m x 0.74m x 0.14m weighing 119.9KG. Because of this, the

batteries in the Mobile Wave Crawlers will be more similar to the Powerpack 2 specifications, which is capable of storing 200 kWh (2.185 m × 0.822 m × 1.308 m at 1,622 kg).

To hold 20 MWh, the Powerpack 2 would need to be 100x larger. Therefore, each dimension would be scaled by $3\sqrt{100}$ (≈4.64) resulting in the new specification being approximately 4.6X (4.641588834…) bigger in each direction resulting in the following dimensions: 1005.1 cm x 378.12 cm x 601.68 cm (approx. 10m x 4m x 6m). This scale-up would also result in a battery with 100 times greater mass.

The battery we use will need to fit in the boats without causing instability, and so will need to relatively small in the vertical direction. The exact dimensions of the battery can be modified and changed, provided the components are kept the same and the same volume is retained (approx. 240 m^3). As a result, using a power storage unit with the following specification would still deliver the required storage capacity:

Storage capacity (MWh)	Power (MW)	Mass (tonnes)	Dimensions (HxWxD m)
20	1	162.2	3 x 5 x 16

The boat itself will likely be a feeder class vessel with a length of 50m. A vehicle of this class can, on average, carry a mass of 2000 tonnes. A mass of 162.2 tonnes is therefore a viable mass, even with the additional equipment required for the power generation.

DISTRIBUTION

The large size of the batteries means that they will not be very mobile. Because of this limited mobility, the boats, once they are docked, will have to distribute the batteries' power into sub-storage units which can be taken by lorry to the desired location. This is as much a legal as a physical constraint, as a 162.2 tonne piece of equipment will not be able to be carried by even the largest lorries, nor will this action be legal due to regulations on the maximum load of lorries.

We would need enough sub-units to store 20 MWh of energy, and these sub-units together would comprise a whole battery. This system would also allow the batteries to be lifted from the boats more easily. The sub-storage units that make up a whole 20 MWh battery will also have to be provided and will have the following specifications:

Storage capacity (MWh)	Power (MW)	Mass (tonnes)	Dimensions (HxWxD cm):
5	1	40.55	300.84 x 189.06 x 1005.1

Once the power has been distributed by the boat it can return to the water or be taken in for maintenance as necessary. The lorries would then be able to drive the locations which

would require this power for their emergency back-up, there it can be stored ready for use if the time comes.

LOCATIONS

There are already a number of ports in the area, including ones that support large boats of the size needed (and significantly greater). Since the arms with the buoys are upright when not in use, the boat shouldn't be wider than a standard boat of that size; hence, width shouldn't be an issue when considering docking.

We would negotiate with cargo ships in the area to tow the boats out into a suitable location, and then back when the battery is fully charged, whenever possible. However, we will work with the worst-case scenario that this is never possible when considering our estimates for the amount of electricity that will be required to move the boat to and from its location in the English Channel.

NUMBERS OF BOATS AND BATTERIES REQUIRED

These boats are intended to act as a secondary power generation method to supplement our nuclear power station by providing on-demand energy that can be added to the grid whenever necessary. This system will also act as a backup plan for supplying roughly 20% of Solent City's energy in case of a major failure that disrupts our main energy systems. The system will be implemented by sending out the boats with batteries to charge them, then swap them for drained batteries once the initial batteries are completely charged and returned.

To cover the 20% emergency backup power, we will require 20 boats and 40 batteries, since each boat generates 20 MWH over 20 hours before returning and offloading the battery. As soon as the battery has been offloaded, a new battery is installed into the boat and it is sent back out to sea to be recharged. The energy in the offloaded battery can then be transferred to the national grid when needed, or into secondary batteries that can be distributed to emergency services to cover their backup electricity supply.

CONSTRUCTION/COST OF EACH ASPECT

THE BOAT

Normal boats of this size tend to cost somewhere in the region of 8-24 million USD. Despite the fact that these boats are often intended for a great number of people to spend days, months or even years in, so include appliances and features that would not be required for our Mobile Wave Crawlers, the price would be roughly the same, so we will use an estimate of 16 million USD, or roughly £11.5 million. We would be able to buy a boat ready-made and then convert it to fit our specifications, but it is likely to be easier, and potentially cheaper in the long run, to commission them from scratch. The boats would last for the foreseeable future, provided they were adequately maintained. The total cost of basic boat manufacture would be £230 million.

THE FLOAT ARMS

Since our boats can be brought back to the marina if the weather is rough, the six float arms needed for each boat don't have to be as resistant to erosion as a traditional wave power station, but the water can still wear away at the vessel during normal operation, so this will still need to be considered when choosing our materials. Another factor to consider is weight, because the lighter the boat the less of its electricity it will have to expend when travelling. The float arms will therefore be made from plastic reinforced with fibreglass, because it is strong and durable while still being reasonably lightweight. We would buy six beams for each boat. The cost of the materials themselves would be relatively low; fibreglass costs less than £100 / m^2. Because of this, the cost of the beams will be insignificant in comparison to the battery and boat costs and will not be considered in detail.

THE BUOYS

It is difficult to estimate the buoy size we will require; however, the six buoys for each boat are unlikely to incur considerable costs, given that they are essentially large floatation devices with no moving parts.

THE MOTION CONVERSION MECHANISMS AND GENERATORS

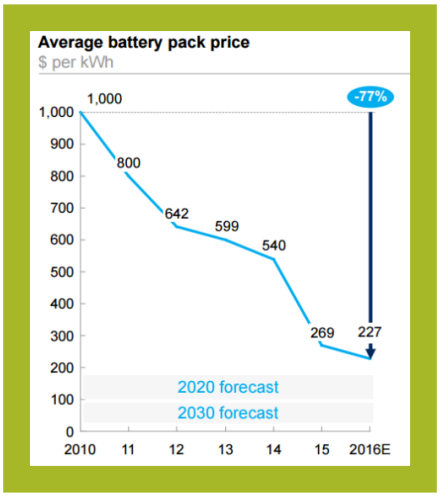
To convert the oscillations of the float arms to a linear/reciprocating motion in order to drive the generator, we will need six cam or crank systems on each boat. As with the buoys, the cost of such a mechanism is likely to be low based on our analysis of smaller scale versions.

Since the batteries require 1MW in total, and there are six generators contributing to each battery, each generator will need to be approximately 166kW. Generators with this wattage can be bought for about $40,000 individually, so one boat can be equipped for

£240,000, meaning that in total £4.8 million will need to be spent on the 120 generators needed for all 20 boats. Of course, this may not be accurate as this was based on rotary generators rather than linear ones, but the price is likely to be similar and the figures for linear generators are not currently available.

THE BATTERIES

The batteries we plan on using are a scaled-up version of traditional lithium-ion batteries, similar in design to the Powerwall model created by Tesla. We will therefore use the Tesla Powerwall specifications as our starting point.



We will have a total of 40 batteries, so that every battery can either be discharging to the grid (or to another battery) or be charged by a boat. The batteries will be switched into and out of the boats to be charged so that we will always have 20% of the daily power requirements available in case of emergency. When this project is realised in the 2020s, battery costs are estimated to be £107.24/kWh ($150/ kWh). Our batteries will therefore cost around £2.15 million each, so our 40 will cost a total of £86 million.

Each battery will be charged every 20 hours by the fleet of 20 boats to keep a continuous supply of full batteries to all critical services. The Tesla Powerwall can last from between 1000-1500 cycles, and so if every battery was charged every 20 hours, they would undergo 438 charges per year, and last up to 3 ½ years. In reality, cheaper and more energy dense batteries are likely to be created in this time period, which would replace the older batteries. Hence, the cost of replacing the batteries would decrease significantly over time (from the graph, the cost appears to half every 4 years or so – although this isn't rigorous analysis, it does indicate a general trend).

DOCKING AND STORAGE

BOATS

We will need to pay for annual berths at one of the local ports/marinas that is large enough to support 50m boats, which are generally classified as superyachts. The Ocean Village Marina gave us a quote of £42,775 per year for a boat of that size, so all twenty would give us a total yearly docking cost estimate of £855,500.

BATTERIES

The batteries will have to be stored when they are fully charged. To ensure that they remain working and do not discharge power wastefully when it is not wanted, they should

be stored at a temperature of 15°C and in dry conditions. This can be accomplished by storing them in a sealed warehouse with limited cooling facilities, as room temperature will suffice to keep the batteries running at optimum levels. There are a number of warehouses in Southampton, but they do not appear to be large enough to provide storage for all of our batteries, especially since they will have cargo from other customers to consider. An alternative option to this is building our own warehouse next to the docking area; This option is likely to be considerably better, since the batteries will need to be stored indefinitely, with specialist equipment running to keep them cool and operational.

The cost of constructing warehouse space is about £4 per square ft (£43.06/m2); the 20MWh batteries to be stored each have dimensions of 3m x 5m x 16m (HxWxD). This is a surface area of 80 m^2. For all 40 batteries (as they may need to be stored if the boats are taken for maintenance etc.), this results in a minimum 3200 m^2 surface area. This amount of storage space would cost £137,800 to construct.

MISCELLANEOUS

This includes the parts previously mentioned as having a negligible cost, as well as the setting up of the electricity generating components. Altogether, these shouldn't cost more than 1% of the overall cost.

TOTAL COST

The capital cost of creating a fleet of Mobile Wave Crawlers would therefore be:

Boats = £230 million

Batteries = £86 million

Generators = £4.8 million

Constructing storage = £137,800

£230 million + £86 million + £4.8 million + £137,800 = £320.94 million

Miscellaneous costs = 1% = £3.2 million

£320.94 million + £3.2 million = **£324.15 million**

The boats main maintenance costs would be incurred from the rental of marina space. This is estimated at around £855,500/ year. Additional miscellaneous costs (battery storage, repair costs etc) are likely to raise the cost of storage to around £1.5 million / year.

The operating costs of the boats are the sum of the cost of replacing batteries (per year) and the storage costs (fuel costs can be neglected as the boats could generate their own

energy) & siphon it from the batteries (while still charging the batteries to full power). These are as follows: £86 million / 3.5 years + £1.5 million / year = **£26.1 million**

CARBON COST

While the operation of the boats would have minimum environmental impact, the construction of the boats, and specifically the batteries, would release considerable amounts of CO_2 into the atmosphere.

BOATS

The boats used would be powered by a small amount of electricity from their battery, and so would not release CO_2 from their fuel. Although they would release a small amount of CO_2 in their construction, this amount is small enough to be negligible in comparison to the large volumes of CO_2 emitted elsewhere.

BOAT BATTERIES

The boat batteries have a capacity of 20 MWh each. The Global Warming Policy Forum estimates that the construction of batteries releases 150 kg of CO_2 / kWh. As such, the construction of these batteries would release 3 million tonnes of CO_2. As the batteries must be replaced every 3.5 years, the construction of the batteries effectively results in CO_2 emissions of **860,000 tonnes CO_2 / year**.

IMPLEMENTATION

Designing the boats, batteries and facilities to use would take a considerable time, around 5 years for a project of this scale.

Constructing a boat of the required size takes around one year. As the boats would be constructed concurrently, the total time to construct the boats would therefore be a year.

Constructing a battery of the required size is likely to also take around one year or less. Tesla recently constructed a 100MW battery for use with the energy grid in South Australia, taking 6 months. As the batteries intended for use in Solent City have a total power capacity of 40 MW, they would be expected to take a similar time to construct.

The storage facilities for the batteries in use would take less than a year also. However, to allow time for these facilities to all be constructed to the required standards, construction of all elements would be allowed 2 years.

From this information, the implementation schedule for the Mobile Wave Crawlers is as follows:

REDUNDANCY FOR CRITICAL SYSTEMS

INTRODUCTION

If a power outage were to occur in Solent City, resulting in an 80% loss of power, certain services would have to be prioritised in terms of energy. In reality, the likely cause of this power loss would be the failure of the nuclear power plant in Solent City, and so other power generation sources would have to be used. The critical services in the city would still require a constant supply of energy during a power loss, and so their energy requirements must be calculated in advance to ensure that they all get the energy they need to remain operational. These critical services include hospitals, fire stations, military bases and coast guard stations.

IDENTIFICATION OF CRITICAL SERVICES

Services that need constant power are the ones that are directly involved in the protection of the public, or ones that pose a risk to the public should their power be cut off. Services that protect the people include the fire service, the police, hospices, medical services, search and rescue (including confined space search and rescue), military bases, and coast guard stations. Services that pose a risk if their power is shut off include lighthouses, airports and landing lights, zoos, jails and research labs.

POWER REQUIREMENTS OF CRITICAL SERVICES

20% of the city's energy requirements must be met for 24 hours after the main power suffers an outage. This means that *9.963 TWh / year divided by 365 x 20%* = 5.46 GWh of energy must be available to supply to critical services.

All the areas of buildings have been calculated using Google Maps, taking into account the number of floors of the buildings, assuming there are no basements, and assuming that all floors are the same size.

HEALTHCARE SERVICES

A study on a Norwegian hospital stated that the electricity intensity could reach 400 kWh/ m^2 per year, but could be lower (356 kWh/ m^2 per year). The higher figure will be used, to ensure that enough energy is produced. For a 24-hour period, there would have to be an energy supply of 1.096 kWh/ m^2. There are 11 hospitals in the area (some which are in the same building, i.e. Royal South Hants Hospital and the Southampton NHS Treatment Centre). The total area of all of the hospitals in Solent City (approx.) is 884840 m^2. This means that the hospitals will require 969784.64 kWh of power in the event of a loss of 80% of the energy supply.

Anyone with a condition that requires a constant supply of energy, such as being deaf, having refrigerated medicines and recovering from recent medical treatment, will also need to be taken into account. This will include those who are either in hospices or staying with the equipment at their home. Those who require equipment at their houses wouldn't need much more than the average household usage which, according to the OVO energy company, is 4000kWh/year in Britain (approximately 10.96kWh a day). There is a website for people to apply to get energy in the event of a power cut, and this website would be advertised strongly, to make sure that everybody gets the power they need in an emergency. We will assume that 27007 households will need this, using data from the 2015 UK census and gov.uk. This means that the total energy requirement would be 295,996 kWh. The website to apply for emergency power, and the selection criteria, are listed below:

https://www.ukpowernetworks.co.uk/power-cut/priority-services-register

You are entitled to emergency power if:

- You rely on medical equipment
- You have refrigerated medicines
- You have a serious or chronic illness
- You have a disability
- You or someone you care for is living with dementia
- You are of pensionable age
- You have children under five in your household
- You need extra support for a short time period (e.g. If you are recovering from medical treatment)

For energy values pertaining to hospices we contacted Sue Ryder, a hospice charity, to ask for their rough energy usage per day. However, there has not been a reply as of yet. Therefore, as they are quite similar to hospitals in that they use a lot of medical machinery, we will use the figure for hospitals as a rough overestimate of the power required. There are two hospices in the area, with a total area of 2683 m^2. This means that they would require 2940.6 kWh of energy in a day.

RESCUE SERVICES

An average fire station uses 42.79kWh of energy per square foot per year. This is 0.117 kWh per square foot per day. There are eight fire stations in the area, having a total area of around 13338.2 m^2 (143571.2 square feet). Therefore, the energy needed to power the fire stations in the area for one day would be 16797.8 kWh.

The police stations in the area have a total area of 50055.3m² (538790.8 square feet). They can be assumed to use a similar amount of energy as a fire station, so the energy needed to power them would be 63038.5 kWh.

There are 4 coast guard, life guard and search and rescue buildings in the area. These buildings can be assumed to use the same amount of energy as a fire station. These buildings have a total area of 11539.4 m² (124209.1 square feet), resulting in a total energy requirement of 14532.5 kWh.

Military bases don't publish their energy usage per day to the public, for obvious reasons. There are six military bases in the area. They probably would not use more than a hospital in terms of energy, so this figure will be used to estimate how much energy they will require. All the military bases have an approximate area of 29290.4m², leading to an energy requirement of 32102.3 kWh.

INDIRECT RISKS

There are no jails or lighthouses in the area, so that is not a concern for Solent City. There are 4 wildlife parks and 1 aquarium, with a total area of 15535 m². According to Omaha's Henry Doorly Zoo & Aquarium energy and sustainability plan, their zoo used 440 kBtu/ft² (1388 kWh/m²) per year, or 3.803 kWh/m² per day. The zoos and aquariums in the area will need 59075.6 kWh of energy for the 24 hours.

Other dangers include airport landing lights. The total length of all the 3 runways at Solent Airport is 3208.97 metres. The lights use 450w each and have a diameter of 146mm. The interval between the lamps is 60m, so the number of lamps would be 53 lamps (3208.97 m / (60+0.146) m) on one side of the runway, and 106 lamps on both sides. There is also the addition of 175 lamps prior to the main runway (such as lamps in the approach landing area and extra lights in the landing threshold lines) creating an additional 525 lamps. With the addition of an extra 318 lamps in the first half of the runway (as seen in the image opposite), this sums to a total of 949 lamps overall. Therefore, the total power consumption of these lamps will be 427.05 kW, and their energy consumption over 24 hours 10.2492 MWh.

Laboratories are another indirect risk, and should be supplied with power to prevent the expensive (or dangerous) loss of experimental control. A study on the Kirschner Laboratory in Harvard listed some common pieces of lab equipment and their energy consumption;

totalling these gives a rough estimate of an energy consumption of 721.3 kWh per day. There are three research labs in our area, so the rough energy usage would be 2163.9 kWh.

TOTAL ENERGY REQUIRED FOR ALL CRITICAL SERVICES

Using all the figures calculated above, there is a power requirement of 155.8 MWh for all the critical services, which is well within 20% of the total power. It is assumed that the remainder of power stored in batteries will be distributed to the most vulnerable households.

QUANTITY AND COST IMPACTS OF POWER REDUNDANCY SYSTEMS

MOBILE WAVE CRAWLERS

Batteries on par with the Tesla Powerwall will provide uninterruptable energy for the most critical services (e.g. hospitals). Each of these batteries will have enough energy to last a single power outage, thus supplying energy for 24 hours. The capacity of batteries used will be tailored to the individual service it is powering. As 5.46GWh of electricity must be stored, and as battery costs per capacity are expected to be £107.24/kWh, these batteries will cost **£585.5 million**.

However, these batteries will be charged from the 40 batteries operated by the Mobile Wave Crawlers. At any one time, 20 MWh x 20 batteries = 400 MWh of energy capacity with which to charge batteries will be available. This is 13.65 times less than the total energy to be supplied (5.46 GW / 400 MW = 13.65). As a result, the distributed batteries will be charged fortnightly, or 26 times per year. The batteries are likely to last for around 1500 charge cycles (see The batteries) – at 26 charge cycles / year, the batteries will last around 57 years. This makes the batteries essentially a capital investment.

Constructing such batteries would release 150 kg of CO_2 per kWh capacity. As the total capacity of these batteries would be 400 MWh, the gross CO_2 release from the construction of the batteries would be 60 million tonnes of CO_2, or **1.05 million tonnes for each year they operate.**

All areas of buildings have been calculated using Google Maps, taking into account the number of floors of the buildings, assuming there are no basements, and assuming that all floors are the same size.

DEALING WITH POLLUTANTS

CARBON NEUTRALITY

INTRODUCTION

For a multitude of reasons, some transport technologies necessitate the burning of fossil fuels and therefore the release of carbon dioxide into the atmosphere. For example, long-distance ships cannot be powered by any fuel other than "bunker fuel", a product of crude oil, and so will always release carbon dioxide into the atmosphere from their fuel.

The challenge clearly states that Solent City must be completely carbon neutral; therefore, we needed to find a way to cancel out these unavoidable "positive emissions" with "negative emissions". This could be done in number of ways:

DIRECT CARBON CAPTURE FROM THE AIR

Recent advances in carbon capture technology mean that "sucking" carbon dioxide from the air has become a technological possibility. The Climeworks AG facility near Zurich opened in 2017, and has been extracting CO_2 gas directly from the air. The extracted CO_2 can either be sold, for example for use producing carbonated beverages, or disposed of geologically. However, the total cost of this project has been estimated at $1,000 per ton of CO_2. Part of the reason for this high cost is that CO_2 gas in the atmosphere is at a very low concentration of around 400 ppm; similar carbon capture projects at coal or gas fired power stations are as much as 10 times cheaper per ton due to the increased concentration of CO_2 gas.

Unfortunately, carbon capture schemes at coal powered stations (which have the highest emissions of any modern power plant) are predicted to use between 10% and 40% of the total energy produced by the plant. Such reductions in plant efficiency are intolerable to energy consumers, as they will raise the price of energy considerably (as much as doubling industrial energy costs). Furthermore, this reduction in energy production would contribute to a rise in resource consumption, as more fuel would be required to produce the same quantity of energy. In recent years, the UK government has commissioned and cancelled two air carbon capture schemes on economic grounds, and so would be unlikely to fund another. These concerns, twinned with fears that reliable and cheap carbon capture technology is decades away, mean that direct carbon capture at the source of the emissions will not be a viable method of achieving carbon neutrality for Solent City.

AFFORESTATION

The large-scale planting of trees would generate negative emissions, as trees convert carbon dioxide into oxygen through photosynthesis. This approach would, however, require

a large amount of land, which could be used for the planting of crops or as space for new homes, which may be more beneficial to the city and its residents. Small scale projects, like creating more green spaces in the city, and planting more trees in local areas, would be more practical and economical. Furthermore, this approach is not allowed under the rules of the E4E competition.

However, the rules do not prevent underwater afforestation. A project called Seagrass Grow works to offset CO_2 emissions by planting seagrass in the coastal parts of the oceans. It is claimed that an acre of seagrass is 45 times more effective than a similar area of the Amazon Rainforest at soaking up CO_2 emissions. Supporting projects such as this would have the potential to reduce Solent City's net CO_2 output, while also aiding ecosystems in the ocean.

ENHANCED WEATHERING

Over geological time periods, carbon dioxide is removed from the atmosphere by weathering processes. When silicate minerals dissolve in rainwater, carbon dioxide is drawn from the atmosphere into the solution and trapped as bicarbonate ions. These ions eventually end up in the ocean, where they sink to the ocean floor and hence are removed from the carbon cycle for millennia. Researchers from Oxford University, among others, have hypothesised that spreading crushed silicate minerals in soil would accelerate the weathering process due to their increased surface area and biological activity in the surrounding soil (which will naturally speed up weathering).

However, it is still unknown whether this technique will be effective, because the technology is still in its infancy. Although the technology could, in theory, be realised in the next ten years, it is highly unlikely that legal issues would be resolved in this time period; legislators would require long-term studies into the environmental effects of the technology, and these, by definition, could not be conducted in a short time frame. As the technology is unlikely to be available in the foreseeable future, it will not be a viable method of reducing Solent City's carbon emissions to zero.

OFFSETTING EMISSIONS ELSEWHERE

To cancel out X tons of carbon dioxide emitted from Solent City, it would be sufficient to prevent X tons of carbon dioxide emissions elsewhere. This technique requires no additional technology, as the simplest way of preventing large quantities of carbon dioxide being released into the atmosphere is preventing coal or natural gas fired power stations from generating electricity. If the nuclear power station in Solent City can generate a surplus of electricity, this electricity can be sold back to the national grid, which would reduce the need for "unclean" electricity.

Coal-fired power stations are being phased out of use by the UK government, and will not be generating power in 2025. However, the government is actively supporting the construction of new natural gas fired power stations. Hence, emissions from gas power stations instead of coal power stations will be offset by the nuclear power station in Solent City.

CARBON NEUTRAL CALCULATIONS

TABLE OF EMISSIONS

Project	CO_2 emissions (tonnes / year)
Intra-city transport	107,000
Transport by sea	61,600,000
Air transport	28,900,000
Household heating	5,100,000
Mobile Wave Crawlers	860,000
Redundancy for critical systems	1,050,000
Total	**97,617,000**

The emissions from Solent City's nuclear power station are not summarised in this section, because they will offset themselves from the overproduction of clean energy.

The CO_2 output of Solent City has been calculated as 97.617 million tonnes of CO_2.

In order to offset these emissions, clean energy will be overproduced by the nuclear power station in Solent City.

CALCULATIONS

Gas-fired power stations release 499 tonnes of carbon dioxide per GWh electricity supplied; in contrast, nuclear power stations release just 29 tonnes of carbon dioxide per GWh electricity supplied. These figures are based on a meta-analysis of 20 studies into the CO_2 output of various power generation techniques, and are hence highly accurate. Therefore, every GWh of electricity produced by nuclear power that results in an equivalent decreased demand electricity produced by gas power reduces the net CO_2 emissions of Solent City by 470 tonnes.

The total energy production in the city is the sum of the energy produced by the Mobile Wave Crawlers and the nuclear power plant:

(20 MW + 1244 MW capacity) x 8760 hours in a year = 11.073 TWh produced / year.

The energy requirements of the city are 9.963 TWh / year. Therefore, energy is being overproduced at a rate of 1.11 TWh / year.

This will result in a reduction of (1100 GWh x 470 tonnes) = - 521,700 tonnes of CO_2.

In order to remove the remaining 97,095,300 tonnes of CO_2 per year, sea forestation techniques will be used. Seagrass Grow estimate that the CO_2 footprint of Solent City would be offset by 8,349,224,847 m^2 of seagrass.

The cost to the city (£695,882,015) is on par with other carbon capture techniques (e.g. reforestation in other parts of the world) at around $10 / tonne. The benefits of this particular scheme are two-fold; firstly, that the payment would be single-time as once the seagrass has been planted, it will continue to extract CO_2 from the oceans indefinitely (with a negligible protection fee); and, secondly, it is a very scalable scheme and so will work to absorb very high levels of CO_2.

In the event that this scheme proves infeasible, a portfolio of carbon neutral offsets will be purchased at a similar price.

OTHER POLLUTANTS

Other than carbon dioxide, pollutants that will be monitored in Solent City include carbon monoxide (CO), nitrogen oxides (NOX), and methane (CH_4). These are all bad for human health, the environment, or both, and so levels of them need to be reduced as much as possible in the city.

These chemicals include:

- Particulate matter (PM)
- Nitrogen oxides (NO_x)
- Carbon monoxide (CO)
- Sulphur dioxide (SO_2)
- Greenhouse gases

Particulates, such as black carbon, are found in car exhausts (formed by incomplete combustion) and can both cause health problems as well as contribute to global warming. If breathed in, they have been linked to causing or worsening respiratory diseases such as asthma.

Nitrogen oxides, especially nitrogen dioxide, have also been linked to causing or worsening the symptoms of respiratory diseases. To lower the parts per million of these pollutants, only electric cars will be allowed into the city, which don't have exhausts, and therefore aren't releasing any direct emissions.

Carbon monoxide is formed from incomplete combustion - i.e. in the hot car engines, where there is often not enough oxygen for the carbon particulates to react with to form carbon dioxide (which is still a bad pollutant and greenhouse gas, but not as harmful to humans as carbon monoxide), so carbon monoxide is formed. Carbon monoxide restricts the amount of oxygen red blood cells can carry, reducing oxygen flow to the heart. To reduce the amount of carbon monoxide emissions in Solent City, we plan to have electric cars, and only allow electric cars (with exceptions to emergency vehicles) into the city. The advantages to owning an electric car will also be advertised to encourage people to buy them, therefore decreasing these emissions nationwide.

Sulphur dioxide is most commonly found in the combustion of impure fossil fuels and other industrial processes, when the sulphur molecules will react with the oxygen during combustion to form sulphur dioxide. Short-term exposures to high levels of sulphur dioxide can be life-threatening, exposure to 100 parts per million of sulphur dioxide is considered immediately dangerous to life and health as sulphur dioxide is a known irritant to the lungs, throat and nose when inhaled and can cause severe throat constriction as well as inflammation and irritation of the entire respiratory system which is especially dangerous

to those with breathing difficulty (e.g. asthmatics and those with cystic fibrosis). To reduce the amount of sulphur dioxide we have used renewable fuels in almost all our processes in Solent City which will not release sulphur dioxide as well as providing incentives to use less hydrocarbon-based fuels, resulting in a decrease of this type of emissions.

Nitrogen oxides are mainly found in the burning of fossil fuels (~80%) and metal & oil refining processes, as well as other industrial processes; this occurs when nitrogen in the air is put under the right conditions to react with oxygen (normally done in a combustion). Nitrogen dioxide inflames the lining of the lungs, and it can reduce immunity to lung infections. This can cause problems such as wheezing, coughing, colds, flu and bronchitis. Increased levels of nitrogen dioxide can have significant impacts on people with asthma because it can cause more frequent and more intense attacks. Other nitrogen oxides will help to form smog and acid rain, as well as assist in forming ground level ozone when it reacts with other pollutants all of which have adverse health effects, especially noticeable with the prominence of smog in heavily industrial areas such as Hong Kong and metropolitan China. Another issue with nitrogen oxides is the damage to the environment which has been observed in the Epping forest in Europe with effects such as leaf damage and reduced growth (http://www.icopal-noxite.co.uk/nox-problem/nox-pollution.aspx). To reduce the amount of nitrogen oxides present in the air we have used renewable fuels in almost all our processes in Solent City which will not release nitrogen oxides as well as providing incentives to use less hydrocarbon-based fuels, resulting in a decrease of this type of emissions.

COSTING SUMMARY

The costing for different projects has been accounted for in the section associated with each major project. However, this section is intended to provide a summary of costs, and potential ways they could be met.

TABLE OF COSTS

The following table summarises all gross costs for our major proposals. If a cost is less than tens of millions of pounds, it will not be included in this table and is instead marked N/A.

Project	Capital cost (£)	Operating cost (£/year)
Intra-city transport	£591.4 million	£205.1 million
PRISM reactor	£5.91 billion	£153.6 million
Mobile Wave Crawlers	£324.15 million	£26.1 million
Redundancy for critical systems	£585.5 million	N/A
Offsetting CO_2 emissions	£695.9 million	N/A
Total	£8.107 billion	£384.8 million

FUNDING

The PRISM reactor is predicted to earn £18.31 billion in electricity sales over its lifetime of 60 years. After paying back loans for the capital costs (of all services), £10.203 billion would be left to fund other services. Over a 60-year period (the lifetime of the plan), this amounts to £170.05 million / year. Hence, the operation of the reactor could be funded, along with £16.45 million for the Mobile Wave Crawlers each year.

This leaves a net cost of £214.75 million to fund in other ways, as discussed below.

The projects in this report will all be funded in different ways:

- The intra-city transport scheme will be funded in part from an additional tax on residents, as well as ticket fees. This scheme will be sufficient to cover the operating costs of the scheme; just £102.55 per resident would cover the operating costs. Given that the scheme will eventually remove the need for privately owned cars, residents will be able to afford this payment to spend on transport.
- The PRISM nuclear power station will generate sufficient low-cost electricity to fund itself after initial investment from government.

- The Mobile Wave Crawlers and batteries will be supplied by a government grant, as the cost of energy they generate per kWh is greater than current market rates. They will also receive financial aid from electricity sales from the PRISM reactor.
- The redundancy batteries will be supplied by a loan, which can then be paid off over the course of their lifetime with electricity sales from the PRISM reactor.

IMPLEMENTATION SCHEDULE SUMMARY

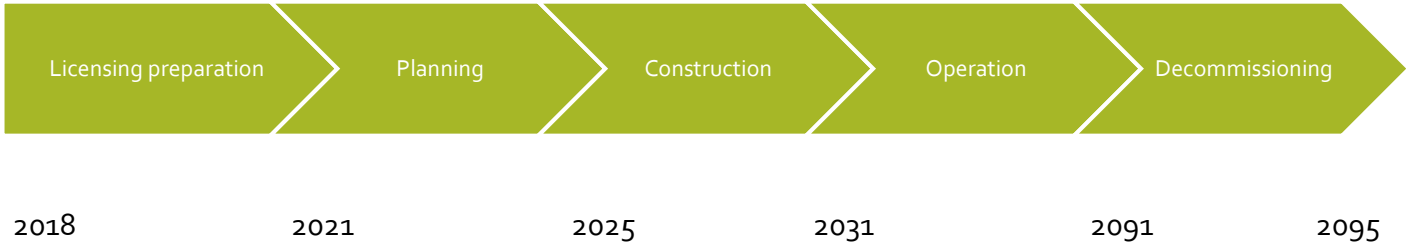
Project specific implementation schedules in more detail can be found in the following sections:

- Autonomous vehicle scheme
- PRISM nuclear reactor
- Mobile Wave Crawlers scheme

All systems will be online by 2031 in this proposal, with the full operation of autonomous cars timed to coincide with the beginning of operation of the nuclear power plant. The Mobile Wave Crawlers will take less time to implement, and so will be operational before other projects.

AUTONOMOUS VEHICLE SCHEME

PRISM REACTOR



MOBILE WAVE CRAWLERS & REDUNDANCY SYSTEMS

2018 2023 2025

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