Behind the eye-catching new gardens on Singapore’s waterfront, created by a team of UK engineers and architects, lies a combination of measures that hold lessons for the sustainable design of buildings in hot and humid conditions. The team devised innovative techniques to ensure the conservatory air conditioning remained carbon-neutral, winning RIBA’s 2013 Lubetkin Prize. *Ingenia* talked to Patrick Bellew RDI FREng, of environmental engineers Atelier Ten, who outlined the engineering challenges and solutions generated by the Gardens by the Bay project.
CITY IN A GARDEN

Gardens by the Bay is part of the Singapore government’s vision of transforming the sovereign city-state into a garden city. It chose Grant Associates of Bath to lead the £550 million Bay South project, Wilkinson Eyre as the primary architects and Atelier One and Atelier Ten – both based in London – serving as, respectively, the structural engineers and the environmental and building services engineers. The project emphasises sustainability and demonstrates environmental responsibility.

Early plans were to harness solar power to provide the energy needed to cool and dehumidify Singapore’s hot and humid air for the domes without imposing a large carbon footprint. The UK is known internationally for its expertise in reproducing environments for non-native plant species to grow, such as in London’s Kew Gardens and the Eden Project in Cornwall. But while those projects keep hothouse plants warm in a cool climate, it was a greater challenge to cool plants in a subtropical climate in an energy-efficient manner.

Part of the answer was in the creation of the garden’s most distinctive features – the concrete-cored, steel-clad ‘Supertrees’, some nearly 50m tall. Covered in plants, these structures provide sustainable energy while simultaneously providing the infrastructure supporting the site’s enormous climate-controlled conservatories.

The discussions showed that NParks was maintaining and pruning several million trees in metropolitan Singapore, including sending tonnes of tree cuttings a week out of the city, mostly to landfill or for incineration. So a 7.2MW biomass boiler was developed to burn the horticultural waste. To reduce the moisture content to the optimum level, it was decided to mix this with waste parking cars, conveniently available from the nearby freight terminal. Steam from the boiler now feeds a turbine that delivers electricity to the site’s centre – with any surplus fed into the grid.

The high-temperature water downstream of the turbine drives absorption chillers, which generate chilled water. Once cleaned, the resulting exhaust gases from the biomass furnaces needed to be released from a very high level, necessitating the use of chimneys. In response, the team devised the plant-covered SuperTrees around the chimney flue.

To reduce the moisture content to the optimum level, it was decided to mix this with waste parking cars, conveniently available from the nearby freight terminal. Steam from the boiler now feeds a turbine that delivers electricity to the site’s centre – with any surplus fed into the grid.
**Desiccant Technology**

Flower dome sectors, also known as the cool-dry biome. This conservatory is maintained at a temperature and humidity suitable for growing European plants (25°C and 60% relative humidity during the day). Air is introduced for cooling at ground level through integrated slots in the main service tunnel between the cloud domes and returning it to the strong desiccant tank where it can be reused. A series of regenerator units which remove the water from the ‘weak’, or dilute, solution. This weak solution is then passed through a series of arches comprising a steel grid shell to hold the glazing, tied with hangars to more-sturdy external steel arches. The grid shell supports itself, while the arches resist wind loading. This allows the grid to be remarkably slender: the ribs of the grid shell have been made as thin as possible, with their edges tapered inwards in section, to minimise the solar shading.

**Reducing Energy Use**

The Cloud Dome and Flower Dome. Paul Baker of Wilkinson Eyre Architects says: “The complementary yet distinct curved forms of the biomes are generated from the geometry of a hyperbolic curve, and relatively small area utilised for a large volume enclosure. Not only is this geometry enable the structure to lean forward (away from the arches, allowing them to be a steel grid shell to hold the glazing, tied with hangars to more-sturdy external steel arches. The grid shell supports itself, while the arches resist wind loading. This allows the grid to be remarkably slender: the ribs of the grid shell have been made as thin as possible, with their edges tapered inwards in section, to minimise the solar shading.

**Architectural Challenges**

The shape of the shell for each dome was generated from a rotated hyperbolic curve, planned by the structural engineer and architect, with the apex tilted towards the north. The sloping had the beneficial effect that the north walls became near-vertical so that little or no solar gain would enter on this side, thus eliminating the need for external shading, maximising daylight and at the same time saving cost. The shape also introduced asymmetry which required some special engineering measures, such as pre-stressing the arches, particularly for the Flower Dome. Here, the nose or apex of the hyperbolic surface was attached to the arches and tensioned, effectively pre-stressing the arches to form a rigid boundary. Between this boundary and the ground spans the large south gridshell. The key to this is that the grid shell is braced along the line of the apex, forming effectively an arched beam at right angles to the arches, and this beam is then tensioned against the arches forming a ‘rigid’ boundary. The surface, since it is exposed to low wind loads, did not require support from the arches, allowing them to lean forward (away from the glass façade) from the arches, allowing them to be a steel grid shell to hold the glazing, tied with hangars to more-sturdy external steel arches. The grid shell supports itself, while the arches resist wind loading. This allows the grid to be remarkably slender: the ribs of the grid shell have been made as thin as possible, with their edges tapered inwards in section, to minimise the solar shading.

The south gridshell would have been easiest, but this would have trapped heat at the highest level within the dome. The answer was an ingenious system of retractable external shades across all but the northern faces of the two domes. Some 400 triangular polycarbonate shades roll up and completely concealed within the lower section of the steel arches when not in use, and are actively controlled to deploy by cable when required to modulate internal daylight levels to the desired level. An intelligent self-learning algorithm controls each shade individually, adjusting the shading to match the conditions at the time. The introduction of the shades required another inspirational piece of engineering. To maintain the blinds’ cable system and motors, it is necessary to access the whole external surface of the dome. The novel solution is a building maintenance unit that can travel all the way over the surface between pairs of arches. A lattice-frame beam, spanning adjacent arches, supports two independent cradles and a crane hook for replacement of glass panels.
SINGAPORE’S SUPER TREES

This is probably the world’s first large-scale biomass-powered environmental system generating power, refrigeration and dehumidification from a single waste stream.

HOT AIR CON

The principal means of air conditioning the domes is a displacement air supply system that delivers dry and cooled air at low level into the occupied zone. Relative densities dictate that the cool air remains below the hot air which limits the volume of the building that needs conditioning, so reducing plant capacity and energy use. It also allows the conditioning air to be delivered at around 18°C (rather than at 12°C which would be the norm for a conventional conditioning system) and this elevated supply temperature results in significant energy savings.

The displacement air is supplemented by the cooling of the pathways and pavements within the domes (by chilled water pipes embedded in the concrete) in order to absorb and remove incident solar radiation. This reduces the amount of heat gain to be dealt with by the air systems, and also improves comfort for visitors.

In the Cloud Forest Dome, direct evaporative dehumidification (misting) is used to provide the very high humidity levels required and also enhances cooling performance. Determining the necessary air supply and modelling its distribution within the domes was a major challenge. Initial calculations were done using dynamic thermal energy models to predict peak heat gains and mass flow balances to estimate flow rates; these gave the scale of the cooling required. Subsequently, computational fluid dynamics (CFD) modelling was used as an iterative design tool to detail, analyse and optimise the air flow.

The early CFD studies showed that the air surrounding the mountain in the Cloud Forest Dome would become hotter than acceptable at high levels with the displacement system alone. As a result, a hybrid ventilation system was developed: air is supplied through displacement terminals at the bottom of the building and at the top of the mountain, but at intermediate levels within the mountain, jet diffusers are used to drive local mixing, thus limiting local stratification. Above the mountain, the air is allowed to stratify (as in a normal displacement system), before being extracted and re-circulated back to the basement plant.

SUSTAINABLE CREDENTIALS

At the start of the project, the Singapore government instructed the design team to endeavour to make the carbon emissions from the conditioning systems no worse than would be experienced in a modern Singapore office building – a major challenge considering the demanding requirements of the plants and the high light levels required. The resulting system ensured that the displaced carbon from onsite renewable energy generation (biomass supplemented by photovoltaic power) totals 2,050 tonnes of CO₂ per year, compared with carbon emissions from the cooling systems for conditioning the domes of 1,770 tonnes of CO₂ annually.

This is probably the world’s first large-scale biomass-powered environmental system generating power, refrigeration and dehumidification from a single waste stream, and though few future cities in Asia, the Middle East and elsewhere.

Desiccants are relatively unused and have plenty of potential, particularly where (as with Gardens by the Bay) designers can work with clients to identify waste from outside the site that can be harnessed for energy. Many humid cities have large central cooling plants that simply dump the waste heat, and this could be harnessed to dry desiccants. In cities with a lot of sunshine, solar power could be used for the same purpose.

Certainly, when it was announced that the Gardens by the Bay project had won RIBA’s 2013 Lutkenhouser Prize, the judges congratulated the winning team for having created greenhouses covering two hectares that were carbon-neutral and for pushing the boundaries not only environmentally but also structurally, giving the city a new and public landmark.

PLANT HABITAT

A large variety of plants will grow naturally and abundantly in Singapore’s tropical climate – including the national flower, the orchid – and these fill much of the Gardens by the Bay. But within the two domes it was necessary to create the cooler (and in one case, drier) environments required by non-native plants – the opposite of the tropical glasshouses of western Europe.

Another feature of the gardens is the use of ‘green walls’, both within the domes and outside. These come in three forms: geotextile reinforced-earth walls with planting help to soften steep slopes which would otherwise be concorded; vertical planting panels are used on the sides of the Supertrees and some walls; and ‘living render’ provides a porous and roughly-textured concrete surface that incorporates a proportion of organic material in the concrete mix to create moisture retention and rooting zones for epiphytes (air plants).

CREDENTIALS

SUSTAINABLE

BIOGRAPHY

Patrick Bellew RDI FREng is founding director of Atelier One (1991). He is one of the UK’s Royal Designers and a Chartered Building Services Engineer with more than 30 years’ experience in the design of high-performance buildings and systems.

Hugh Ferguson interviewed Patrick Bellew for Ingenia. He also talked to Neil Thomas, founding director of structural engineers Atelier One.