APPROPRIATE RENEWABLE ENERGY FOR EDUCATION INFRASTRUCTURE IN RURAL SOUTH AFRICA: THE COFIMVABA SCIENCE CENTRE MODEL

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Abstract

The Council for Scientific and Industrial Research (CSIR) has embarked on an innovation investigation through a ministerial initiative brought by the Department of Science and Technology Innovation (DSI). The Cofimvaba Science Centre was envisioned, planned and is currently in construction to build and test theory with regard to the efficacy of multiple innovations in the supply and delivery of building construction projects in South Africa. This is in response to the target set by the National Development Plan (NDP 2011:288) of 2030 for energy efficiency in building standard SANS 204 to achieve 'zero carbon' buildings.

There is a need for alternative teaching platforms for maths, science and technology. At the same time, there is a need for rapid construction of infrastructure with sustainable ongoing power supply in rural areas in South Africa. The innovations could lead to improved teaching outcomes and quality of instruction, as well as improvement in the rate of construction and service delivery, with the added benefit of future economy creation downstream. The building has been constructed by alternative construction methods and materials, with five different energy sources regulated through a microgrid system delivering a planned net zero carbon building. A multiyear building performance analysis will be conducted to gather evidence for future application and appropriateness. A pre-construction investigation of available building technologies was done, and during construction assessments of renewable energy sources and the financial viability of the project continued. Post-construction assessment of the building's performance will be conducted covering materiality, thermal performance, indoor air and sound quality, energy, water and waste use. The alternative building construction method has yielded rapid construction time. However, a slow administrative process has delayed the completion date. Nevertheless, the project suggests that net zero energy can be achieved for Government and private buildings in rural South Africa.

Keywords: appropriate technologies, building performance, construction, net zero, , renewable energy, .

INTRODUCTION

The Department of Science and Innovation (DSI), in collaboration with the Department of Basic Education (DBE) and the Eastern Cape Department of Education (ECDE), is leading an initiative that seeks to examine whether the introduction of innovative and tested technologies would improve the quality of learning and teaching in the Cofimvaba Schools District, Eastern Cape. The initiative includes the development of a science centre and virtual remote science and technology teaching for both student and educator. The Cofimvaba Science Centre (CSC), located on Main Road, Cofimvaba, is a 1 369 m^2 Science Centre and educational facility to assist and encourage learners in the district with the study of science and technology. The location is considered strategically placed, given its centrality to schools in the broader community intended to benefit from the Science Centre programmes. To advance the mission and drive the building industry, the CSIR developed the CSC to demonstrate how ‘deep green’ buildings are designed, contracted, constructed, and occupied, aimed at both creating an education facility and establishing a living laboratory to test appropriate technologies, appropriate contracting and procurement methods for application in rural South Africa.

The CSC aims to advance the goals and objectives of the DSI-led campaign to promote public awareness of, and engagement in, science, and contribute to the development of a skilled and capable workforce particularly with high-level scarce skills in science, engineering and technology (SET) to support an inclusive growth path. In that context, the envisaged CSC will have four strategic focus areas, namely science engagement, Mathematics, Science and Technology (MST), curricular support, SET career education and talent nurturing. The actual design of the programmes under these focus areas is shaped by the needs and expectations of the DSI, the DBE and the ECDE.

The design and planning of the Science Centre itself will contribute to the SET areas through construction using Innovative Building Technologies (IBT) in support of a Cabinet Resolution of 2013 in this regard. The building is designed and planned to be off-grid, meaning that it will be independent of outside services such as water, energy and sewerage. The technologies adopted to achieve this will provide a live working example of the application of IBTs and related technologies. In addition to Solar Photo Voltaic Panels , building-scale wind turbines and hydrogen fuel cells managed by a microgrid system contribute to the net zero carbon energy target. Rainwater harvesting is supported by a constructed reedbed for recycling of grey water, and the treatment of sewerage will be done on site using an Agrément certified bio-based toilet. DSI and the Department of Environmental Affairs with the CSIR embarked on an investigation to conserve a potential ruined natural wetland as a further SET exhibit. However due to seasonal climatic factors and the degraded state of the wetland area, a reconstructed wetland and onsite educational intervention is currently underway.

The Science Centre is very similar programmatically to a school, where the school hall becomes an exhibition centre. This hall is supported by classrooms, laboratories (chemistry, physics and computer) and a multi-purpose lecture theatre that doubles as a planetarium (in support of the Square Kilometre Array or SKA, a project strongly supported by DST). The Science centre is intended to serve as a “living laboratory” in which the methods of design, contracting, construction, commissioning and operation, and the lessons learnt in the process, could be shared and potentially replicated. The CSIR’s experience will therefore serve as a practical model to inform these aspects of future buildings and thereby reduce the buildings’ contribution to the climate crisis.

METHODOLOGY, DISCUSSION AND EVALUATION

The socio-economic context

The town of Cofimvaba falls under the Intsika Yethu municipality and is situated in the Chris Hani District Municipality, a district in the centre of the Eastern Cape. The Chris Hani node is one of four Integrated Sustainable Rural Development Strategy (ISRDS) nodes in the Eastern Cape.

The Chris Hani District Municipality (CHDM) covers approximately 37 294 km^2, with a total population of 840 058 (CHDM, 2018:). The total number of households is estimated at 218 000 in 2016 (CHDM, 2018), with an average family size of 4.8 (CHDM, 2018). The majority of the population is young people between the ages of 0 to 24 (55.9%) (CHDM, 2011). These are largely children of school-going ages. About 39 % of the population in the district is below 15 years of age (CHDM, 2011) and more than half the population is below 20 years of age. The majority of people live in rural areas, townships and informal settlements. The levels of poverty within the district remain high with over half of the district population (52.9%) living in poverty (CHDM, 2011). Due to the high rates of unemployment there is a high dependence on grants and remittances as the main source of household income.

The human development index for the district is below 0.50 (CHDM, 2011). The district is comparatively poor in terms of poverty measures such as Human Development Index (HDI) (0.559); poverty gap and the number of people living in poverty (75.4%) (CHDM, 2011). More than 75% of the economically active age groups are unemployed (CHDM, 2011). Matriculants struggle to further their studies due to financial constraints.

Agriculture is regarded as the backbone of the economy of the district as the largest portion of land is utilised for agricultural purposes. Managing the available resources in a sustainable manner is therefore a priority. The Chris Hani Regional Economic Development Strategy (REDS) has endorsed 4 specific clusters or sectors for prioritisation namely: Agriculture, Agro-processing and Forestry, Manufacturing, Construction and Mining, Tourism and Hospitality and Services, Retail and Logistics (CHDM, 2018). The strategy notes that local beneficiation is key to the district, water infrastructure backlogs must be eradicated, energy security needs to be addressed and transport linkages need to be maximized (CHDM, 2011). The strategy has identified 4 major development corridors. The corridors are seen as key infrastructure to strengthen and enhance potential value chains as they may relate to the strategic economic clusters or sectors.

At an estimated 153 000 people, Cofimvaba has the highest population in the district, with youth being in the majority. Its population is projected to grow at an average rate of 0.6% from 153 000 in 2016 to 158 000 in 2021 (ECSECC, 2017). Its main economic sectors are community services (52%), trade (14.8%) and agriculture (14.6%). The working-age population in Intsika Yethu in 2016 was 84 200. The top five employment sectors in 2016 were Community services (4 910), Trade (3 110), Construction (2 400), Households (1 170) and Finance (1 130) (Ibid). However, the number of people without any schooling decreased from 2006 to 2016 with an annual rate of -4.87% while the number of people within the 'matric only' category increased from 5 380 to 10 000 (CHDM, 2011). A total of 66 700 individuals within the municipal area were considered functionally literate in 2016, equivalent to 67.01% of the population, while illiteracy rate decreased on average by -2.58% annually from 2006 to 2016 (CHDM, 2011)..

The public sector dominates the region's economy with a limited production base and limited private sector investment growth. The area is largely rural which negatively influences the ability to provide health services. The provision of services such as education, youth development and development projects remain a challenge for government. Consequently the region is challenged with a higher demand for basic services as well as housing and infrastructure. More than 75% of households in the district do not have proper and safe forms of sanitation and electricity, while access to social infrastructure is restricted (CHDM, 2011).

A survey undertaken in the node in June 2003 found a rising death rate among the youth due to HIV/Aids together with other common diseases such as cholera and diarrhoea due to the unavailability of purified water and proper sanitation (CHDM, 2011).

The infrastructure problem and appropriate technology opportunity

In 2016 the majority of households used ventilated improved pit toilets (VIPs) at 14 300, followed by no toilet (9 790); pit toilet (9 760); flush toilet (3 430); and bucket system (108). In 2016 Intsika Yethu Local Municipality had a total number of 4 320 (or 9.31%) households with piped water inside the dwelling, 8 900 (19.17%) with piped water inside the yard, and 16 500 (35.59%) had no formal piped water. When looking at the water backlog (number of households below RDP-level) over time, it can be seen that in 2006 the number of households were 28 300, but this had decreased annually at -2.5% to 21 800 in 2016. The number of households in 2016 with electricity for lighting purposes only totalled 4 990 (11.84%); for lighting and other purposes this was 28 200 (66.86%) while 8 980 (21.29%) did not use electricity.

The data reflect the urgent need for alternative technologies in rural areas that could be localized and sustainable. The CSC was designed and planned to test the appropriateness and longevity of such interventions. As the building construction comes to a close (in 2020), the post-occupancy evaluation and five years' of building assessment will provide insight into the successful application and implementation of these technologies in responding to the real needs in community and civil buildings.

Innovative technology options for Cofimvaba Science Centre Project

The core design factors outlined in Table 1 were considered to achieve an appropriate building method and appropriate technologies for the social and economic environment of Cofimvaba. This town in many ways represents a large percentage of rural South Africa. The final selected applications had to support the net zero- energy and net zero-water aspirations, but also support the concept of the living laboratory for teaching purposes.

What are "net zero energy" buildings?

> 'A [net zero energy building is a] building that is highly energy-efficient, and the remaining energy use is from renewable energy, preferably on-site but also off-site where absolutely necessary, so that there are zero net carbon emissions on an annual basis (Net Zero), or if the energy from renewable energy results in more energy being produced than what is used on site (Net Positive)." (GBCSA, 2020).

A net zero water building harvests and reuses as much water on-site as it consumes annually. The design and construction of the CSC has ventured to achieve net zero efficiency for both energy and water, and in doing so aims to be one of only a few such buildings in South Africa, and set a standard for state buildings.

Appropriate technology solutions

In reference to Table 1 potential technologies that were considered. However, not all the technologies have been incorporated, due to either cost and/or eventual viability., After collaborative investigation by the project design team, a large number have been applied, as presented in Table 2. The collective application of several systems is a collaborative intervention that will achieve the intended result more effectively.

Table 1 *Design requirements*

Category	Technology Option	Technology Applied	Comment
Electricity	Photovoltaic Panels Hydrogen Fuel Cell Solar water heaters	Photovoltaic Panels Hydrogen Fuel Cell Solar water heaters	Individual roof mounted External Hot water radiators

	Solar water space heating Heat pumps Energy Management System application	Solar water space Energy Management System Microgrid Wind turbine	Automated energy management
Sanitation	Bio toilets Composting toilet Low flush Reed bed	Bio toilets Low flush Reed bed	Combination of technologies Specification of fittings
Water	Rain water harvesting system Sustainable Urban Drainage Grey water recycling Water Management System	Rain water harvesting system Sustainable Urban Drainage Grey water recycling Reconstructed wetland Retention landscaping	Irrigation purposes Collection and treatment of surface water Two-pipe drainage system Automated management Monitor internal reticulation
Building	IBT System Heat reflective roof Attic ventilation Vented window frames	IBT System Heat reflective roof Attic ventilation	Not brick and mortar Painted roof sheets Extract vents Reduce risk of condensation
Road surfaces	Permeable paving Ultra-thin AC pavement Ultra-thin CRC Solar radiation pavement Air purifying pavement blocks	Permeable paving Solar radiation pavement	Part of Sustainable drainage system
External lighting	Solar street lighting Solar external lights	Solar street lighting Solar external lights	Mast lighting Building lighting
Waste	Recycling facility	Recycling facility (future)	Bins and sorting
Urban agriculture	Communal plots		
Green walls	Solar screens		Vertical planting

Integrated design and delivery solutions

Achieving a high-performance ‘deep green’ building requires an Integrated Design and Delivery Solution (IDDS). Integrated Design and Delivery Solutions (IDDS) are aimed at

> “. . . transforming the construction sector through the rapid adoption of new processes, such as Integrated Project Delivery (IPD), together with Building Information Modelling (BIM), and automation technologies, using people with enhanced skills in more productive environments” (CIB 2009:3).

Integrated Design and Delivery Solutions use

> “. . . collaborative work processes and enhanced skills, with integrated data, information, and knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects” (CIB 2009:3).

Table 2 is summary of the design strategies and the passive feature they provide. The CSC has been developed as a totally passive project with only split conditioning units installed in two internal spaces.

***Table 2** CSC Applied design strategies*

Design Strategy	**Applied technology**	**Passive Design Features Achieved**
Insulation: Insulation plays a significant role in passive design because it allows the building to operate optimally regardless of the external environmental conditions. Insulation keeps the heat out in summer while retaining any heat generated inside the building in winter	The Science Centre external walls are insulated concrete formwork (ICF) and light steel frame (LSF) providing a U-value of x and 0.37 (R-value of 2.68) respectively. SANS 204 requires a U-value of 0.52 for Zone 2 (a total R-value of 1.9). The Science Centre therefore exceeds code requirements. The roof makes use of reflective paint on the roof sheets and 70 mm rigid polyurethane board insulation having a U-value of 40 in the ceiling (R-value of 0.025). SANS 204 requires a roof assembly U-value of 0.31 (R-value of 3.2). External doors and windows are double glazed PVC frames with low e glass with an overall U-value of 2.1 (R-value of 0.47).	Highly insulated building envelope
Capture solar heat gain in winter	The window shading devices are designed to allow solar heat gain in the winter. In addition, heat built up in winter in the passive ventilation towers is captured and forced into the classrooms and administration offices.	Shading devices allow ingress of winter solar heat gain. Passive ventilation towers collect winter solar heat which is forced into the classrooms and administration offices.
Restrict solar heat gain in summer	Shading devices (overhangs, deciduous trees) on the north and west elevations are	Shading devices on north and west elevations. No

	designed to shield the sun from solar heat gain.	fenestration on the east elevation.
Natural ventilation	The Science Centre relies on natural ventilation. The classrooms cross ventilate from openable windows to a passive vertical tower driven by a solar heat source at the discharge level. The administration office relies on a Trombe wall to drive cross ventilation. The exhibition space relies on displacement ventilation with low level air entry on the south elevation and high level exhausts on the east and west gables of the saw-tooth roof.	Provide natural ventilation using passive ventilation towers, Trombe wall, and displacement ventilation.
Reduce temperature swings with thermal mass floors	The Science Centre uses an uncovered concrete thermal mass floor slab to store any internal heat energy in summer and winter.	Thermal mass floor
Use of daylight as a primary light source	The Science Centre relies on daylight as a primary lighting source. The window area, narrow floor plate for the classrooms and administration offices, orientation, and the saw tooth roof allow the building to be entirely daylit, reducing the need for energy-intensive internal lighting. The daylighting also increases productivity and reduces stress. If and where necessary, artificial task lighting will be used. The exhibition centre uses a south facing saw tooth roof for lighting. The classrooms and administration offices make use of fenestration for daylighting.	Use daylight as the primary light source
Air tightness	The Science Centre relies on strict construction detailing to avoid leakage. The building is constructed from ICF and LFS which both provide the dual benefit of high performing insulation and air tightness. Two coats of tape and air barrier material is applied to the joints of the LSF to ensure tight seals between the boarding. The joints between the fenestration frame and the wall are sealed by a purpose-made rubber sealing strip. Opening sections have a rubber seal between the opening edge and the frame (windows and doors).	Sealing of all gaps

External views	The Science Centre makes use of a narrow floor plate for the classrooms and the administration offices together with controlled fenestration opening to ensure external views. The saw tooth roof of the exhibition hall provides external views of the sky, while strategically positioned windows allow external views to the east and the south.	Maximize external views
Sanitation	Smart San system & Reed bed, utilising a combination of technologies Specification of fittings	Re-use of water and pre-cycling of black and grey water
Water	Rain water harvesting system Sustainable Urban Drainage Grey water recycling Water Management System	On site re-use
Electricity	Photovoltaic Panels Wind turbine Hydrogen Fuel Cell Solar water heaters Energy Management System application (Microgrid)	Automated energy management using national grid as backup

Due to limits on this paper's length, only the energy technologies and construction systems applied in the CSC will be discussed.

IBT structure & insulated concrete insulation

Light steel frame construction can be described as an off-site method of construction since a lot of the manufacturing takes place in a factory, and the components transported to and assembled on site. This method is also known as 'dry construction' as no wet materials, such as cement, are used during the erection process. This speeds up construction as workers do not have to wait for the wet materials to dry and/or cure, and it also reduces the consumption of water, a scarce resource in South Africa. Light steel frame building consists of structural wall panels and/or trusses, assembled using cold-formed steel sections made from thin gauge high-strength galvanised steel sheet. Sections are joined together – typically in a factory – using rivets or self-tapping screws, to form structural wall panels and/or roof trusses which are then transported to site for erection on foundations and floor slabs. The wall frames are clad externally and internally on site with a range of cladding materials, with the services (data, electrical and plumbing conduits) and insulation material installed in the wall cavity. A wide range of exterior and interior cladding is available, and a number of insulation materials may be used including fibre thermal insulation mats, loose fill thermal insulation, reflective foil laminates, flame retardant grade expanded or extruded polystyrene, and rigid polyurethane foam and poly-isocyanurate.

Light steel frame building can either be erected in accordance with the South African National Standard SANS 517:2013 'Light steel frame building', or by rational design prepared by a competent person. The vertical steel sections of the wall panels are at 400 mm centres and the horizontal sections are at 1 200 mm centres. The steel frames are clad externally with 18 mm timber shutter board and finished with cement fibre boards. Internally the steel frame is clad with gypsum board. Insulation is inserted into the steel frame cavities. Typically light steel frame can be used for up to double story building with a maximum height of 6 m, thereafter additional structural support is required (SASFA 2007).

Insulated concrete composite (ICC) generally comprises two external skins of reinforced, high-strength concrete and an inner core of insulation. Various insulation materials are used, including fibreglass, rock wool and polystyrene, although extruded polystyrene (XPS) and expanded polystyrene (EPS) are most commonly used. The sheet size can vary according to the project requirements and window and door openings made in the sheet prior to delivery to site. Generally EPS sheets are erected on site and supported by structural light gauge steel framing inserted into the centre of the insulation sheet. A steel or fibre mesh is attached to the sheet and a 22 Mpa concrete layer about 25 mm thick is sprayed onto the mesh. Typically R-values of 5.0 (U-value of 0.20) can be achieved. Once erected, the ICC wall panels are sprayed on both sides with a high density, fibre-cement technology, called Fibrecote. The combination of Neopor, the *in situ* reinforced substructure, and Fibrecote acts as a composite member, providing load bearing or non-load bearing walls with unparalleled strength with the look, feel, and durability of masonry construction, while offering far superior insulation and STC values, reduced construction time and all at an affordable cost. The Imison 3 Building System (Agrément Certificate) is used on the CSC and comprises:

- concrete surface bed with thickened foundation beams
- a galvanised light gauge, cold rolled structural steel frame
- core infill panels made up of:
- expanded polystyrene (EPS) with a density of 16 kg/m
- galvanised steel reinforcing mesh cladding to both sides of the wall panel
- alkali resistant woven fibreglass reinforcing mat to both sides of the wall panel
- spray applied fibre reinforced plaster 25 mm thick
- light gauge steel trusses
- light weight roof cladding

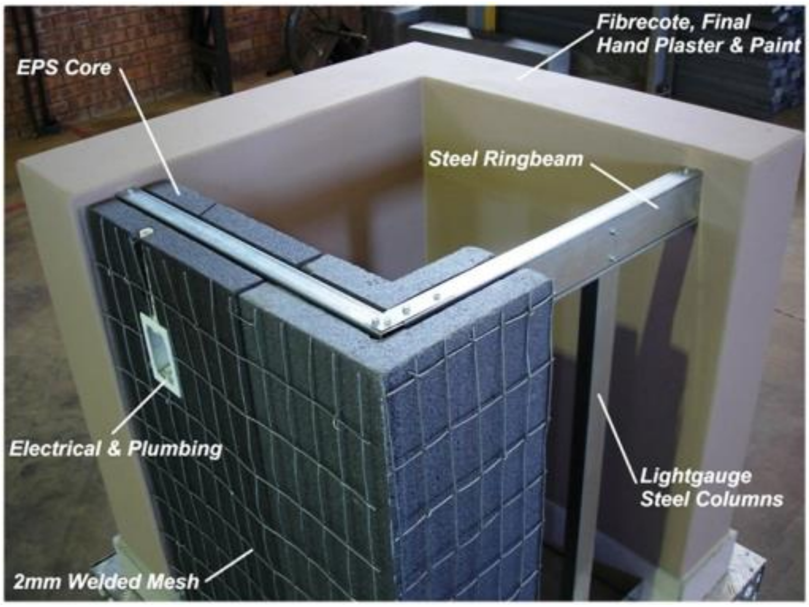

Figure 1 *Typical system detail (Imison 2019)*

Energy Generation and Storage

The passive design strategies employed for the Science Centre has resulted in a lower energy demand enabling the Science centre to produce enough energy through the solar panels on the rooftop and the small scale wind turbines to power the building. The Science Centre is also an example of a grid asset: due to the on-site energy generation under circumstances when the building is not consuming all of its energy, the surplus can be fed back into the grid. Based on a comparable science centre the projected energy demand is estimated at 110 000 kWh/year. The power provision of the Cofimvaba Science Centre is unique as it relies on multiple energy sources. It consists of the fuel cell, battery, PV, wind and grid supply with solar water heaters to reduce energy demand. This also introduces complexity into the control system, which is discussed later. The fuel cell system is a PEM (proton exchange membrane) type which is regarded as highly efficient and designed to produce clean energy; in the system chemical energy is converted to electricity (Jian et al. 2015).

The energy efficiency from a fuel cell stack can be as high as 80% (Emanuelsson & Persson, 2007). In the design of the system, two options were considered for providing hydrogen, namely stored hydrogen and an electrolysis process. Renewable energy sources should power the electrolyser, which, in conjunction with battery storage, gives a hybrid energy system with increased reliability and security. This system represents the favoured approach to decarbonized hybrid microgrid systems (Mohammed et al. 2014).

The design of hybrid microgrid systems including fuel cells has been undertaken by a number of authors (Mohammed 2014, Taklimi & Hosseini, 2011, Méziane, Khellaf and Chellali, 2012). These systems are composed of renewable energy sources (photovoltaic panels and wind turbines) and battery backup and storage systems. In such systems the grid is limited to less than 10 000 kWh per annum.

The system at the Cofimvaba Science Centre will use stored hydrogen at 200 bar, to provide 112 kWh per day. The fuel cell system does increase the cost of the system, the number of operations of the system with fuel cell increases significantly. When stored hydrogen is used the fuel cell is expected to operate for 755 hours per annum. Data on the annual generation and load profiles will be used to develop the controller. With the cost of hydrogen expected to decline, this system has the potential to demonstrate the viability of small scale decarbonised hybrid systems, inviting wider adoption of this technology.

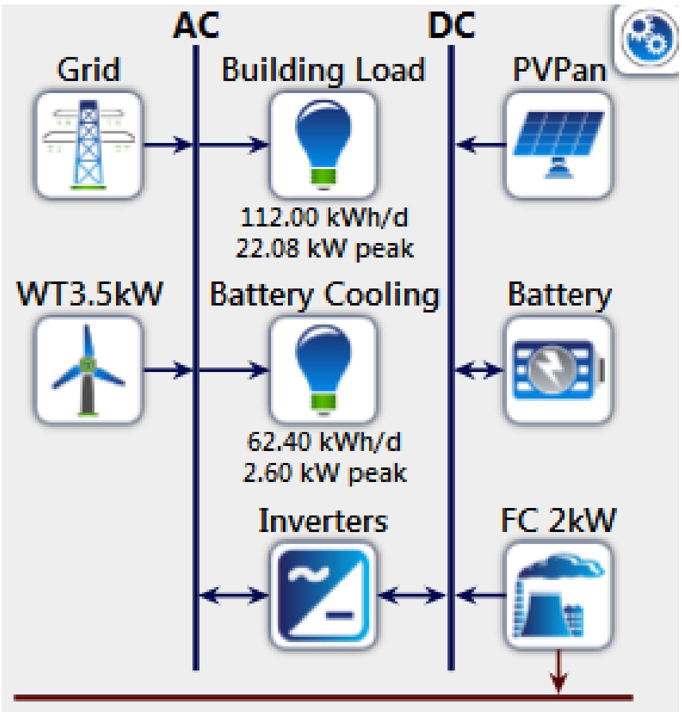

Figure 2 *Electrical System design layout (excluding the HFC (Element Consulting Engineers & CSIR, 2019)*

Microgrid generation dispatch merit order:

- 1) Solar PV, wind
- 2) Battery storage
- 3) Hydrogen fuel cell
- 4) Eskom utility grid

Eskom utility grid function:

- Energy reserve
- Backup supply

Requirements

- Stable standalone grid, strong DC bus
- Complies to SMA design rule
- Cost effective solution
- Single load bus controller
- Seamless synchronisation of Eskom voltage and frequency

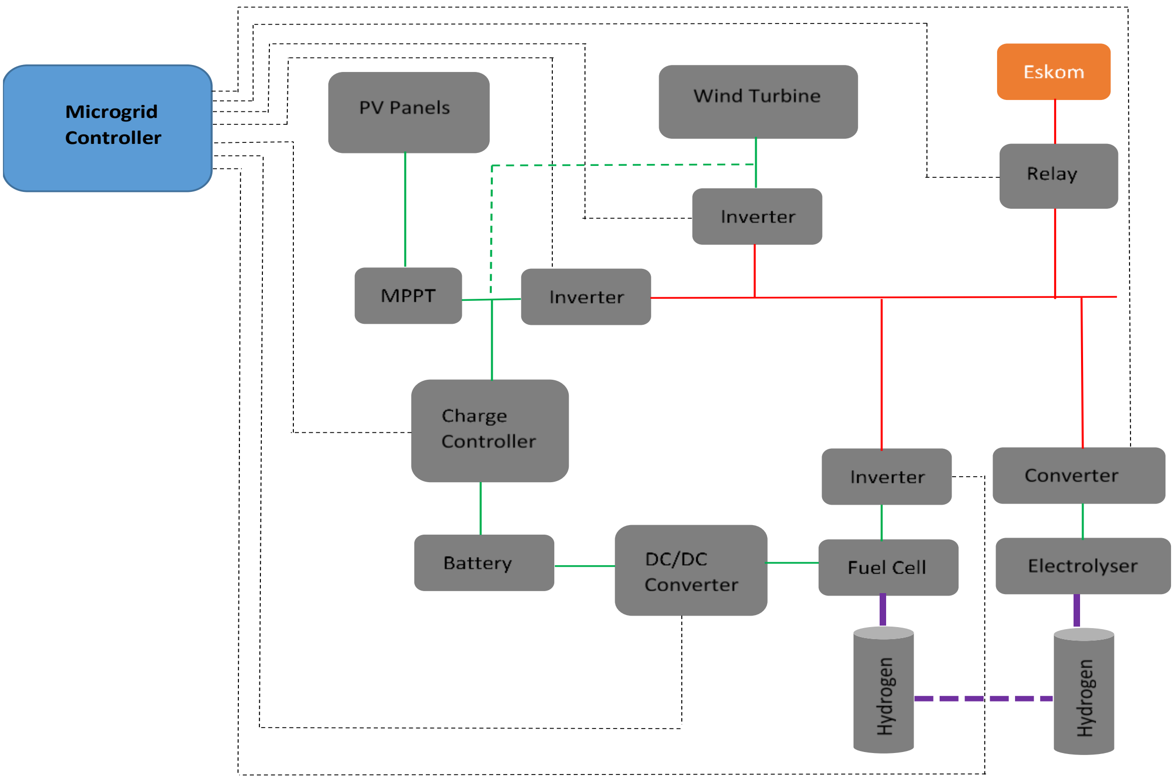

Figure 3 *Electrical system Phase 2 control architecture including the HFC (Element Consulting Engineers & CSIR, 2019)*

CONCLUSION

The selection and application of appropriate technologies will be an ongoing point of debate. However, when considering the rural built environment of South Africa, solutions are needed. Not only for households but in delivering services. New and innovative approaches are required to deal with old problems and new educational needs. The CSC presented an opportunity to combine cutting edge science and technologies combined with practical passive solutions. The following five years' worth of building performance data will support the next generation of IBT and sustainable technologies for rural environments in South Africa. It goes without saying that the success of any project lies in administrative and procurement efficiency. The technologies applied will improve consumption, demonstrate rapid construction and will reduce lifecycle cost. However, the fiduciary climate and financial controls currently in place for infrastructure procurement in the public sector does not support the gains achieved in this project.

The CSC project will provide educational support to numerous young minds, will broaden and stimulate the future thinkers of the Eastern Cape and serve as a prototype for future civic buildings, net zero government infrastructure and a new model for education and educator support. The building serves as a living laboratory for science and technology, to incorporate curriculum teaching through the building systems as practical aspects. The virtual online streaming and teaching hosted from the SCS site to in excess of 80 rural schools is a 1st for the South African schooling system.

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