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The design and installation of a combined concentrating power station, solar cooling system and domestic hot water system

Jeremy P. Osborne[a], Paul Kohlenbach[b], Uli Jakob[b], Johan Dreyer [c], Jamey Kim[a]

[a]*Energy Analysis & Engineering, 608 Harris St, Sydney NSW 2007, Australia*
[b]*SOLEM Consulting, Stendaler Str. 4, 10559 Berlin, Germany*
[c]*NEP Solar, Unit 20, 14 Jubilee Ave, Warriewood NSW 2102, Australia*

Abstract

The University of Technology, Sydney (UTS) has built a unique tri-generation system that provides chilled water, hot water, and electricity to their new Faculty of Engineering and Information Technology (FEIT) building. It integrates parabolic trough collectors, flat plate collectors, photovoltaic panels, and wind power as generators with thermal and chemical energy storage. The heat from the parabolic trough collectors is used to run a small-scale Organic Rankine Cycle (ORC) unit as well as a small-scale ammonia/water absorption chiller to provide either electricity or chilled water, respectively. The condenser heat from both units is fed into the domestic hot water (DHW) supply of the building in addition to the solar heat from the flat plate and the parabolic trough collectors. The design concept including the main system components and the system control strategy are described in detail. Further, the lessons learned during the installation and commissioning of the complex tri-generation system are given. As a novelty in this area, the tri-generation system has been specifically designed to allow students and researchers to work with it, hence this paper also describes the wide range of teaching opportunities for undergraduate and graduate engineering students as well as post-doc researchers.

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1. Introduction

The urban environment resides more than 50 % of the world's population. It is desirable to employ distributed sustainable energy technologies in order to supply its energy needs and to lower the impact on the environment [1]. In general, energy consumed is used for space heating and cooling, hot water heating and electrical devices/appliances. The tri-generation system described in this paper demonstrates how multiple renewable energy

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systems can be integrated together and successfully supply these loads within a highly urbanized multi-level building. The University of Technology, Sydney (UTS) has built a sustainable tri-generation system that provides chilled water, hot water, and electricity to their new Faculty of Engineering and Information Technology (FEIT) building. It is also a teaching and research tool for their next generation of engineering students and researchers. It integrates concentrating solar thermal collectors, flat plate collectors, photovoltaic panels, and wind power as generators with thermal and flow battery chemical energy storage. The result is an independent mini-grid that has zero net energy consumption from the grid. The tri-generation systems electrical component powers a completely stand-alone (or island) grid within the building. The hot water and chilled water systems augment the hot water and chilled water generation in the building.

2. Design concept

The system uses concentrating parabolic trough collectors that convert the sun's energy to thermal energy, delivered as 175°C (347°F) pressurised hot water. This hot water is used to either generate (i) electricity from an Organic Rankine Cycle (ORC) power generator, (ii) chilled water of 12°C (54°F) from an absorption chiller or (iii) domestic hot water of 78°C (172 °F) directly from the solar collectors or through the condenser heat of ORC and chiller. The domestic hot water is delivered in parallel to a flat plate solar collector system which was designed as a secondary stand-alone system for research purposes. Figure 1 shows a schematic of the overall energy supply to the building, Table 1 shows the design parameter of the main components.

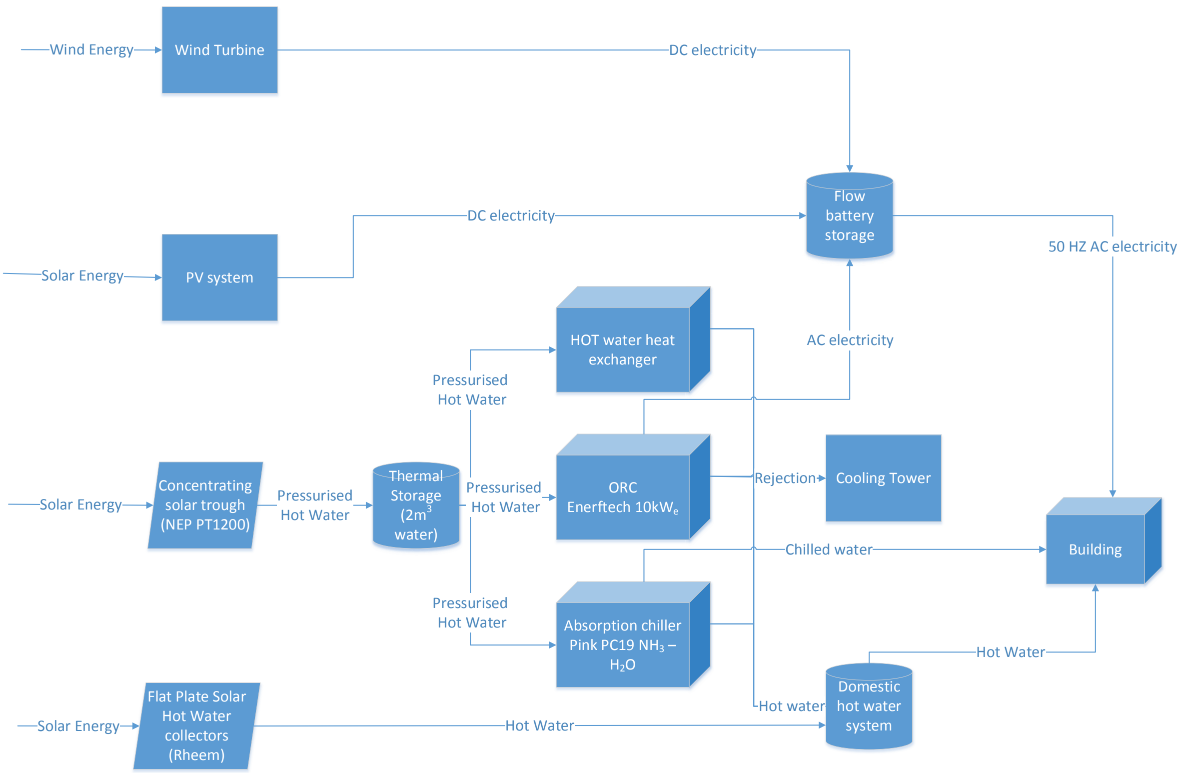

Figure 1. Schematic of tri-generation system at University of Technology, Sydney.

Table 1. System design parameters

System component	Design parameter	Value/Unit
Parabolic trough concentrating collectors	Aperture area	115 m^2
Flat plate collectors	Aperture area	45 m^2
Photovoltaic panels	Peak power	22 kW_p
Organic Rankine Cycle	Nominal power	10 kW_e
Absorption chiller	Nominal cooling capacity	19 kW_r
Wind turbine	Nominal power	10 kW

The electricity generated from the ORC is integrated with a photovoltaic array and a wind turbine combined to charge a Zinc-Bromide flow battery providing electricity to the building. The design of the battery, PV array and wind turbine is outside the scope of this paper.

2.1 Design criteria

The University of Technology Sydney (UTS) set the following design criteria for the tri-generation system at the beginning of the project:

- It must provide teaching and research opportunities
- It must be able to produce electricity, chilled water, and hot water.
- Only commercially available components are to be installed, excluded R&D equipment.
- It must be able to be installed in a short period of time.
- It must use four NEP SOLAR PolyTrough 1200 collectors or equivalent.

3. Selected system components

Based on the design criteria given by UTS the following components for the tri-generation system were selected, taking into account different selection criteria described below.

3.1 Absorption chiller

Seven absorption chiller models were considered suitable for the capacity and application in this project. These were reviewed for:

- Risk of failure – A product was considered low risk of failure if it was factory built, non-experimental, with manufacturer having prior experience and offered a warrantee, and factory testing report.
- Delivery time – It was desirable to take delivery of the unit within 6 months of ordering, dictated by the building construction schedule,
- Cost – The total cost of the chiller was an important factor, and dictated the size of the unit.
- Flexible operation - As the main objective of the system was its teaching and research opportunity, a machine that was robust and would not be easily damaged by a wide range of operating conditions it might be faced by students.
- Physical size and transportability – The physically size was set by the building passage ways and elevator size, weight, floor point pressure limitations,

The Pink PC19 absorption chiller was selected. Pink GmbH from Austria has supplied many small scale units to universities around the world. It was able to deliver in the required project time frame. The chiller’s cooling capacity is 19 kW_r which is only 50% of the required cooling capacity for the project. However, UTS decided to purchase only one chiller which leaves provisions for a second one to be installed later. This was considered for reasons of flexibility in order to install further experimental chillers as part of their research later on. The PC19 is an ammonia-water chiller which offers a wide range of operation as there is no concern of crystallisation faced by LiBr-H_2O chillers. It is designed in a way that enables easy access to the internal operation of the chiller providing good learning opportunities for students. See Figure 2 for an image of the chiller. A hybrid cooling tower in closed circuit configuration from LU-VE is used for heat rejection of the chiller. The hybrid circuit minimises water consumption by only using water when the dry bulb temperature is insufficient to provide cooling at the desired temperature.

Figure 2. Pink PC 19 absorption chiller. Source: Pink GmbH

3.2 Organic Rankine Cycle (ORC) generator

There are very few models for organic Rankine generators available in the required capacity range. Three manufactures were identified. Eneftech from Switzerland was selected as it had nine years experience with manufacturing small scale units from 5-30 kW_e. The model selected was the ENEFCOGEN Green 010GRE-01 with a peak output of 10 kW_e. A sterling engine was also considered as a solar-driven power generator however a commercially suitable model could not be identified. The selected ORC generator offers an increased learning opportunity to be able to demonstrate 10kW_e of power output for a short time period. Figure 3 shows an image of the generator. Condenser heat from the ORC can also be rejected via the hybrid cooling tower.

Figure 3. Eneftech ORC generator 010GRE-01. Source: J. Osborne

3.3 Storage

The thermal storage is a pressurized hot water vessel that can operate up to 175°C (347°F), and stores 2,000 litres of fluid. ORC and Chiller have a maximum inlet temperature of 150°C (302°F) and 110°C (230°F), respectively, which is lower than the maximum storage temperature. This results in a higher storage capacity, allowing for smaller physical size of the vessel in order to fit into the plant room. The storage capacity enables an estimated four hours of chiller operation and 90 minutes of ORC operation at $5kW_e$ power output. The storage vessel is fitted with 60 kW_e of electric heating elements to serve as a backup and during commissioning. The electric elements are not designed for normal operation but rather for commissioning and experimental purposes.

3.4 Solar arrays

There are two solar thermal arrays in use. The parabolic trough concentrating collector array consists of four NEP Solar PolyTrough 1200 modules of 29 m^2 aperture area each, yielding a total of 115 m^2 aperture area. The size of the concentrating collector array was limited by the roof size. This array provides up to $60kW_{th}$ of heat at a maximum supply temperature of 175°C. The heat transfer fluid is pressurised water. The flat plate collector array consists of 50 m^2 flat plate collectors from Rheem Australia. It supplies hot water to the domestic hot water system, operating up to 75°C. The heat transfer fluid is water. See Figure 4 for an image of the two collector arrays.

Figure 4. View of parabolic trough (rear) and flat plate collectors (front) on the roof of the UTS building. Source: J. Osborne

3.5 Hydraulics

The hydraulics have been designed in order to allow maximum flexibility of the system, ie to allow the coupling of the main thermal components with each other. This was done to provide a wide range of learning opportunities for the students and researchers at UTS. Figure 5 shows the piping and instrumentation diagram (PID). There are three main circuits worth mentioning:

The distribution circuit delivers the hot solar fluid from the storage tank to either the ORC, the absorption chiller or the heat dump heat exchanger. This is done at the respective design temperatures, controlled via a 3-way mixing valve and the bypass valves on each piece of equipment.

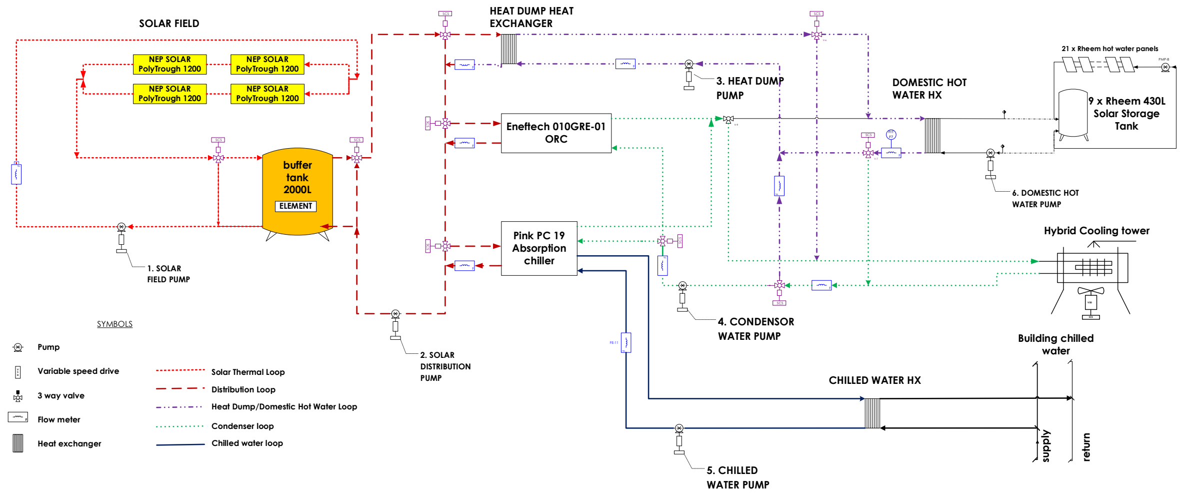

Figure 5. Piping and instrumentation diagram (PID) of the tri-generation system at UTS.

The condenser circuit removes the reject heat from both ORC and/or absorption chiller and delivers it to either the domestic hot water system or to the cooling tower. The flat plate and the concentrating collectors pre-heat the domestic hot water tanks in parallel. The reject heat from ORC condenser and Chiller has a maximum temperature of 45°C (113 °F), however heat directly from the concentrating collectors (through the heat dump heat exchanger) can deliver up to 78°C (172 °F). The flat plate collectors can deliver heat up to 75°C (167 °F). Having both the flat plate collector system and concentrating trough system on the same roof supply to the same load will provide excellent side-by-side comparison tests.

In the heat dump circuit, heat can be dumped from the 2,000 litre buffer tank to the cooling tower or to the domestic hot water, if required. The temperature delivered to the domestic hot water is limited to 78°C (172 °F). The use of the cooling tower as a heat dump allows any load conditions to be simulated. This provides good flexibility for the students' learning outcomes.

The chilled water from the absorption chiller contributes to reducing the cooling load of the building. It is delivered indirectly to the building's chilled water distribution line, via a heat exchanger that cools the return line of the building distribution. Thus, the load on the conventional chillers - which provide the majority of the building's cooling load - is reduced. No additional pump was required in this configuration.

3.6 Parasitic energy consumption

The estimated parasitic electrical power consumption at design conditions is predicted below in Figure 6. The total power consumption is expected to be 1.7 kW_e during chiller operation and 1.2 kW_e during ORC operation. This includes all the energy used by the supporting equipment and is estimated through the manufacturers' informationp. It does not include the cooling tower fan, which is shared with an existing cooling tower in the building. As the system is still in the final commissioning phase there are no experimental results for the parasitic power available.

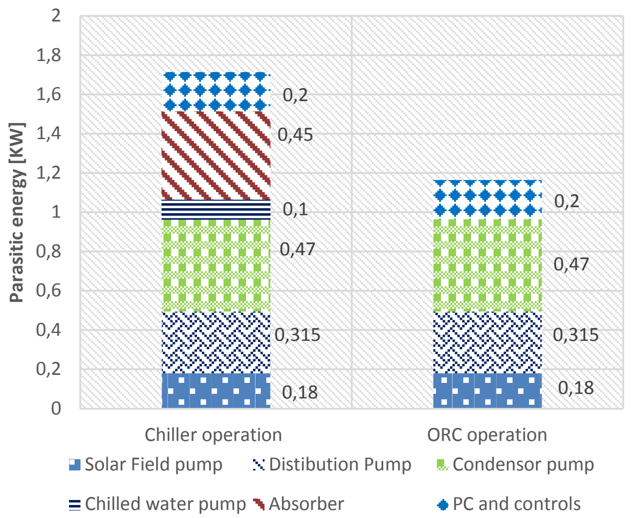

Figure 6. Parasitic power consumption of main components.

3.7 *System control strategy*

The system was designed primarily for research purposes, hence the primary objective of the system control strategy was to provide the necessary frameworks which will allow students to individually control each major system component. The control strategy was designed for two major operating modes:

- automatic operation, which allows the system to operate autonomously , and
- manual operation, which allows users to control various aspects of the system.

Furthermore, the control system was designed to ensure the absorption chiller, ORC and domestic hot water systems did not operate simultaneously, but rather individually depending upon which section of the tri-generation system is being assessed. Innovative system architectures and workflows were developed to design a customised system control interface which will allow students to visually identify and analyse the working fluid temperature and flow rate being calculated by the various temperature sensors and flowmeters located in each design loop. Figure 7 shows a screenshot of the control interface.

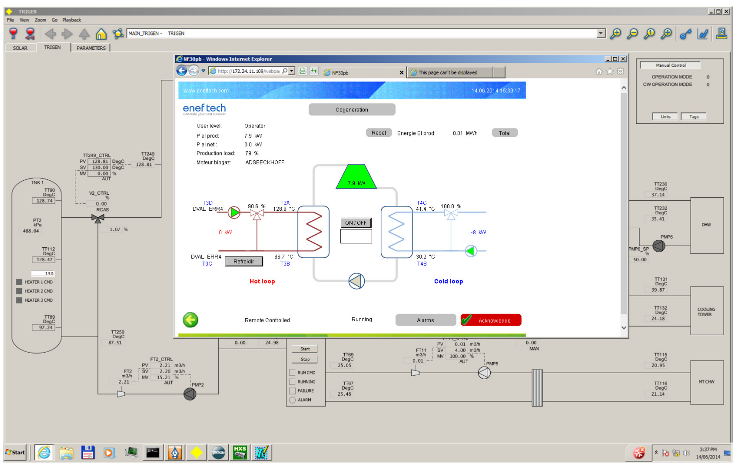

Figure 7. Screenshot of control interface, showing ORC parameter as a callout.

4. Results and discussion

The tri-generation system is still in the final phase of commissioning. Constraints on site have so far prevented the achievement of real operational results as the system has been unable to operate. However, the authors believe the difficulties and lessons learned during installation and commissioning are worth mentioning instead. Furthermore, the teaching opportunities for students as well as the research possibilities are described.

4.1 Difficulties and lessons learnt

- Available components in this size - Due to the small scale nature of the system it proved difficult to find suitable commercially available equipment. This was especially true for the ORC generator. The ORC chosen is a $10kW_e$ generator which will operate nominally at $5kW_e$. Larger systems should prove less challenging. Following the learning from this project, equipment could be designed specifically for such integrated systems.

- Balancing commercial design with innovation - The restraint placed on the project by specifying all equipment to be commercially available was significant. The concept of a small solar thermal based tri-generation system in itself is innovative, however further innovation would be possible if the system was not restrained by budget, schedule and the use of commercially available equipment.

- Not able to cascade design - The initial concept design was for a cascaded system; i.e. the condenser (recooling) side of the ORC was intended to drive the absorption chiller and its condenser side to drive the DHW system. Experimental systems or commercial system to which the suppliers were willing to make modifications could be obtained, but these did not come with commercial guarantees. Further development of ORCs and chillers could provide components suited to such a cascaded system.

- Integration of electrical power with no grid - The entire system design of the island grid of renewable power falls outside of the scope of this paper (and the design and supply of the solar thermal tri-generation system) however it must be noted that much effort was required to develop the system as truly isolated from the main power grid. The ORC employs an asynchronous motor to generate power; however the generator is not connected to the main grid, but to a battery system. Should the batteries not be charged the battery system does not provide an alternating current (AC) grid and as a result the ORC cannot operate. This was overcome by starting the system from the mains grid power and then switching over to the island grid power system.

4.2 Teaching and research opportunities

The system at UTS provides a wide range of teaching opportunities for undergraduate and graduate engineering students. UTS has invested into significantly more measurement equipment than required for the operation of the system. This allows the monitoring and data logging of nearly all system parameter and subsequent analysis of those by students. Also, the system design allows for future expansion of selected components, which is also an opportunity for students to participate. The tri-generation system at UTS provides teaching opportunities in the following areas:

- Concentrating solar collectors: mirror technology, optics, heat losses and heat transfer
- Non-concentrating collectors: design aspects, efficiency calculations, shading
- Solar cooling: Annual coefficient of performance calculations (COP), optimization
- Heat rejection: improving the control strategy of the cooling tower (fan speed, pumps)
- Annual performance analysis: monitoring equipment, data logging, analysis
- Simulations: generating physical models of the system components, varying load conditions using different system configurations
- Validation: using experimental results to validate simulation results for all components

The aim was to provide a teaching and research opportunity for the academic community at UTS, and at other institutes through collaboration. The tri-generation system offers students the ability to run eg. a micro CSP plant, a solar cooling plant or an industrial solar thermal plant all at the click of a button. It can offer students the ability to validate simulation results, to see, touch and feel a real system, and to study the operation of the individual components. It offers researchers the ability to push the current boundaries of knowledge. Selected research topics can include:

- Economic optimisation of the control strategy integrating all of the sources and loads.
- Validation and performance characterisation of the individual equipment.
- Development and validation of standards
- Optimising the control to minimise parasitic power consumption.

5. Conclusions

The University of Technology, Sydney (UTS) has built a unique tri-generation system that provides chilled water, hot water, and electricity to their new Faculty of Engineering and Information Technology (FEIT) building. It integrates parabolic trough collectors, flat plate collectors, photovoltaic panels, and wind power as generators with thermal and chemical energy storage. The heat from the parabolic trough collectors is used to run a small-scale Organic Rankine Cycle (ORC) unit as well as a small-scale ammonia/water absorption chiller to provide either electricity or chilled water, respectively.

As a novelty in this area, the tri-generation system has been specifically designed to allow students and researchers to work with it. Measurement and data logging equipment installed allows a nearly all system parameters to be measured. Flexible hydraulics and some undersized components provide space for future extensions. The tri-generation system provides a wide range of teaching opportunities for undergraduate and graduate engineering students as well as post-doc researchers.

It can be concluded that the design and installation of such a small-scale solar thermal tri-generation system using commercially available components to suit a limited budget is challenging and system design and integration is easily underestimated. This system however demonstrates that such a system is indeed possible and lays the foundation for future research and development in the field.

References

[1] Kohlenbach, P. und Jakob, U. (2014). Solar Cooling: The Earthscan Expert Guide to Solar Cooling Systems. Routledge/Taylor & Francis. ISBN 978-0415639750