The Innovation Hub

for Affordable Heating and Cooling

Report #LLHC4-005

Healthcare Living Laboratories: Queensland Children's Hospital – GMG Thermal-XR Coating System Technology Evaluation Report

27 May, 2022

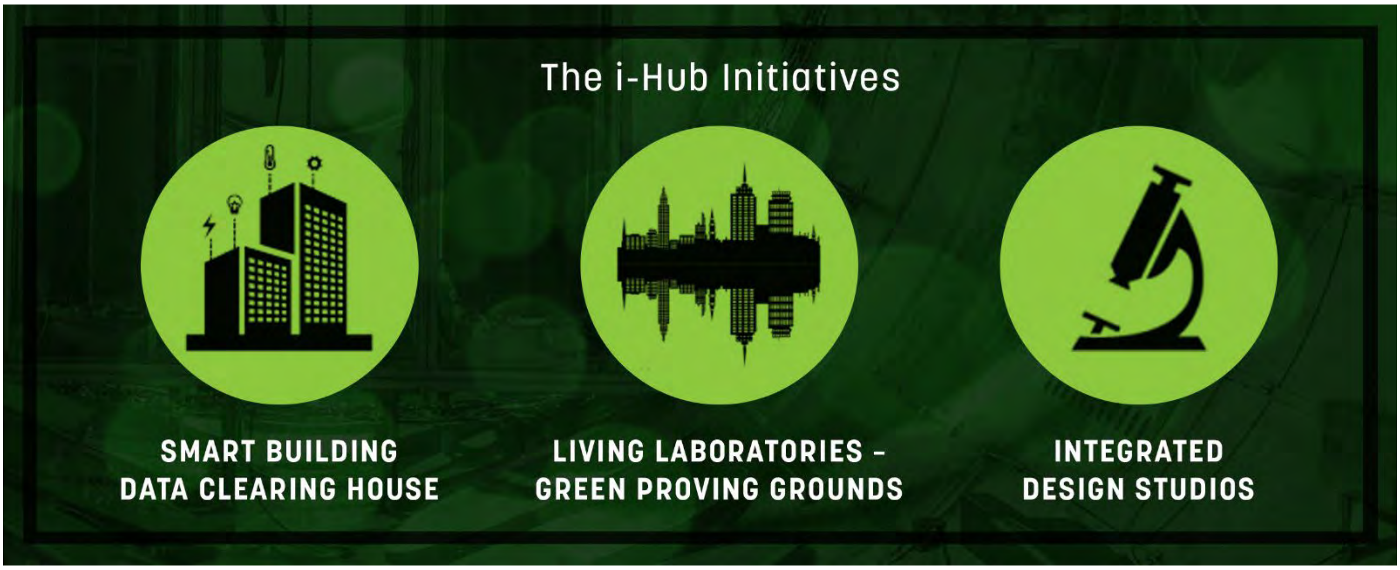
QUT

About i-Hub

The Innovation Hub for Affordable Heating and Cooling (i-Hub) is an initiative led by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) in conjunction with CSIRO, Queensland University of Technology (QUT), the University of Melbourne and the University of Wollongong and supported by Australian Renewable Energy Agency (ARENA) to facilitate the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry's transition to a low emissions future, stimulate jobs growth, and showcase HVAC&R innovation in buildings.

The objective of i-Hub is to support the broader HVAC&R industry with knowledge dissemination, skills-development and capacity-building. By facilitating a collaborative approach to innovation, i-Hub brings together leading universities, researchers, consultants, building owners and equipment manufacturers to create a connected research and development community in Australia.

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.
The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.



Healthcare Living Laboratories: Queensland Children's Hospital – Thermal-XR coating system

The Living Laboratory in Queensland Children's Hospital (QCH) will support the hospital sector to transition to a net-zero energy/demand future. In particular it has validated the impact of emerging technologies in demand reduction, demand management, renewable energy and enabling technologies, in terms of core health services (patient and worker health and comfort), building maintenance and operations, environmental impact and financial management (including participation in energy markets). Graphene is a nanomaterial and can help increase heat transfer rate when graphene is added to cooling liquid or painted on heat exchanger surface. Thermal-XR coating system includes a graphene dosed paint product. When Thermal-XR coating system is applied to condensers' heat exchangers, the energy performance of condensers may be improved due to higher heat transfer coefficients on the heat exchangers. The in-situ performance improvement of Thermal-XR on QCH outdoor condensers has been independently quantified.

Lead organisation

Queensland University of Technology (QUT)

Project commencement date

01/06/2019

Completion date

30/06/2022

Date published

30/06/2022

Contact name

Dr. Aaron Liu

Email

L50.liu@qut.edu.au

Living Lab Activity Leader

Associate Professor Wendy Miller
W2.miller@qut.edu.au

Project website

www.ihub.org.au

Project participants:

Queensland Children's Hospital (Living Lab host, part of Children's Health Queensland, Queensland Health)
Graphene Manufacturing Group (Technology Provider)
Fusion HVAC and Zenith Energy (HVAC engineering and energy metering services)

VERSION HISTORY

ID & Version #	Prepared By	Revision Date	Approved By	Approval Date	Description
1.0	Aaron Liu	05/04/2022			Draft for reviewing
2.0	Aaron Liu	26/05/2022			For reporting

Table of contents

List of Tables

List of Figures

1 INTRODUCTION

1.1 Problem Statement

Heating, ventilation, air conditioning and refrigeration (HVAC&R) is essential in most settings to ensure a pleasant, comfortable, safe work environment and food supply. In commercial buildings around the world, 70% of energy usage and 63% of greenhouse gas emissions are estimated to be contributable to heating, cooling and ventilation. HVAC typically accounts for 40% to 50% of the total energy bill for businesses and commercial buildings. Inefficient HVAC&R system may lead to higher than expected electricity bills and continuous breakdowns.

The heat exchanger is a key component of an air-cooled condenser (right side of Figure 1). Corrosion over time degrades the heat exchanger surface, and system efficiency continues to deteriorate over the life of the condenser coil. With corrosion comes a slow but inevitable loss of heat exchange efficiency which ultimately wastes electricity and increase energy costs. Outdoor condensers are highly susceptible to corrosion, due to environmental factors and operational conditions. Once corrosion has started, the lost efficiency is difficult to recover. If the corrosion is significant, the coil will need to be replaced at a high cost. Thermal-XR graphene painting may be a potential technology to help protect a corroded coil with a thermally conductive coating and restore its heat exchange efficiency.

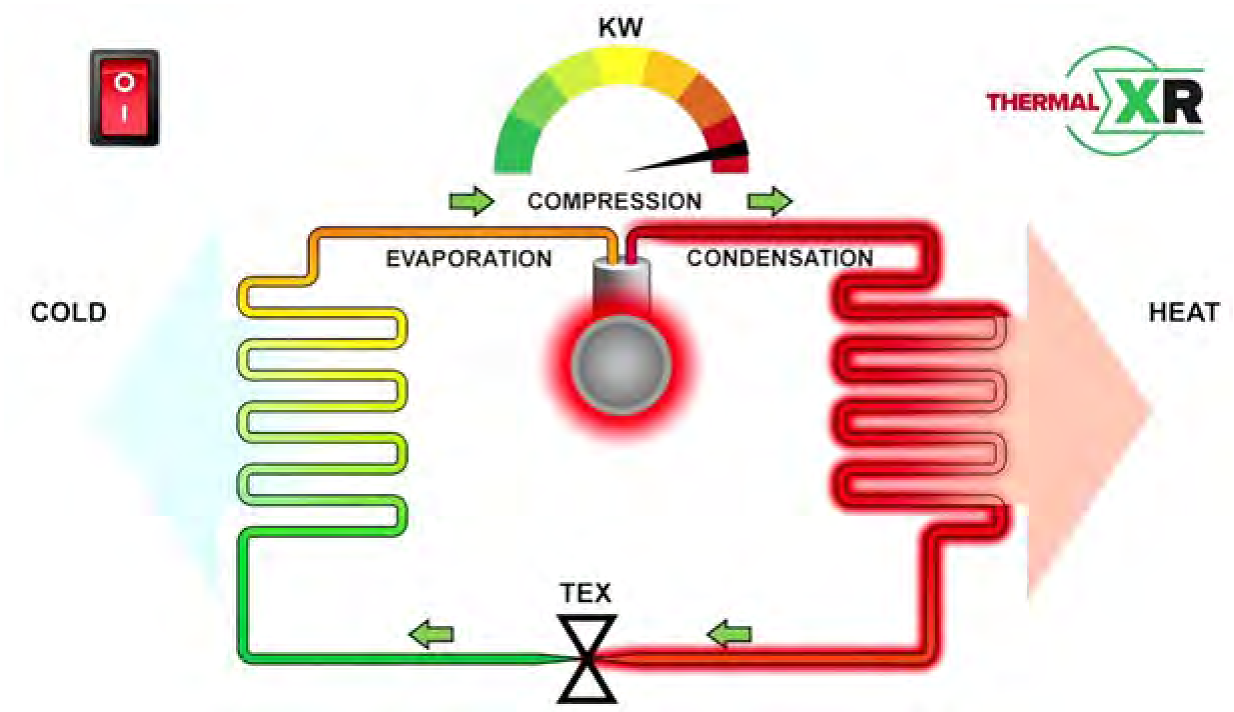


Figure 1 HVAC&R Process Overview

(Credit: GMG and Thermal XR)

1.2 Technology Overview

Compared to standard anti-corrosive coating, graphene may offer multi-faceted benefits in energy efficiency and non-toxic anti-corrosion properties. Graphene technology may provide an increase in thermal conductivity and when applied to aluminium or copper coils, the graphene coating may expedite the release of heat as well as increases the surface area or pathway the heat must travel. This would mean that the heat exchanger operates under less stress requiring less power and in parallel reducing carbon emissions. The graphene also provides a super-hydrophobic surface allowing no condensation build-up, reducing future opportunity for corrosion.

The Thermal-XR process of preparing, activating, coating and then maintaining the heat exchange surface of condenser coils is expected to deliver energy efficiency and long-term corrosion protection for those valuable assets. Thermal-XR Restore coating stops corrosion by creating a thin shield protecting the metal surfaces from continued deterioration. The graphene added coating is safe to use, environmentally friendly, and can increase thermal conductivity. This technology may deliver energy savings and make existing HVAC&R equipment and HVAC&R systems more efficient.

Thermal-XR can be applied to condensers with 4 different products applied in 4 steps (Table 1). The whole process helps the coating's adhesion (steps 1 and 2), and ensures long term thermal conductivity and corrosion protection (steps 3 and 4). The following figures and writing provide a visual explanation of the four steps for applying the Thermal-XR coating system. The specific product applied in each step is included in the brackets in each figure's caption.

Graphene added paint is applied in Step 3 which is intended to recover/improve heat transfer of corroded condenser coils and provide anti-corrosion properties. This project evaluated the impact of Step 1, 2 and 3 on QCH condensers in two stages.

Table 1 Thermal-XR process description

Step	Product	Purpose	Description
1	Thermal-XR Prep	De-ruster, degreaser and phosphator	Clean condenser heat exchange surfaces for the next step
2	Thermal-XR Activate	Treat aluminium and enhance adhesion	Activate heat exchange surfaces for coating in the next step
3	Thermal-XR Restore	Restore thermal efficiency and build up anti-corrosion properties	Apply graphene added paint to heat exchange surfaces for better thermal conductivity and durability
4	Thermal-XR Maintain	Remove dirt and contamination on coil	Maintain the coating and condensers' efficiency (every 12months)

Step 1: Preparation. Thermal-XR Prep is used to clean the condenser heat exchange surfaces.

Figure 2 Cleaning process (Thermal-XR Prep)

Step2: Soak the heat exchanger’s surface with Thermal-XR Activate

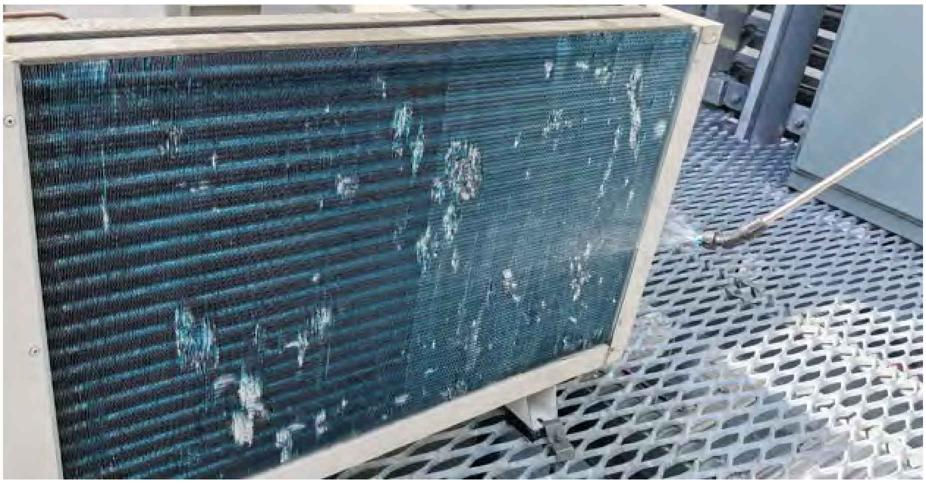


Figure 3 Thermal-XR activate surface for painting (Thermal-XR Activate)

Step 3: Spray graphene added paint

Figure 4 Painting (Thermal-XR Restore)

Step 4: Maintain the coating and capacity with regular cleaning (e.g., annually)

Figure 5 regular maintenance (Thermal-XR Maintain)

1.3 Objectives

The main objective of this project is to, through in-situ experimentation, quantify Thermal-XR's impact on the energy performance of QCH outdoor condensers.

There are five stages for the technology test:

- Energy monitoring prior to Thermal-XR Prep (in-situ without any treatment)
- Application of Thermal-XR Prep
- Energy monitoring post Thermal-XR Prep and before graphene coating
- Application of Thermal-XR Prep, Thermal-XR Activate, Thermal-XR Restore (graphene coating)
- Energy monitoring post graphene coating

2 TEST DESCRIPTION

2.1 Site Descriptions

Queensland Children's Hospital has outdoor condensers that service cold rooms and a freezer in the hospital's kitchen. More information about QCH's energy infrastructure and baseline data can be found in [1] and [2]. These condensers are located on a non-covered plant area of the hospital. The energy performance of these condensers has been measured before, during and after the application of the treatment system. Refer to the following section for a full description.

Figure 6 QCH site for Thermal-XR testing

Figure 6 shows the QCH outdoor condensers plant room where Thermal-XR system is applied to four of the condensers. Information about those tested condensers is provided in Table 2.

QCH facility management and QCH kitchen staff were consulted to confirm the availability of these condensers for testing.

Table 2 Condensers at site

Item	Description	Asset ID	Model	Testing
2	Relaxing Cold Room	CU-QCH-03.02	APB6.OML2-4	Cleaned with Thermal-XR Prep to return to OEM status (control case)
3	Dairy Cold Room	CU-QCH-03.03	APB6.OML2-4	Cleaned and coated
4	Fruit/Veg Cold Room	CU-QCH-03.04	APB6.OML2-4	Cleaned with Thermal-XR Prep to return to OEM status (control case)
5	Cool/Chill Cold Room	CU-QCH-03.05	APB6.OML2-4	Cleaned and coated

2.2 Tested Item Description

The item to be tested is the Thermal-XR coating system, supplied by GMG. Specific products and the application process are provided in Table 1.

3 METHODOLOGY

3.1 Test Approach and Description

This quantitative research utilised experimental data (in-situ data) and energy data analysis methods. Performance of the Thermal-XR coating system was evaluated with the following data:

1. quantitative data collection for 5th October 2021 to 28th March 2022. Data include energy use logged at 5min intervals, ambient temperature and humidity.
2. baseline energy data for condensers without any treatment (5th Oct 2021 to 6th Dec 2021)
3. energy data for 2 condensers with only cleaning (on 7th Dec 2021), as testing control cases for comparison
4. energy data for 2 condensers with cleaning (on 7th Dec 2021) and graphene coating (on 18th Jan 2022)

Figure 7 Test stages

The test stages are shown in Figure 7.

Prior to Cleaning:

Prior to cleaning the condensers' heat exchangers, measurements were taken to establish the energy and performance baseline. Those measurements included 5-min interval energy data and weather data from an onsite weather station.

Cleaning and post cleaning:

The technology used for the cleaning process was Thermal-XR Prep (Step 1 in Table 1). Comparison was made to energy measurements prior to cleaning and post cleaning to quantify condensers' energy performance improvement due to the cleaning process.

Coating and post coating:

The ingredients in Thermal-XR Step 1 Prep, Step 2 Activate, and Step 3 Restore complement each other. The time gap between application of Step 1 and Step 3 should not be more than 24 hours. Therefore, the cleaning step with Thermal-XR Prep was redone prior to Thermal-XR Activate and Thermal-XR Restore on 18 Jan 2022. Then, a comparison was made to energy measurements prior to coating and post coating to quantify any energy performance improvement of the condensers due to the graphene coating technology. Findings from the site testing were extrapolated to a national wide study.

3.2 Excluded Items

Items specifically excluded from testing are summarised in Table 3.

Table 3 Excluded items

Item Not to be Tested	Comment
Steady state COP	Steady state conditions cannot be achieved or maintained for condensers in operation.
Part-load efficiency performance (IPLV, or NPLV AS4776.1.1)	This is unable to be quantified for condensers in operation.

3.3 Roles and Assigned Responsibilities

The roles and responsibilities are provided in Table 4.

Table 4 Roles and responsibilities

Role	Responsibility
Bruce Bonney, Jason Sanders (QCH)	Living lab host, facilitate access to the building and test site. Coordinate the research requirement with QUT. Report any problems that might hinder/stop the testing.
Andrew Nielson and Tim Scheiwe (GMG)	Supply and implement Thermal-XR system at QCH on 18th Jan 2022; provide training to QUT and QCH on maintenance scheduling and regular visual inspection; provide all required documents in section 3.1, 4.1 of this test plan.
Ken Thomson, Emily Campbell, Doug Ross **(Fusion HVAC and Zenith Energy)**	Electricity meter installation and data dashboard; implementation of Thermal-XR Prep for 4 condensers on 7 Dec 2021.
Aaron Liu (QUT)	Project manager of the test and research living lab; organise and coordinate the testing; analyse data and write the test report; distribute the test report according to contractual arrangements.
Wendy Miller (QUT)	Project Leader; oversee the test regime and report writing / distribution.

4 TEST RESULTS

This section presents energy data quantitative analysis results and impacts in terms of cost effectiveness and emission reduction.

The dataset starts from 10am 5th Oct 2021 (Brisbane, Australian Eastern Standard Time - AEST) to mid-night on 28th Feb 2022 (147 days in total). In the analysis, three days are excluded:

- 5th Oct 2021 for installing two WattWatcher energy meters
- 7th Dec 2021 for cleaning all four condenser units heat exchangers (fins) with Thermal-XR Prep
- 18th Jan 2022 for cleaning and graphene coating two condenser units with Thermal-XR Prep, Activate and Restore.

Factors influencing the condensers' energy use may include:

- Weather, such as ambient temperature
- Use of the cool rooms, such as frequency of using the cold rooms

To ensure a reasonably fair comparison, weather normalised energy use is often considered, such as energy use normalised by cooling degree hours [3][4] or cooling degree days [5][6]. For this project, cooling degree hours were used for normalising energy use, as the QCH Living Lab had installed a high-quality weather station on site, providing detailed interval data. As presented in the following equation, weather normalised electricity use was obtained by dividing electricity use with cooling degree hours (CDH).

$$Weather\ normalised\ electricity\ use = \frac{electricity\ use\ (kWh)}{Cooling\ degree\ hours\ (CDH)}$$

To calculate cooling degree hours, the following equation was used with 4°C as the base temperature for the refrigeration systems [7].

$$Cooling\ degree\ hours = \sum_{from\ 00:00}^{to\ 24:00} (measured\ temperature\ - base\ temperature) * time\ factor$$

$time\ factor$ is 5/60=0.0833 when temperature measurements are taken at 5-minute intervals.

One challenge for the performance analysis relates to the site being a major operational hospital. There are many operational variables which may increase the uncertainty for the analysis, for example hospitalisation rates and the impact on catering (and hence the utilisation of the cold rooms and freezers). On this front, measures have been implemented to minimise the uncertainties:

1. weeks of data from four condenser units' data are analysed rather than on shorter intervals in an attempt to smooth out potential daily operational variations;
2. condenser units (03 and 05) are cleaned and coated following the whole process; the other two condenser units are used as control cases, cleaned but not coated.

Those control cases are useful when there are potential changes in catering and refrigeration needs.

4.1 Quantitative Results

4.1.1 Energy performance evaluation for cleaning

The cleaning process (Thermal-XR Prep) was applied to four condenser units on 7th Dec 2021. Table 5 presents the weather and energy comparison between one week before the cleaning and three one-week periods after the cleaning.

As presented on Row 3, 5 and 7, post the cleaning, two of the one-week periods had higher cooling degree hours, indicating higher energy needs for refrigeration. However, all four condenser units tended to show lower energy use compared to Row 1 (a week before the cleaning), except CU 05 on Row 5. When weather normalisation was conducted, Table 6 presents a clearer picture.

Table 5 Energy comparison between prior to cleaning and post cleaning

		Mean daily			**Mean daily energy use**			
No.	Duration	Maximum temp. (℃)	Minimum temp. (℃)	Cooling degree hours (CDH)	CU 02 (kWh)	CU 03 (kWh)	CU 04 (kWh)	CU 05 (kWh)
1	Prior to cleaning (29 Nov to 5 Dec 2021)	27.57	20.29	463.70	18.39	19.46	18.50	17.21
2	Post cleaning (8 to 14 Dec 2021)	29.86	19.57	479.93	18.34	N.A. (Note 1)	17.91	17.16
3	% changes vs 1st row	**8.3%**	**-3.5%**	**3.5%**	**-0.3%**	N.A. (Note 1)	**-3.2%**	**-0.3%**
4	Post cleaning (13 to 19 Dec 2021)	29.57	20.57	499.36	18.18	18.66	18.27	17.35
5	% changes vs 1st row	**7.3%**	**1.4%**	**7.7%**	**-1.1%**	**-4.1%**	**-1.2%**	**0.8%**
6	Post cleaning (27 Dec 2021 to 2 Jan 2022)	26.00	19.14	439.24	17.30	17.55	16.61	16.20
7	% changes vs 1st row	**-5.7%**	**-5.6%**	**-5.3%**	**-5.9%**	**-9.8%**	**-10.2%**	**-5.8%**

Note:

1. CU-QCH-03.03 (CU 03) works 7 days on and 7 days off, due to duty share with another condenser.

After weather normalisation was conducted, Row 3, 5 and 7 of Table 6 present the three one-week energy performance in comparison with the week before the cleaning. Energy savings for the four condenser units are in the range between 0.4% and 11.2% with an average saving of **5.6%.** The results are visually presented in Figure 8.

Table 6 Energy comparison between prior to cleaning and post cleaning (weather normalised)

No.	Condensers	CU 02 (kWh/CDH)	CU 03 (kWh/CDH)	CU 04 (kWh/CDH)	CU 05 (kWh/CDH)
1	Prior to cleaning (29 Nov to 5 Dec 2021)	0.040	0.042	0.040	0.037
2	Post cleaning (8 to 14 Dec 2021)	0.038	N.A. (Note 1)	0.037	0.036
3	% changes vs 1st row	**-4.2%**	N.A. (Note 1)	**-7.1%**	**-4.1%**
4	Post cleaning (13 to 19 Dec 2021)	0.036	0.037	0.037	0.035
5	% changes vs 1st row	**-8.5%**	**-11.2%**	**-8.5%**	**-6.5%**
6	Post cleaning (27 Dec 2021 to 2 Jan 2022)	0.04	0.04	0.04	0.04
7	% changes vs 1st row	**-0.8%**	**-4.9%**	**-5.4%**	**-0.6%**

Note:

1. CU-QCH-03.03 has a duty share with another condenser: 7 days on and 7 days off.

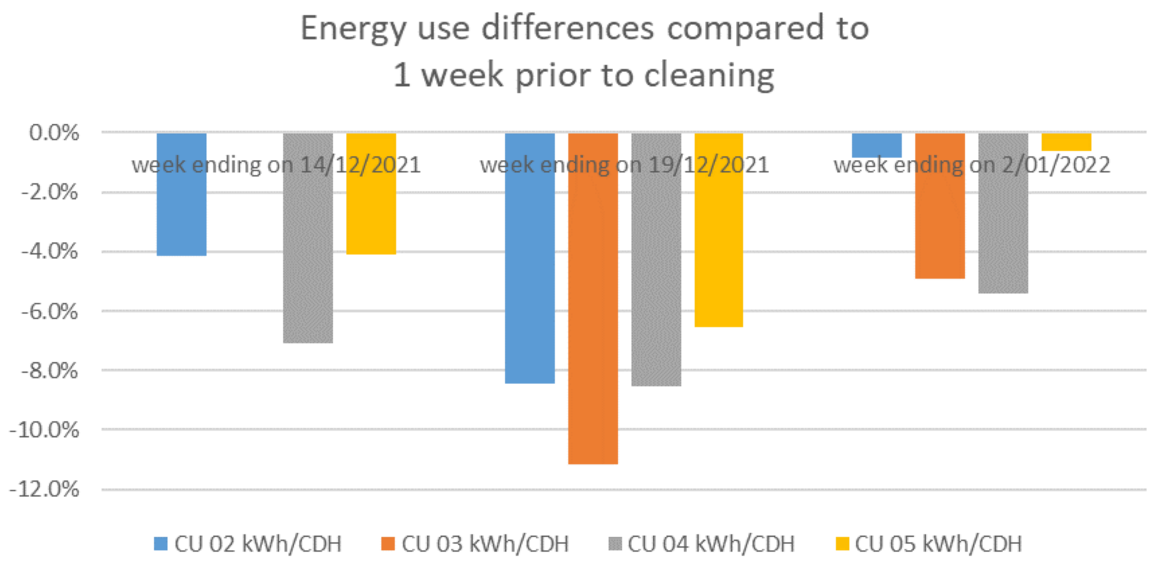


Figure 8 Energy use comparison for cleaning

4.1.2 Energy performance evaluation for coating

On 18th January 2022 during high peaks of COVID19 Omicron waves, Thermal-XR Prep, Activate and Restore (graphene coating) was applied to condenser units 3 and 5; condenser units 2 and 4 are control cases without coating.

Table 7 presents the mean daily temperature statistics and mean daily energy use for the four condenser units for one week before the coating and three one-week periods post the coating.

For the control cases condenser unit 2 and 4, they mostly had slightly increased energy use (refer to Row 5 and Row 7), even though there had been fewer cooling degree hours in the three one-week periods. This indicates a possibility of increased operational needs for the catering/refrigeration services. A potential factor may have been the COVID-19 Omicron wave that may have led to increase hospital services (beds, emergency department, clinical areas), impacting on catering. There is no data to verify or eliminate this possibility.

Condenser unit 3 had 11.8% of energy use increase on the second week after coating (Row 5, comparing CU 03 on Row 4 to Row 1); this percentage value is high and significantly divergent from other percentage values. In statistics, this value may be classified as an outlier.

Table 7 Energy comparison between prior to coating and post coating

		Mean daily			Mean daily energy use			
No.	Duration	Maximum temp. (°C)	Minimum temp. (°C)	Cooling degree hours (CDH)	CU 02 (kWh)	**CU 03 (kWh)**	CU 04 (kWh)	**CU 05 (kWh)**
1	Prior to coating (10 to 16 Jan 2022)	29.43	20.86	507.21	18.22	18.63	17.77	17.14
					Control case (no action)	**Coated** on 18 Jan 2022	**Control case** (no action)	**Coated** on 18 Jan 2022
2	Post coating (19 to 25 Jan 2022)	28.29	20.57	479.38	19.38	N.A. (Note 1)	17.61	16.91
3	% changes vs 1st row	-3.9%	-1.4%	-5.5%	6.4%	N.A. (Note 1)	-0.9%	-1.4%
4	Post coating (24 to 30 Jan 2022)	28.86	21.57	499.44	18.78	20.83	18.18	17.15
5	% changes vs 1st row	-1.9%	3.4%	-1.5%	3.1%	11.8%	2.3%	**0.1%**
6	Post coating (7 to 13 Feb 2022)	28.71	19.14	469.83	18.34	17.67	17.43	16.65
7	% changes vs 1st row	-2.4%	-8.2%	-7.4%	0.7%	**-5.1%**	-1.9%	**-2.9%**

Note:

1. CU-QCH-03.03 has a duty share with another condenser: 7 days on and 7 days off.

After conducting weather normalisation taking temperature variation into account, Table 8 presents energy comparison between the week before the coating and the three one-week periods after the coating.

The raw data on Rows 3, 5 and 8 show increased energy use for both control cases and coated units. Conservative estimates of the energy performance evaluation are presented on Row 6 and 9 as adjusted energy percentage changes. On Row 5, because the control units had a minimum of 4% increase in the second week post coating, 4% is deducted from the Row 5 percentage changes for condenser units 3 and 5. On Row 8, because the control units had a minimum of 5.8% increase in the third week post coating, 5.8% is deducted from the Row 8 percentage changes for condenser units 3 and 5.

Those estimate figures are obtained by deducting the smallest energy increase values (CU 04).

The average energy saving for coated condenser units 5 (Row 6, 8) and 4 (Row 9) is **2.3%.** Condenser unit 3 on Row 6 is excluded in this calculation because there might be operational uncertainties which caused this percentage to be an outliner.

Table 8 Energy comparison between prior to coating and post coating (weather normalised)

No.	Mean daily energy use	CU 02 (kWh/CDH)	CU 03 (kWh/CDH)	CU 04 (kWh/CDH)	CU 05 (kWh/CDH)
1	Prior to coating (10 to 16 Jan 2022)	0.036	0.037	0.035	0.034
		Control case (no action)	**Coated** on 18 Jan 2022	**Control case** (no action)	**Coated** on 18 Jan 2022
2	Post coating (19 to 25 Jan 2022)	0.041	N.A. (Note 1)	0.037	0.036
3	% changes vs 1st row	13.5%	N.A. (Note 1)	5.6%	5.0%
4	Post coating (24 to 30 Jan 2022)	0.038	0.042	0.036	0.034
5	% changes vs 1st row	4.7%	13.6%	4.0%	1.6%
6	Adjusted % changes vs 1st row		13.6% - 4%= 9.6%		1.6% - 4%= **-2.4%**
7	Post coating (7 to 13 Feb 2022)	0.039	0.038	0.037	0.035
8	% changes vs 1st row	8.9%	2.3%	5.8%	4.8%
9	Adjusted % changes vs 1st row		2.3% - 5.8% = **-3.5%**		4.8% - 5.8% = **-1.0%**

Note:

1. CU-QCH-03.03 has a duty share with another condenser: 7 days on and 7 days off.

For best industry practice in maintenance of plant and equipment, refer to Australian Institute of Refrigeration, Air-conditioning and Conditioning (AIRAH)'s DA19 [8]. To manage for a system's resilience, consider consulting AIRAH's resilience checklist [9]; Another useful AIRAH factsheet [10] demonstrates the importance of cleaning coils. A discussion on the combined impacts of the cleaning and coating is in the next section.

4.2 Energy and Financial Benefits

On the average, the cleaning process (Thermal-XR Prep) helped improve the refrigeration condenser units' energy performance by 5.6% and the graphene coating process helped further reduce energy use by 2.3%. This is a total potential of **7.9%** energy performance improvement for the QCH condensers. Table 9 presents potentials in energy and bill savings assuming the technology's impacts last 12 months.

Each of the tested condenser units uses about 6000 ~ 8000 kWh electricity each year. With the cleaning and graphene coating technology, there may be a yearly bill saving of $24 to $506 depending on electricity prices and rating of condenser units.

Table 9 Energy and bill savings for different condenser sizes

	Condensers yearly energy use (kWh)					
	6,000	**8,000**	**10,000**	**12,000**	**14,000**	**16,000**
Cleaning energy saving (kWh)	336	448	560	672	784	896
Coating energy saving (kWh)	138	184	230	276	322	368
Total yearly saving (kWh)	474	632	790	948	1,106	1,264
Electricity prices (AU$/kWh)	**Yearly bill savings (AUD)**					
$0.05	$24	$32	$40	$47	$55	$63
$0.10	$47	$63	$79	$95	$111	$126
$0.15	$71	$95	$119	$142	$166	$190
$0.20	$95	$126	$158	$190	$221	$253
$0.25	$119	$158	$198	$237	$277	$316
$0.30	$142	$190	$237	$284	$332	$379
$0.35	$166	$221	$277	$332	$387	$442
$0.40	$190	$253	$316	$379	$442	$506

Outdoor condenser units are exposed to dirt, debris, air pollutants and weather. Dirty coils reduce airflow around the condenser, reducing heat transfer and degrading the dehumidification process. Dirty condenser coils are reported to increase energy consumption whilst decreasing the efficiency and effectiveness of the cooling system. For example, it may take longer to provide the cooling or provide less cooling. Also, dirty coils may reduce the life of the cooling system, because of decreased life of motors due to increased heat while operating. The typical figure quoted by the US Department of Energy is that a dirty condenser coil can increase compressor energy consumption by 30% [10].

4.3 Environmental Benefits

Table 10 presents yearly CO_2 reductions when the technology is applied to various condenser sizes. A range of electricity CO_2 emission intensity is considered because CO_2 intensity varies depending on locations, states, generation mix, and point in time in terms of low carbon transition [11].

For example, in the U.S., its grid electricity CO_2 emission intensity was 0.386kg/kWh in 2020 [12]. Within the Australian national energy market (NEM), the CO_2 emission intensity was 0.725kg/kWh in the state of New

South Wales and 0.825kg/kWh in the state of Victoria in 2021. The NEM overall CO_2 emission intensity was 0.965kg/kWh in 2006 and the intensity was 0.678 kg/kWh in 2021 [13][14].

For a condenser using 6000 kWh electricity each year, the CO_2 emission reduction would be about 379kg a year in Queensland in 2021 (QLD grid CO_2 intensity 0.8kg CO_2-e/kWh).

Table 10 CO_2 emission reduction for different condenser sizes

Electricity CO_2 emission intensity (kg CO_2-e/kWh)	Condensers yearly energy use (kWh)					
	6,000	8,000	10,000	12,000	14,000	16,000
	Yearly CO_2 reduction (kg)					
0.386 (in U.S. 2020)	183	244	305	366	427	488
0.45	213	284	356	427	498	569
0.50	237	316	395	474	553	632
0.55	261	348	435	521	608	695
0.60	284	379	474	569	664	758
0.65	308	411	514	616	719	822
0.678 (in NEM 2021)	321	428	536	643	750	857
0.70	332	442	553	664	774	885
0.75	356	474	593	711	830	948
0.80	379	506	632	758	885	1011
0.85	403	537	672	806	940	1074
0.90	427	569	711	853	995	1138
0.95	450	600	751	901	1051	1201
0.965 (in NEM 2006)	457	610	762	915	1067	1220

4.4 Limitations

A few limitations are noted for the technology test:

- This technology test was conducted in an in-situ environment where is was challenging to ensure all operational and environmental variables were controlled or known. Adjacent weeks' energy data at daily intervals have been analysed to smooth out operational uncertainties.
- Cooling degree hours have been used to normalise the impact of weather and quantify energy savings in adjacent weeks of operation. There may be other methods to calculate energy savings for the technology.
- There has not been a full year of testing and measurements, due to lockdowns and technician shortage resulted from COVID impacts. Long term monitoring and energy performance evaluation may be a future step (subject to funding availability).

The site findings are not applicable to air conditioner units, as air conditioners have different technology configurations and operation patterns, and the thermal/physical properties of air-conditioned buildings are also very different to the properties of refrigerated rooms.

5 SUMMARY FINDINGS AND CONCLUSIONS

5.1 Overall Technology Assessment

The technology tested in this project was Thermal-XR Prep, Activate and Restore. Taking weather variation into consideration, the technology demonstrated an average **total 7.9% energy savings** for these refrigeration condenser units. Energy performance improvement may vary depending on site and equipment situation. Note the site is in an urban built-up environment and these condenser units are relatively new, typically 3-6 years old.

5.2 Barriers and Enablers to Adoption

Australia is on a low carbon transition. In terms of energy and sustainability management, energy efficiency approaches may be one of the first sets of options which need to be considered. This Thermal-XR technology is one of the available and feasible HVAC & R related energy efficiency options. It does not require ongoing operational support, nor does it need any other infrastructure to function. Potentially, there is low to no maintenance needed, except an annual Thermal-XR Maintain application. (Note that this evaluation does not extend to the longevity of the treatment, i.e., it has not quantified how long the cleaning and coating applied would provide energy savings).

Despite quantification of the savings potential of this technology, the project revealed two interconnected barriers to the broader uptake: the costs associated with cleaning and coating the condensers, and the submetering required to make the savings visible to asset owners. This presents a slight investment decision conundrum, as a benefit: cost analysis would be required incorporating the cost of installing submeters (if not already present), the cost of cleaning and coating, and the costs of analysing the data to report on impact. It is hoped that this report will help facility managers to build the business case for regular maintenance of outdoor condensers, and the benefits that graphene enhanced coatings provide in terms of heat rejection.

AIRAH Design Application manual 19 (HVAC & R) specified economic life for cooling and heating coil is 20-25 years. Regular maintenance of outdoor condensers probably remains as a critical factor to ensure assets can achieve reasonable efficiency through the economic life period.

5.3 Future Work

This study has only evaluated the short-term energy savings impact of cleaning and coating the condensers. As the submetering and onsite weather station continue to provide data, it is hoped that in 12 months' time (early 2023) it will be possible to evaluate the longer-term impact of cleaning only, and cleaning + graphene coating. It is expected that the graphene coating may provide longer-term protection than cleaning alone. This longer-term data will help to determine recommended cleaning schedules for this site (e.g., annual or more or less frequent). It would also be helpful to determine whether machine learning could be applied to the data to detect changes in performance, indicating a need for cleaning. This falls under the category of predictive maintenance using data analytics and condition monitoring, as opposed to schedule cleaning as part of preventative maintenance [15][16]. A visual representation for asset performance vs predictive maintenance and preventive maintenance is provided in Figure 9.

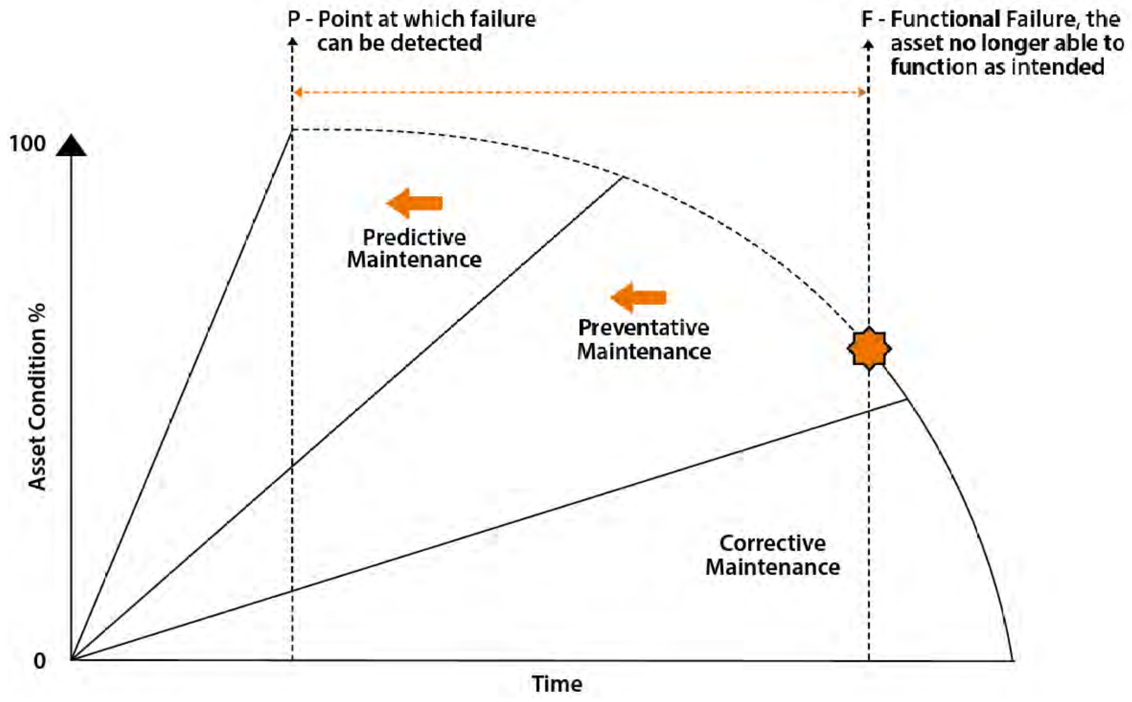


Figure 9 performance vs failure curve – early detection (adopted from [8])

As a result of this technology evaluation process, Fusion HVAC have been carrying out additional early stage testing of the impact of applying graphene to the internal workings of HVAC systems, such as graphene additive to coolant. A larger scale evaluation of this application of the technology would be beneficial to GMG, the HVAC industry and building owners.

Similarly, evaluating the impact of the cleaning and graphene coating process on air conditioning systems (as opposed to refrigeration systems) would be beneficial.

5.4 National Impact Study

Based on Cold Hard Fact's report (2020), every year Australia uses about 19,700 GWh of electricity for refrigeration in cold food chain (RCFC) [17].

If the technology is applied to Australia nationwide, assuming a similar magnitude of energy saving is applicable to Australia's annual RCFC electricity use, the estimated total bill savings would be around $389 million dollars a year considering electricity price is $0.25/kWh (Table 11). There would be over 1 million tonnes of CO_2 emission reduction each year due to the energy savings.

Table 11 National impact for the technology

	Gigawatt-hour (GWh)	Bill impact (considering $0.25/kWh)	Equiv. CO_2 tonnes (AEMO. 2021)
Annual electricity in RCFC	19,700	$ 4,925,000,000	13,356,600
Potential benefits from cleaning	1103	$ 275,800,000	747,970
Potential benefits from coating	453	$ 113,275,000	307,202
Total benefits	1556	$ 389,075,000	1,055,171

REFERENCES

[1] A. Liu, W.F. Miller, Healthcare Living Laboratories: Queensland Children's Hospital - Energy Baseline Data, Australian Institute of Refrigeration, Air-conditioning and Heating (AIRAH), Brisbane, QLD, Australia, 2020. https://www.ihub.org.au/llhc4-queensland-childrens-hospital/.

[2] A. Liu, W.F. Miller, Healthcare Living Laboratories: Queensland Children's Hospital - Operation Manual and Baseline Data, Brisbane, Queensland, Australia, 2020. https://www.ihub.org.au/llhc4-queensland-childrens-hospital/.

[3] Z. Wang, T. Hong, H. Li, M. Ann Piette, Predicting city-scale daily electricity consumption using data-driven models, Advances in Applied Energy. 2 (2021) 100025. https://doi.org/10.1016/j.adapen.2021.100025.

[4] J. Li, J. Jurasz, H. Li, W.Q. Tao, Y. Duan, J. Yan, A new indicator for a fair comparison on the energy performance of data centers, Applied Energy. 276 (2020) 115497. https://doi.org/10.1016/j.apenergy.2020.115497.

[5] A. Liu, W. Miller, G. Crompton, S. Zedan, Has COVID-19 lockdown impacted on aged care energy use and demand ?, Energy and Buildings. 235 (2021). https://doi.org/10.1016/j.enbuild.2021.110759.

[6] A. Liu, W. Miller, J. Chiou, S. Zedan, T. Yigitcanlar, Y. Ding, Aged care energy use and peak demand change in the COVID-19 year: empirical evidence from Australia, Buildings. (2021). https://doi.org/10.3390/ buildings11120570.

[7] Food Standards Australia New Zealand, Temperature Control – Fact Sheet 4, Australia, 2007.

[8] V. Aherne, G. Brown, A. Clifford, P. Drury, P. Eagling, S. Gregson, B. Hawkins, P. Jenkinson, J. Mottley, C. O'Neil, J. Penny, I. Pearce, B. Precious, B. Price, A. Rowan, C. Stamatis, P. Wilkinson, A. Venn-Brown, AIRAH DA 19 HVAC & R Maintenance Design Application Manual, 4th ed., Australian Institute of Refrigeration, Air-conditioning and Heating (AIRAH), Melbourne, Australia, 2019.

[9] A. Fok, S. Gregson, N. Groenhout, G. Johnson, L. Lecamwasam, R. Le Miere, W. Miller, S. Monti, E. Moore, N. Parker, B. Precious, M. Ryan, A. Scotland, P. Stoller, L. Taylor, K. Wilmot, AIRAH Resilience Checklist, (2020) 3138.

[10] C. Gregoire, N. Sheehan, B. Price, AIRAH Factsheet The Importance of Cleaning Coils, (2013) 1–3.

[11] M. Evans, M. Belusko, A. Taghipour, M. Liu, P.F. Keane, J. Nihill, R. Amin, A. Liu, J. Assaf, T. Lau, K. Xing, T. Rainey, C. Stanley, A. Date, B. Bonney, J. Leak, J. Hossain, W. Miller, G. Rosengarten, F. Bruno, RACE for 2030 CRC Research Theme B3 Electrification & Renewables to Displace Fossil Fuel Process Heating Opportunity Assessment Final Report, 2021. https://www.racefor2030.com.au/publications/.

[12] U.S. Energy Information Administration, How much carbon dioxide is produced per kilowatthour of U. S. electricity generation ?, (2021). https://www.eia.gov/tools/faqs/faq.php?id=74&t=11 (accessed March 16, 2022).

[13] Australian Energy Market Operator · , Carbon dioxide equivalent intensity index 2021 summary file, (2022).

[14] Australian Energy Market Operator (AEMO)., CO2 emission intensity historical snapshot 2006, (2007).

[15] M. Cholette, H. Yu, P. Borghesani, L. Ma, G. Kent, Degradation modeling and condition-based maintenance of boiler heat exchangers using gamma processes, Reliability Engineering and System Safety. 183 (2019) 184–196. https://doi.org/10.1016/j.ress.2018.11.023.

[16] H. Truong Ba, M.E. Cholette, R. Wang, P. Borghesani, L. Ma, T.A. Steinberg, Optimal condition-based cleaning of solar power collectors, Solar Energy. 157 (2017) 762–777. https://doi.org/10.1016/j.solener.2017.08.076.

[17] P. Brodribb, M. McCann, Cold Hard Facts 2020, 2020.