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Evaluation of in-depth energy modelling for the design and operation of a net-positive energy Solar Decathlon house

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Abstract. The Solar Decathlon is an international competition that challenges collegiate teams from around the world to design and build functioning, sustainable, solar powered houses. The competition is split into ten sub-contests which vary from competition to competition. Contests are a combination of juried (judged by a panel experts) or measured (such as energy usage and thermal comfort) contests. This paper will focus on the measured contests, in particular; energy management, comfort conditions and house functioning. To ensure optimal house performance during the competition, extensive energy and thermal modelling is required to ensure the solar PV and on-site energy storage can achieve net-zero energy while also ensuring the heating, ventilation and air conditioning (HVAC) system can meet the strict indoor thermal comfort requirements set by the competition. This paper will review the energy and thermal modelling process of Team UOW Australia's net-positive energy house, the 'Desert Rose', that achieved second place in the Solar Decathlon Middle East (SDME) competition in 2018. Upon reviewing the energy modelling process, the results from the energy simulations will be compared to the real data that was obtained during the SDME competition to determine the validity of the energy simulations and the subsequent benefits of in-depth energy modelling for competing in a Solar Decathlon.

1 Introduction

The Solar Decathlon is a competition that was created in partnership with the U.S. Department of Energy to promote renewable and emerging technologies in the residential building sector [1, 2]. The competition was first held in 2002 in Washington DC. Since then, the competition has involved 150 collegiate teams and 18,000 students in the U.S. [3]. The Solar Decathlon has also expanded internationally to Europe, China, Latin America, Africa and the Middle East involving 160 teams and approximately 19,000 students [3]. The goal of the organisers was to not only have universities design and build solar powered homes but to use them as an exhibition and teaching tool for the general public [1].



Fig. 1. Desert Rose house at the SDME Solar Hai

entry was the Illawarra Flame house, which demonstrated how to effectively retrofit a typical existing residential Australian building to increase its energy efficiency. This approach proved to be extremely successful with Team UOW winning that competition. On the back of that success, Team UOW entered the Solar Decathlon Middle East (SDME) 2018 competition, which was held in Dubai, UAE.

Team UOW entry into SDME, the Desert Rose house (DRH), shown in Fig. 1, was a net-positive energy house catered to those living with age related illnesses, such as dementia. The Solar Decathlon consists of ten competitions, for SDME these were: Architecture, engineering and construction, energy management, energy efficiency, comfort conditions, house functioning, sustainable transportation, sustainability, communication, and innovation. The inaugural SDME was organised by Dubai Electricity and Water Authority (DEWA) and was held at Mohammad bin Rashid Al Maktoum (MBR) Solar Park during November 2018.

This paper will focus on design, modelling, implementation and evaluation of the solar PV and HVAC systems that contributed to the measured, energy management, comfort conditions, and house functioning contests. In particular, how the design and simulation of energy production/consumption of these systems compared with the measured values obtained during the SDME competition period.

The University of Wollongong (UOW) first competed in the Solar Decathlon in China, 2013. The Team UOW

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2 House Design & Energy Modelling

During the design phase, DRH was modelled extensively to ensure the house could maintain strict indoor thermal comfort conditions while using minimal energy. The objectives of the design and simulation process were to:

- Explore the climatic conditions of MBR Solar Park and identify possible passive design strategies;
- Identify the best performing building envelope and active energy system to provide constant thermal comfort using the least amount of energy;
- Design an innovative HVAC system that could effectively control indoor ambient temperature, humidity, and CO₂ concentration;
- Calculate the electrical energy requirements of all active systems within DRH; and
- Design a hybrid solar PV and energy storage system that can cover the annual energy requirements of DRH to achieve net-zero energy.

2.1. Climate Data & Weather Analysis

As part of the SDME competition, DEWA provided all teams with historical weather data for the MBR Solar Park from the years 2014 and 2015. Data included direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), global horizontal irradiance (GHI), ambient temperature, wind speed, wind direction, relative humidity and hourly rainfall (a subset is shown in Fig. 2). This data was used for all electrical and thermal modelling throughout the design process.

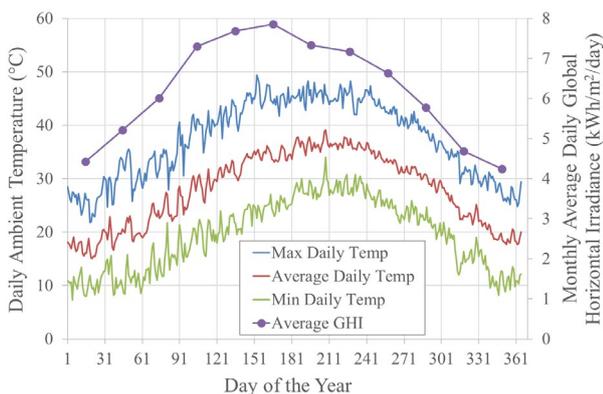


Fig. 2. Average ambient temperature and global horizontal irradiance from DEWA for MBR Solar Park.

Upon analysing the data, it became evident that maintaining strict indoor thermal comfort conditions of temperature between 23°C-25°C and relative humidity between 35%-60% would be difficult in the hot and humid Dubai climate. The ambient temperature falls within this band for only 11.1% and 11.0% for years 2014 and 2015 respectively with an average of 62.5% of the time spent above 25°C and 26.4% spent below 23°C. This illustrates a need for active cooling measures to remain within the required temperature band [4].

The weather data was analysed in greater detail for the month of November when the competition was to be held. From the data, it was shown that ambient temperature and relative humidity were only within the required band simultaneously for 4.2% and 3.3% of time in 2014 and 2105 respectively [4]. This meant that natural ventilation would rarely be able to be used to remain within required comfort bands. However, due to potential benefits relating to reduced energy consumption, automated windows for natural ventilation were employed in the DRH.

2.2 HVAC System Design Consideration

The DRH HVAC system was designed to be able to effectively control the indoor temperature, humidity and CO₂ concentration in the harsh Dubai climate. To achieve this, Team UOW included multiple devices in the design that were able to control these conditions independently, creating a mixed mode hybrid ventilation system.

The primary source of cooling was a Daikin Altherma air-to-water heat pump that was coupled with two fan-coil units. The heat pump supplies chilled water to the fan-coil units which subsequently supply cool air to the indoor environment. The device used to control humidity in the DRH is a dehumidifying heat pump desiccant unit known as 'DESICA' from Daikin. The key feature of DESICA is two desiccant coated heat exchangers (DCHEs) which serve as condenser and evaporator of the heat pump, respectively. Since moisture can be more effectively trapped on desiccant material at a lower temperature, the desiccant coated heat exchanger enables the removal of adsorption heat during the air dehumidification process when it serves as an evaporator, which significantly improves the dehumidification performance. The desiccant can then be switched and regenerated by using the released heat when the DCHE is served as a condenser, which provides a reliable and energy-saving approach for regeneration. The coefficient of performance (COP) of the DESICA can be over 5, which significantly improves the energy efficiency for air conditioning [4].

An energy recovery ventilator (ERV) is used in the HVAC system to reduce the heating and cooling loads introduced by fresh air. Automated windows were also incorporated in the house design due to the potential benefits related to reduced energy consumption of the HVAC system during the competition period and to reduce the indoor CO₂ concentration where necessary. A summary of the major HVAC devices incorporated in the DRH is shown in Table 1.

Finally, the HVAC system also incorporates an innovative water-based thermal energy storage (TES) system that utilises phase change material (PCM) to store cool energy. Completely designed and built by Team UOW students, the TES can be used to supply

cool water to the fan-coil units, providing cool air to the building. The primary purpose of the TES is to shift peak load from the middle of the day, to the evening when the price of electricity is cheaper and the ambient temperature is lower, during the SDME competition.

Table 1. Desert Rose House HVAC Equipment

Device	Model	Rating/Performance
Air-to-water heat pump	Daikin EBHQ011BB	11.20 kW/12.85 kW COP 4.38/EER 3.32
Fan coil unit 1	Daikin FWC11C	5.01/11.14 kW
Fan coil unit 2	Daikin FWC03C	2.9/2.90 kW
Dehumidifying heat pump	Daikin DESICA HDMP25D	250 m ³ /h
ERV	Daikin VAM-350GJVE	350 m ³ /h $\eta = 79-82\%$
Window controller	WindowMaster WCC320PLUS	13 actuators (9 windows)

2.3 Desert Rose House HVAC Modelling

2.3.1 Free Running House Performance Analysis

A detailed EnergyPlus [6] model of the DRH was created in DesignBuilder [7] to simulate the annual and competition thermal loads and free running performance. This included detailed modelling of the DRH envelope along with modelling all internal heat gains due to occupants, lighting, and appliances. These results were used to appropriately size all HVAC components. The summary of energy requirement of the DRH are summarised in Table 2.

Table 2. Desert Rose House Cooling Loads

Desert Rose House Performance Analysis	
Annual cooling energy	10,297 kWh
Competition cooling energy	163.9 kWh
Peak sensible cooling load	4.0 kW
Peak latent cooling load	2.12 kW

2.3.2 HVAC System Energy Simulation

The DRH HVAC system was designed and optimised using the software tool TRNSYS [8]. TRNSYS is a tool used to simulate transient systems. The primary goal of simulating the active systems in DRH was to ensure the HVAC system could maintain the strict indoor thermal comfort conditions year-round and to also determine the annual consumption of electricity of the HVAC system.

MBR Solar Park weather data for Dubai was used in the TRNSYS model. The schedules for internal gains for the DRH were based on the Australian Nationwide House Energy Rating Scheme (NatHERS). For the SDME competition period (18/11/2018 – 27/11/2018), internal gains were modelled based on the competition calendar provided by DEWA. This provided a more accurate

representation of the specific times appliances and lights were being used and their subsequent contribution to the internal heat gains. Table 3 shows the design simulation conditions applied in TRNSYS.

Table 3. TRNSYS HVAC Simulation Settings

Design Condition	Simulation Settings
HVAC	Heating and cooling setpoint: 24°C, Relative humidity: setpoint 47.5%
Natural ventilation	When $T_{ambient} < T_{indoor}$
Occupancy	2 people, 8 people during SDME dinner parties
Heat pump chilled water temperature	13°C
Fan coil unit supply air temperature	16°C
Fresh air flow rate	15L/s/person (minimal fresh air flow rate to keep indoor air CO ₂ concentration < 800 ppm)
Total chilled water flow rate	0.7L/s for supply chilled water loop

2.3.3 HVAC System Energy Results

The TRNSYS model was simulated over the course of a year, recording average power values at 30-minute intervals. The results of the analysis for both the annual and SDME contest period are shown in Table 4.

Table 4. HVAC Electrical Energy Results

HVAC Device	Annual Expected Energy (kWh)	Competition Expected Energy (kWh)
Heat pump	3861.9	76.1
Fan coil units	1051.2	28.8
Desica	1208.0	25.4
ERV	188.0	1.8
Primary water pump	404.1	10.9
Total	6713.2	143.0

2.4 Desert Rose Electrical Load Modelling

To model energy consumption of other systems within the house, the nameplate value for appliances along with their daily/annual energy consumption was extrapolated to produce average load profiles for each appliance (washer/dryer, cooktop, oven, dishwasher, hot water, home electronics). The same process was used to model the lighting system within DRH, along with the EV charger, as these systems primarily have fixed power values. This was then used to calculate the total expected energy used annually and during the SDME competition period for systems that were not HVAC. A summary of the total expected energy used annually and throughout the SDME competition for DRH is shown in Table 5.

Table 5. Electrical Load Energy Consumption

Device	Expected Annual Energy (kWh)	Expected Competition Energy (kWh)
HVAC	6713.2	143.0
Appliances	2779.4	95.2
EV Charger	2920.0	27.6
Hot Water	438.0	12.0
Lights	328.5	26.8
Standby power	744.6	20.4
Total	13923.7	324.9

3 Solar PV Design & Modelling

Based on the extensive energy analysis performed in Section 2, it was possible to optimally size the DRH solar PV system to ensure the house meets the SDME requirements of net-zero energy. To simulate the annual energy production of the DRH under different solar PV designs and weather conditions, a custom script was developed in MATLAB. This script utilised equations from Chapter 6 of [5] in conjunction with MBR solar park weather data to calculate the expected annual global horizontal irradiance (GHI) at the SDME competition site. This was then used to calculate expected power output of the DRH solar PV system at any tilt angle or kWp rating. Results were validated with photovoltaic system software, PVsyst [9].

3.1 PV System Design Considerations

The focus of Team UOW when designing the DRH solar PV system was to incorporate a building integrated photovoltaic (BIPV) system that is aesthetically pleasing and could achieve net-positive energy both during the SDME competition and annually. To achieve net-positive energy, it was decided to size the system 25% larger than the expected annual energy consumption of 13,923.7 kWh. Therefore, the solar PV system should produce at least 17,404.6 kWh annually. Another design consideration set by DEWA as a part of the SDME competition was that the AC side of each house's inverter(s) must never exceed 8 kW. Finally, the system must fit on the southern facing 10° pitched roof of DRH.

3.2 BIPV Technology

Eclipse solar tiles from Australian company Tractile were chosen for the BIPV technology of the DRH. The solar tiles are a building integrated photovoltaic-thermal (BIPV-T) system as they produce both electricity and hot water (the tiles have water channels that run under the PV). The tiles use monocrystalline technology with a rated output of 100 W per tile with an efficiency of 20.4%. Team UOW incorporated the solar tiles into the design of DRH to create a 5-in-1 system, as the tiles not only produce electricity and hot water, but they also

become the roof construction on the southern facing portion of DRH. By running water underneath the tiles, they are effectively cooled, which increases overall PV efficiency. Finally, by cooling the tiles, they act as an additional insulating element on the roof.

3.3 PV System Design & Simulation

Based on technical data for the Eclipse solar tile, simulations were performed with MBR solar park latitude and longitude (24.77°S, 55.37°E) and PV tilt angle of 10° (pitch of DRH roof). The BIPV system power output was calculated every half hour over the course of a year. From the results, it was decided to size the system at 10.4 kWp (104 solar tiles). It was calculated that a 10.4 kWp system should produce 19,005 kWh annually, and have a peak power output of 7.6 kW during competition. The system was also expected to produce 398.7 kWh during the SDME competition, which comfortably covers the total expected consumption of 324.9 kWh. Finally, the system fitted perfectly on the DRH pitched roof, thus, the system met all of Team UOW's design goals.

4 System Installation & Commissioning

The modular DRH was constructed twice in Australia before it was shipped to Dubai for the SDME competition. The initial build took place at TAFE Illawarra campus, located in Wollongong. During this build, the primary house structure was completed along with internal wiring, installation of HVAC components in the ceiling cavity, and some of the plumbing work. The house was then packed into shipping containers and taken to UOW's Innovation Campus where it was built for a second time. It was here all mechanical and solar systems were installed and commissioned.

4.1 HVAC Installation

During the design phase of the project, both the structural team and HVAC team for DRH performed extensive Building Information Modelling (BIM) to ensure the complex HVAC system would fit within the ceiling, without any clashes with the house structure. The other benefit of this coordination between teams meant that a majority of the HVAC equipment (in particular, the large fan coil unit, ERV and DESICA) could be installed in what was called the 'HVAC cage'. The HVAC cage is a large section of the DRH roof that was assembled on the ground, and later installed on the house once all mechanical equipment was installed. By installing the HVAC equipment in the HVAC cage while it was on the ground the installation was much safer and quicker compared to installing the equipment in the ceiling. Fig. 3 shows the HVAC cage being lifted into place at the second build of the DRH.



Fig. 3. HVAC cage installation

4.2 Solar PV Installation

The DRH solar PV system was designed to be plug-and-play to ensure quick and easy installation during the SDME competition. The 10.4 kWp system was connected to two all-in-one hybrid inverter/energy storage units. The model of the all-in-one unit is an S10 mini from German company E3DC. Each unit contains a 7 kW inverter along with 6.9 kWh (combined total storage of 13.8 kWh) of lithium-ion energy storage. Each inverter has 5.2 kW of solar PV connected across two maximum power point (MPP) channels. Fig. 4 shows the solar tiles being installed on the DRH roof.



Fig. 4. Desert Rose house BIPV solar roof

5 SDME Competition Data & Comparison with Simulations

The DRH took 15 days to construct before the SDME competition began. All measured data for the competition began being recorded on 18/11/2018 at 12:00am and finished on 27/11/2018 at 11:59pm.

5.1 HVAC System Thermal Comfort Results

Throughout the SDME competition, the DRH was able to maintain all thermal comfort conditions extremely well. Preference was given to maintaining temperature

and reducing energy consumption as maintaining temperature within 23°C-25°C was worth 70 points and load consumption per surface area was worth 60 points, compared to 15 points allocated to maintaining humidity between 60%-35% and 5 points to maintaining CO₂ below 800 ppm.

Fig. 5 shows the power consumption of the DRH HVAC system over the course of a day and the ability for the system to maintain the indoor temperature within the strict bounds of 23°C-25°C. As a result of the well thought out design and simulation process, Team UOW achieved first place in the comfort condition contest.

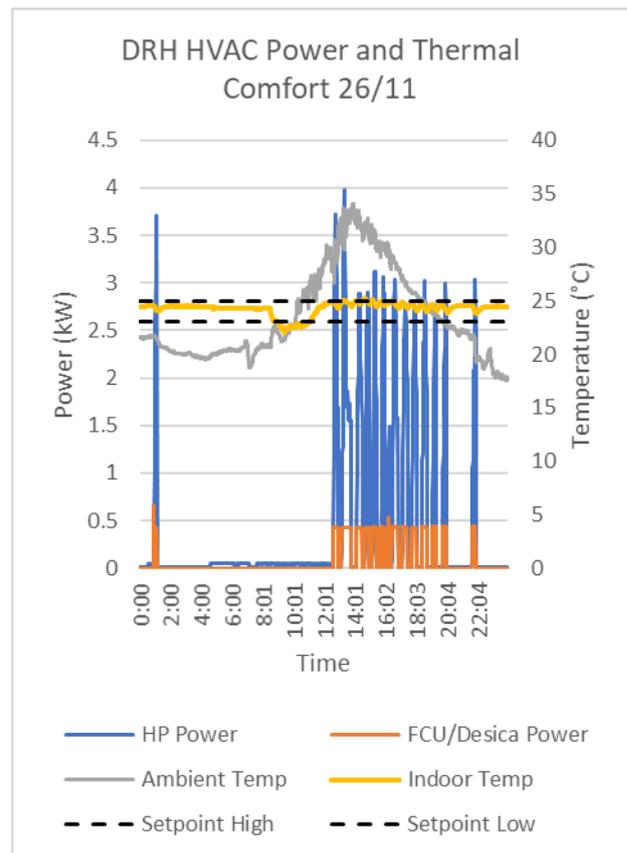


Fig. 5. DRH measured HVAC data from SDME 2018

5.2 HVAC System Energy Consumption

The total energy consumption of the HVAC system over the competition period was very similar to the expected energy consumption from the TRNSYS model. Unfortunately, each HVAC device was not metered separately in the DRH, so energy consumption of each individual device was not available. Regardless, it is possible to compare the overall energy consumption of the HVAC system. For this comparison, energy data from 18/11 – 21/11 will be omitted as issues with some control hardware led to HVAC equipment remaining on when it didn't need to, which led to increased and unnecessary energy consumption.

Table 6 shows the comparison between Team UOW's simulation values for HVAC energy consumption and values measured during competition. From the data, it was shown that measured values were only 6.79% higher than the expected value from simulation. The high energy consumption on 25/11 can be attributed to an uncharacteristically hot day (the hottest day of competition, with temperatures above 35°C).

Table 6. HVAC Energy Consumption during SDME

Date	Simulated (TRNSYS) HVAC Energy (kWh)	Measured HVAC Energy (kWh)
22/11	13.0	14.1
23/11	13.6	10.6
24/11	12.6	15.2
25/11	13.8	23.5
26/11	14.1	14.0
27/11	14.6	10.3
Total	81.7	87.6

5.3 Electricity Generation and Consumption

Table 7 presents expected energy production and consumption against the values that were measured during competition. The total energy produced by the DRH BIPV system correlate well with expected results from the MATLAB script, with only a 2.8% difference. Fig. 6 shows expected solar PV output against measured data taken from the two S10 mini inverters.

The total energy consumption of the DRH was 11% higher than expected, however, this can be attributed to issues around the HVAC control during the initial days of competition which led to increased consumption.

Table 7. DRH Energy Generation and Consumption

	Total Energy Generation (kWh)	Total Energy Consumption (kWh)
Simulated	398.69	324.89
Measured	387.52	365.00

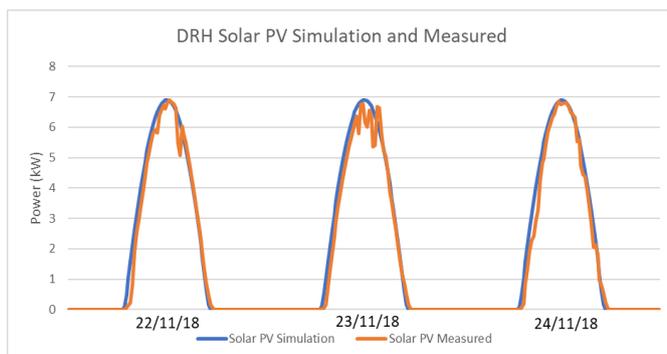


Fig. 6. Solar PV Output Simulation and Measured

6 Conclusion

Extensive energy modelling of active systems in Team UOW's Desert Rose house proved beneficial in successfully designing and building a thermally comfortable, net-positive energy home. Much of this modelling contributed to Team UOW placing 2nd overall at the SDME 2018 competition.

Using TRNSYS for modelling of the DRH HVAC system allowed Team UOW to size the multiple system components appropriately to deal with the harsh Dubai climate. This, along with a well insulated and air tight building envelope, and advanced HVAC control system, were key in Team UOW achieving 1st place in the comfort conditions contest at the SDME competition.

By first modelling all electrical loads in the DRH, Team UOW were able to make an informed and accurate decision on how much solar PV was required to achieve net-zero energy. This ensured the system was not oversized and could meet energy requirements year-round. The 10.4 kWp BIPV-T system generated 387.5 kWh during the SDME competition, only 2.8% less than energy production estimated by the created custom MATLAB model. As the DRH consumed 365 kWh during the 10-day measured competition period, the house was able to achieve net-positive energy, producing more energy than it consumed.

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