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Energy Performance of a Residential Zero Energy Building – R-CELLS in Solar Decathlon China 2022

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ABSTRACT

To achieve the goals of carbon peak and neutrality, energy efficiency and carbon reduction in the building sector are crucial. Zero energy buildings (ZEBs) have emerged as a solution to address these challenges. This paper takes the example of R-CELLS, the champion competition entry from team Tianjin U+ in the Solar Decathlon China 2022 (SDC 2022), to introduce the energy performance of a residential ZEB combined with PEDF (photovoltaics, energy storage, direct current, flexibility). To achieve the building net-zero goal, the R-CELLS integrates various renewable energy sources (building integrated photovoltaics (BIPV), photovoltaic-thermal (PV-T), and building integrated wind turbines (BIWT)), energy storage systems (battery energy storage system (BESS), hot water tank (HWT), and phase change materials (PCM) thermal storage), an alternating current (AC) and direct current (DC) hybrid power distribution system, and a weekly-daily-hourly tri-period energy management strategy. Based on the actual operation during SDC 2022, the performance and influencing factors of R-CELLS in both grid-connected and off-grid modes are analyzed. The results demonstrate that R-CELLS can meet the standards of the residential ZEB and can achieve daily zero-energy consumption.

Keywords: Energy performance, Zero energy building (ZEB), Solar Decathlon China (SDC), Energy system, Off grid

NONMENCLATURE

Abbreviations	
AC	Alternating Current
ASHP	Air Source Heat Pump
BESS	Battery Energy Storage System
BIPV	Building Integrated Photovoltaics
BIWT	Building Integrated Wind Turbines
DC	Direct Current
EMS	Energy Management Strategies
HWT	Hot Water Tank
MPC	Model Predictive Control
PCM	Phase Change Materials
PCS	Power Control System
PEDF	Photovoltaics, Energy storage, Direct current, and Flexibility
PV-T	Photovoltaic-Thermal
RES	Renewable Energy Source
SDC	Solar Decathlon China
ZEB	Zero Energy Building

1. INTRODUCTION

The world is currently facing unprecedented challenges in terms of climate change and energy sustainability. Reducing energy consumption and improving energy utilization efficiency have always been focal points of attention, including the field of building. According to the International Energy Agency (IEA), the total final energy consumption in the operation of global buildings accounted for 30% of the total global energy consumption in 2022 [1]. To reduce energy consumption and carbon emissions, and achieve low-energy or even zero-energy goals in the buildings, zero energy building (ZEB) has become an increasingly prominent topic of concern [2].

Zero-energy building (ZEB), also called net zero-energy building, any building or construction

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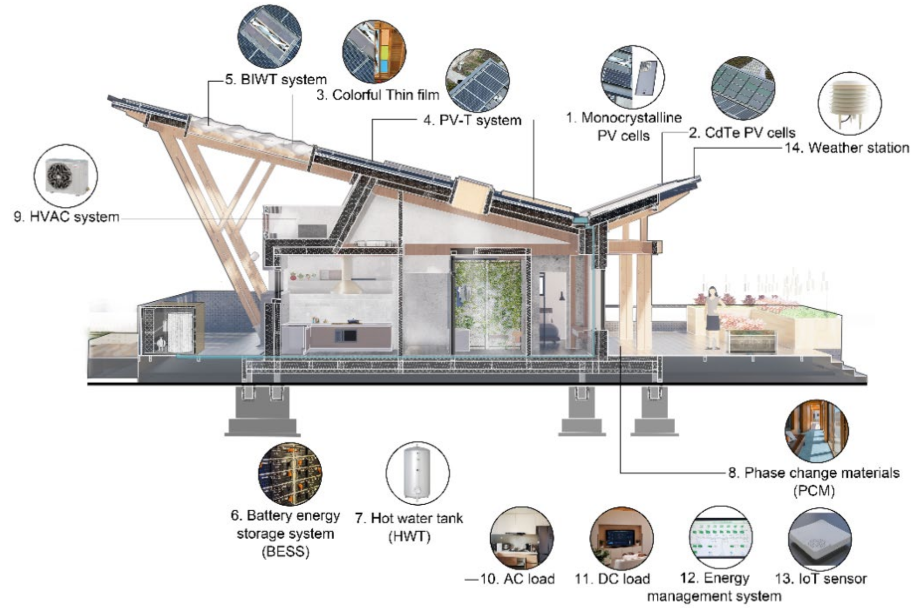
characterized by zero net energy consumption and zero carbon emissions calculated over a period of time [3]. ZEBs or analogous building typologies are progressively being integrated into energy policies on a global scale. In China, to achieve carbon peak and neutrality targets, the 14th Five-Year Plan for the development of energy-efficient and green buildings explicitly states the goal of constructing over 50 million square meters of ultra-low energy and nearly ZEBs by 2025 [4]. The United States [6] and the European Union [5] have proposed similar targets for transform the building stock into ZEBs by 2045 and 2050, respectively.

In addition to meeting zero energy standards in terms of architectural designs, construction and building envelope structure, the building energy system is essential which aims to achieve net-zero energy. PEDF (photovoltaics, energy storage, direct current, and flexibility), as a new kind of building energy system, has provided a feasible solution for the realization of a residential ZEB energy system [7]. The concept of PEDF can be further extended to the main modules in the energy system of residential ZEBs, including distributed RES utilization, various energy storages, electrical appliance applications, energy management strategies (EMSs), as well as DC distribution systems. Extensive researches and practical applications have been conducted in the different modules in energy systems for ZEBs.

Relevant academic competitions have also provided a practical platform for the development of energy systems in residential ZEBs. The Solar Decathlon is a collegiate competition that has inspired thousands of students worldwide to enter the clean energy workforce since its inception in 2002. In regions such as Africa, America, China, Europe, Latin America and the Caribbean, and the Middle East, the competition takes place over a period of 7-14 days, utilizing ten specific evaluation methods based on different regional characteristics and climate conditions [8]. Previous editions of the Solar Decathlon have explored energy


(a) Interior

(b) Exterior



(c) Schematic of R-CELLS energy system

Fig.1. Interior, exterior view and energy system of R-CELLS

systems for ZEBs [9]. In Solar Decathlon Europe 2012 (SDE2012), Omotenashi House developed an EMS to achieve energy balance. The system connected and controlled all electric devices through an information and telecommunication network to reduce power consumption [10].Team UOW in Solar Decathlon China 2013 (SDC2013) combined an HVAC system with PV-T and PCM thermal storage in their Solar Decathlon house 'Illawarra Flame'. This integration allowed for maintaining thermal comfort through logical control strategy [11]. In Solar Decathlon China 2018 (SDC2018), Team SCUTxPoliTo optimized the operation of HVAC systems by adjusting operating schedules and set temperatures based on actual test data. These optimizations improved user indoor comfort, reduced energy consumption, and significantly enhanced their competition performance [12]. Team KIT in Solar Decathlon Europe 21/22 (SDE21/22) employed PV-T, BESS, and a HWT within the rule limitations of a 3 kWp PV-T system and 2.5 kWh BESS. Despite these limitations, Team KIT successfully maintained indoor comfort and achieved positive energy performance [13].

Based on the Solar Decathlon context and ZEB standard, an energy system for a residential ZEB is proposed in this paper to meet various types of internal building demands. The proposed energy system serves for the competition entry named R-CELLS by Team Tianjin U+ in Solar Decathlon China 2022 (SDC2022).

The remainder of this paper is organized as follows: The compositions of the energy system of R-CELLS are introduced in Section 2. The energy performance during the SDC2022 is analyzed in Section 3. The issues encountered during the practical operation of the energy system are discussed in Section 4. Conclusions are drawn in Section 5.

2. ENERGY SYSTEM OF R-CELLS

2.1 General information of R-CELLS

R-CELLS is proposed and constructed by Team Tianjin U+ in response to the triple challenge of Sustainable Development, Smart Connection, and Human Health in the context of the host city, Zhangjiakou, Hebei, China. The name "R-CELLS" has a connotation, where "R" stands for Renewable, Recyclable, Reconstructable, and Replicable. And "CELLS" is an acronym for the five key words of ZEB objectives: Customization, Energy plus, Lifecycle, Livability, and Smart connection.

R-CELLS is a single-story residential building with a gross floor area of 146m2. It is constructed using a three-dimensional modular system with a combination of heavy timber and light timber, the interior and exterior views of R-CELLS are shown in Fig.1(a) and (b). The interior space includes a living room, dining room, two bedrooms, two bathrooms, kitchen, and attached sunspace. The equipment rooms for the BESS, power control system (PCS) and converters are located on the north side of the building and is physically separated from the indoor space to meet safety regulations. The building complies with the standards for cold regions in the standard GB/T 51350-2019 [14].

As shown in Fig.1 (c), the energy system of R-CELLS is combined with BIPV, BIWT, PV-T, BESS, HWT, PCM thermal storage, DC/DC converters, DC/AC converters, AC and DC loads, as well as energy management strategies. Additionally, a weather station is installed on the roof, and IoT sensors are placed indoors to measure indoor temperature, humidity, CO2, and PM2.5.

2.2 Renewable Energy Source Generation

In accordance with the ZEB standards and competition requirements, the utilization of RES is of utmost importance in R-CELLS. The RES of this building includes rooftop monocrystalline PV, cadmium telluride (CdTe) thin-film PV, Colorful thin-film transparent PV, PV-T, and vertical-axis BIWT.

2.3 Energy Storage System

R-CELLS adopt lithium iron phosphate batteries. A battery array with a capacity of 99.84 kWh has been chosen for R-CELLS, with a rated maximum power of 20 kW. Its main purposes include enhancing renewable energy utilization, enabling off-grid operation, providing grid interaction flexibility, and participating in electricity trading for revenue generation. The battery array is connected in series and directly connected to a DC/DC converter for charge and discharge control.

Also, a hot water tank (HWT) is equipped with the heat source coming from the PV-T components installed on the north side of the building. The HWT has a capacity of 120 liters.

R-CELLS also incorporates phase change material (PCM) thermal storage to further enhance the utilization of solar energy. Specifically, PCM is installed beneath the floor of the attached sunspace. PCM thermal storage enables energy storage and release through the heat absorption or release during the phase change process.

2.4 AC and DC hybrid distribution system

Since the RES and the BESS in R-CELLS operate on DC input and output, while most household appliances on the market are designed for AC electricity systems, R-

CELLS has implemented a hybrid system that primarily utilizes DC power and is supplemented by AC power. This design aims to reduce power losses resulting from AC/DC or DC/AC invertors. The DC bus voltage level is set at 220V, which drives household appliances requiring higher power voltage and that residents do not frequently interact with. Lighting, USB sockets, and TYPE-C sockets, which may come into frequent contact with, are supplied with a voltage level of 48V DC. Additionally, to accommodate market availability, R-CELLS reserves 220V AC sockets.

2.5 Energy management strategy

A tri-period energy management strategy (EMS) based on optimized scheduling and rule-based control is proposed to address the requirements of net-zero and off-grid sub-contests in SDC contest, as well as considering the normal operation during non-competition periods. The EMS involves weekly, daily and hourly periods. The scheduling objectives aim to meet the operation under different connectivity states and scenarios with the grid, such as grid-connected, islanded, and power outage scenarios. The basic approach is as follows:

2.5.1 Weekly-period

In the weekly period, the EMS aims to optimize the utilization of renewable energy resources and achieve a balance between energy supply and demand. Depending on the connection status with the external grid, the operational mode for R-CELLS divides into connected mode, islanded mode and hybrid mode to cope with grid-connected, islanded, and power outage scenarios, respectively. The time scale for the weekly-period strategy is a week or more. Through scheduling, the initial values of the BESS and the operational status of household appliances are determined for each scheduling day at the daily period.

2.5.2 Daily-period

In the daily period, once the operating mode and initial states of the devices are determined for each scheduling day, the energy scheduling for each time period of the day can be determined based on user historical behavior and device operating modes. A scheduling period is set with a scheduling interval of 1 hour. The scheduling equations remain consistent with the weekly-period stage. The scheduling plan is then adjusted on an hourly basis using model predictive control (MPC) method for rolling updates.

2.5.3 Hourly-period

In the hourly period, due to the presence of boundary logic in each device to ensure itself safe operation, the EMS proposed at the hourly period focuses on determining the main energy supply components, namely BESS and grid.

3. ENERGY PERFORMANCE OF R-CELLS DURING THE SDC 2022

Fig.2 illustrates the actual energy balance during the competition with the sampling interval of 2 minutes. Fig. 3 shows the energy balance simulation during the competition with the sampling interval of 15 minutes. From 8/8 10:00 to 8/10 10:00, R-CELLS tested in contest off-grid, using the islanded mode. From 8/10 10:00 to 8/13 17:00, R-CELLS operated in connected mode, where energy demand was met by a combination of RES, the grid, and the BESS. From 8/13 17:00 to 8/14 10:00, R-CELLS operated in the hybrid mode, with energy supplied by RES and the grid. Throughout the entire competition period (8/8 10:00 to 8/14 10:00), the building generated 126.89kWh of electricity and consumed 76.58kWh of energy on average per day. The total power generation of R-CELLS is 761.34kWh. The energy self-sufficiency rate during the competition is 165.70%. The net electricity imported from the grid was 179.07 kWh. The interaction with the grid is illustrated in Fig.4, which displays the grid interaction data provided by the SDC organizing committee with a sampling interval of 15 minutes.

The load of R-CELLS during the competition is shown in Fig.5, with a total energy consumption of 459.00 kWh. The main energy-consuming devices during the competition, ranked by electricity consumption from highest to lowest, are the HVAC system (49.03%), AC load (21.67%), lighting (14.95%), and DC load (14.35%). The significant differences between the actual energy consumption during the competition and the simulated results can be attributed to the following factors:

1) The outdoor weather conditions during the competition differed significantly from historical data. The outdoor temperature during the competition period was higher than the historical average. The HVAC system's power consumption is influenced not only by outdoor temperature but also by indoor factors such as humidity, CO2 levels, PM2.5, etc. However, the simulation only considers the relationship between HVAC power and indoor/outdoor temperature.

2) The competition attracted a larger number of visitors (30-40 individuals per hour), resulting in higher internal heat gains, also higher humidity, CO2 and PM2.5. Additionally, frequent door and window

openings, such as visitor entry/exit and showcasing activities involving the opening of skylights, further increased the HVAC system's power consumption.

3) As the competition evaluated factors beyond just energy performance, such as architectural design and aesthetics, a lighting control system was designed and installed to balance energy efficiency and visual appeal. The system included decorative lighting that automatically turned off when sufficient natural light was available. Consequently, the lighting energy consumption during the entire competition period was 68.64 kWh.

4) The simulation did not account for the power consumption of the intelligent control system and

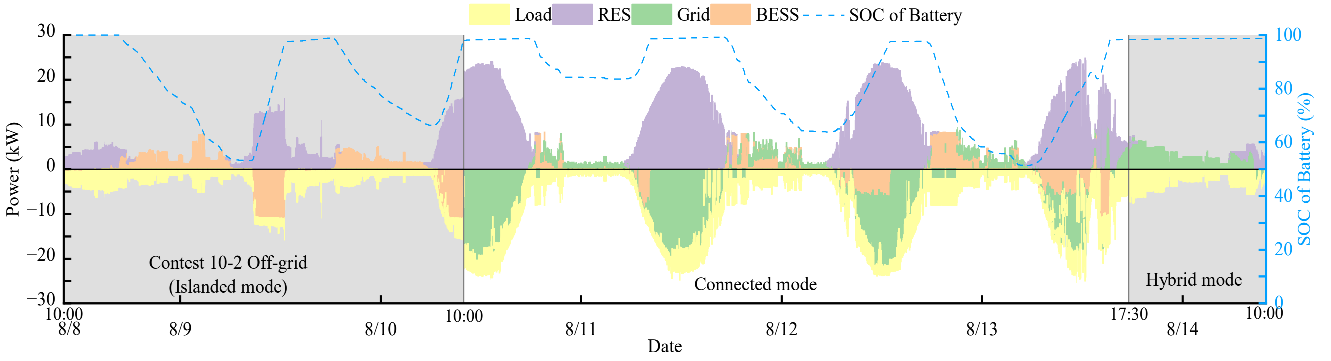


Fig.2. The actual energy balance during the competition

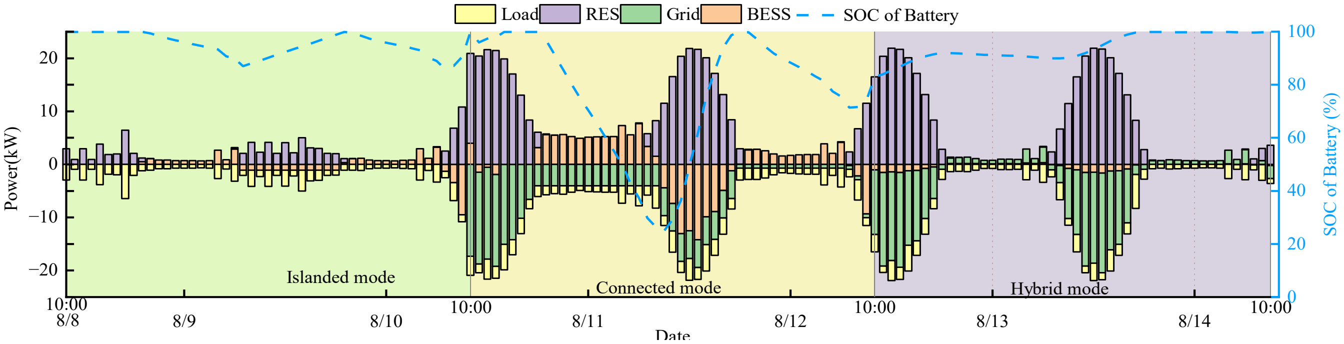


Fig.3. The energy balance simulation during the competition

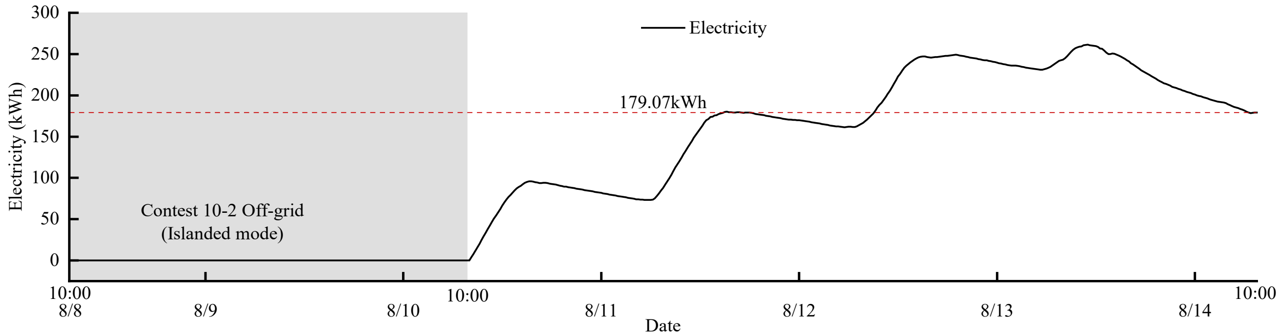


Fig.4. The electricity transmission with the grid

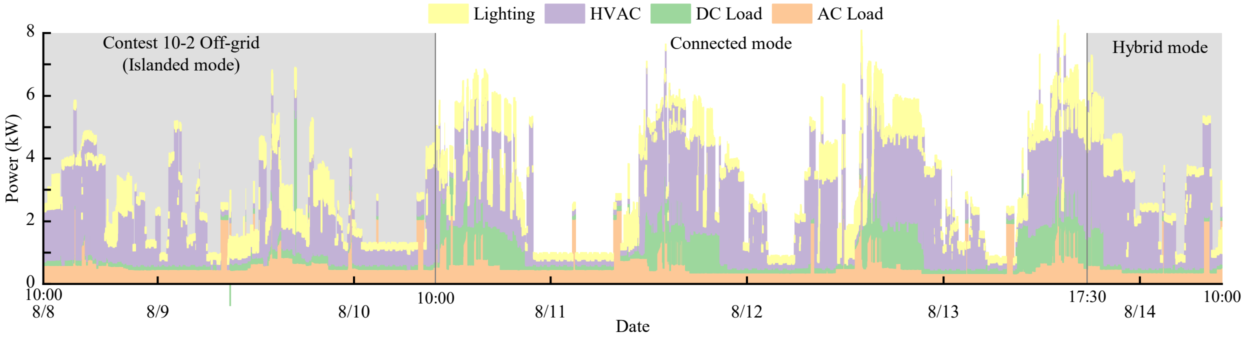


Fig.5. Load of R-CELLS during the competition

cooling devices (e.g., exhaust fans in equipment rooms). During the actual operation, this part of the load accounted for 68.05% of the AC load.

4. DISCUSSION

Based on the operational results of R-CELLS during the competition, there are areas for improvement in the equipment selection and energy utilization efficiency of the R-CELLS energy system.

4.1 Equipment selection in energy system

Due to the time constraint of one year before SDC2022, R-CELLS had limited opportunities for secondary replacement of equipment such as BESS and HVAC system, as the installation space was designed accordingly. Through actual testing during the competition, it was found that equipment selection that meets the operational conditions of a residential ZEB may not necessarily meet the specific constraints of the competition, especially regarding indoor comfort parameters such as humidity, CO_2 levels, and PM2.5. The competition rules imposed specific limits on these parameters, and considering these indoor environmental factors resulted in a 31% increase in energy consumption for the HVAC system. Similarly, the equipment models suitable for the competition may not be optimal for the operational conditions of a residential ZEB. For example, the capacity of BESS and RES was oversized to accommodate the potential needs for research and testing purposes as the building would later be used as a homestay.

4.2 Energy utilization efficiency

Although the use of DC devices can reduce energy conversion losses, the presence of multiple voltage levels and the use of different converters for these voltage levels resulted in actual losses higher than the simulated results. Additionally, the insulation performance of the building envelope, designed to withstand harsh winter climates, led to the generation of heat by converters and BESS, requiring the installation of air conditioning equipment to maintain a safe operating temperature range. This additional energy consumption accounted for 9.77% of the total energy consumption during the competition. In the RES section, the actual performance of the BIWTs was compromised due to differences in installation methods compared to those provided by the manufacturer. Further modeling and testing are necessary to accurately simulate the BIWTs' power generation capabilities.

5. CONCLUSIONS

This paper introduces the energy system and energy performance of R-CELLS, the entry by Team Tianjin U+ in the SDC 2022 competition. R-CELLS achieved the desired goals and secured 8 first-place finishes in various categories, ultimately ranking first overall among 15 participating teams. The energy system of R-CELLS was developed by integrating considerations such as energy equipment, ZEB standards, and SDC competition rules under the constraints of the competition venue's natural conditions. The energy system incorporates renewable energy generation technologies such as BIPV, BIWT, and PV-T systems. In terms of energy storage, it combines BESS, HWT, and PCM thermal storage. The distribution system employs a hybrid AC/DC with voltage levels of 220V DC, 48V DC, and 220V AC. Regarding energy management strategies, a three-period approach (weekly, daily, and hourly) is employed using a combination of MPC methods and rule-based control. This strategy addresses R-CELLS' operation modes under grid-connected, islanded, and power outage conditions. Simulation data demonstrate that the building meets the ZEB standards. The actual operation during the competition validates the reliable performance of the energy system, the effectiveness of the energy management strategy, and the fulfillment of various energy needs of the residents. The specific conclusions are as follows:

1) Proof of off-grid capability during the competition: R-CELLS successfully operated off-grid, meeting the building's energy consumption through RES and BESS, achieving 100% energy self-sufficiency, with a minimum SOC of 53.20% for BESS.

2) Maintenance of indoor comfort parameters during the competition: R-CELLS maintained indoor temperature, humidity, CO_2 levels, and PM2.5 within the specified range, leading to HVAC system energy consumption accounting for 49.03% of the total energy consumption. During off-grid operation, HVAC energy consumption increased by 31% due to the impact of indoor comfort parameters.

3) Utilization of Energy management strategies: Virtual energy storage is used in a ZEB to achieve load shifting, with load shifting accounting for 17.67% of HVAC system energy consumption. Passive regulation capabilities reduced HVAC system energy consumption by 7.71%.

Future work will focus on two areas:

1) Analyzing the annual performance of R-CELLS to validate its compliance with ZEB standards.

2) Using R-CELLS as a test bed, various experimental projects can be conducted to explore different research directions related to ZEBs, such as environmental impact assessment, grid interaction and demand response, occupant behavior and comfort.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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