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Impact of integrating the concentrated solar power on the reliability of the Moroccan electricity system

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ABSTRACT

In Morocco's electrical grid, the percentage of renewable energy used is rising. This growth can have significant impacts on the electrical system's ability to meet load because of unpredictable solar energy production. To evaluate the effects of concentrated solar power (CSP) generation and load evolution on the hierarchical level I (HLI: the capacity to cover the load on the premise of an endless node), this study is evaluating, by employing a Monte Carlo non-sequential simulation, decreasing the impacts on the ability and increasing the reliability of the Moroccan electrical grid. For that, we determine the CSP based on the hourly direct normal irradiation (DNI) for each site, the hourly conventional generation and the hourly load. Then we use these data as input elements in the Monte Carlo simulation to calculate the reliability indices like loss of load probability (LOLP), loss of load expectation (LOLE) and loss of energy expectation (LOEE).

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1. INTRODUCTION

Morocco's National Energy Strategy (NES) was approved in 2009 with aims for 2020. It was updated with additional targets till 2030 before the 21st climate negotiations in Paris at the end of 2015. To reduce the dependence of energy on fossils and accelerate the transition to an energy future with greater energy security and lower carbon emissions by reducing greenhouse gas (GHG) emissions. This is accomplished by looking at the three main challenges of the modern policy of energy: affordability, sustainability, and supply security [1], [2].

Energy supply security is one of the objectives of this NES. It aims to decrease exploration of conventional energy sources, as well as increasing dependency on imported energy carriers through the growth of domestic renewable energy [3]. Nowadays, and based on the NES's targets and the associated national priority action plan (NPAP, 2009–2015) [4], the total RE installed capacity in the electrical sector is about 42% by 2020 (14% wind, 14% solar and 14% hydro) and to 52% by 2030 (20% solar, 20% wind, and 12% hydro).

A crucial component of Morocco's national energy strategy (NES) is the expansion of the country's hydropower projects as well as the Moroccan solar plan. Also, according to the national solar plan since 2009, the installed capacity of combined CSP and photovoltaic (PV) must reach 2000 MW by 2020 to achieve the 2030 goal. Between 2018 and 2030, Morocco plans to increase its renewable energy capacity by around 10 GW, which will be made up of 1330 MW using hydropower, 4560 MW of solar and 4200 MW of wind [5], [6]. In light of these goals, Morocco has decided to build multiple wind, CSP, and PV power plants, these increase renewable power despite CSP power can have significant impacts on the electrical system's ability to meet the load.

Several research investigations have been performed as an evaluation of the impact of renewable energy integration on the Moroccan electrical grid reliability. For instance, Oukili *et al.* evaluated the reliability of the Moroccan grid with CSP, wind and PV integration for the hierarchical level HL1 (HL1) in 2009 using a non-sequential Monte Carlo simulation and well-being indices [7]–[10]. Meanwhile, El Fahssi *et al.* [11] utilized the same approach in order to evaluate the impact of wind power integration on the Moroccan electrical grid reliability in 2019. Karmich *et al.* [12] employed probabilistic methodology to evaluate the impact of the integration of renewable energy production units in electrical systems in 2030. The aim of this paper is the evaluation of the impact of integration the concentrated solar power on the reliability of the Moroccan electricity system using non-sequential Monte Carlo approach with the adequate indices (LOLP, LOLE and LOEE).

In this study, we chose to evaluate this impact on 2019 because this year isn't affected by COVID19. This paper is organized as follows. Section 2 presents the research method; the electrical generation of CSP power plants is discussed in section 3. Then, section 4 describes the electrical generation by conventional power units, while section 5 deals with the Moroccan evolution of the load. Then, section 6 is dedicated to the results and discussion. Finally, section 7 presents conclusions.

2. RESEARCH METHOD

In order to assess the Moroccan electrical system's reliability, a non-sequential Monte Carlo simulation was employed [11], [13]–[16]. This simulation illustrates "network life" as a set of occurrences that change the state of the system and each formed system state is considered every hour. Additionally, it depends on the hierarchical level of the system. For example, the load fluctuations, forced or planned outage of production units for maintenance in the hierarchical level I (HLI: generation), the line unavailability (weather, overload, and falling branches) and substation unavailability (overload or damage of equipment) in the hierarchical level II (generation+transmission), as well as the hierarchical level III concerning the three parts: generation, transmission and distribution. In this research, it should be mentioned that the evaluation of reliability is only for the hierarchical level HLI [17]–[21].

In this research, every conventional (thermal and gas turbine) unit may be classified into two states: available and unavailable. During the Monte Carlo simulation, each generating unit's operational state is determined by sampling a uniformly distributed number (in the interval [0,1]):

a. If $\mu \leq EFOR_d$ (equivalent demand forced outage rate) the duration of unavailability of units due to forced outage when it is in demand [22], [23].
b. If $\mu > EFOR_d$, the generating unit is completely available.

The system advisor model (SAM) is used in this research to generate the hourly CSP power based on meteorological data (solar irradiation, ambient temperature) and technical descriptions of each CSP plant. The hourly load is determined by a correlation approach based on seasonal coefficients from the monthly load. The hourly electrical power and the hourly load are generated during the period of simulation years and are compared in order to calculate the electrical system reliability indices. The number of states to be generated is reached when the reliability indices calculated, for the same system configuration, remain unchanged, moving from one simulation to another. In our case, the number of generated states was set to N=500 years to ensure a precision of 10^{-4} at the level of the recorded indices.

The reliability indices used in this study are as follows [24]–[29]:

a. LOLP, the load cannot be sufficiently covered by the global power available as it is directly less than the load.

$$LOLP = M/(N * 8760) \quad (1)$$

b. LOLE is the duration of the expected annual system.

$$LOLE(hr/yr) = LOLP \times 8760 \quad (2)$$

c. LOEE is the expected energy not supplied, this is called also expected energy not serviced (EENS).

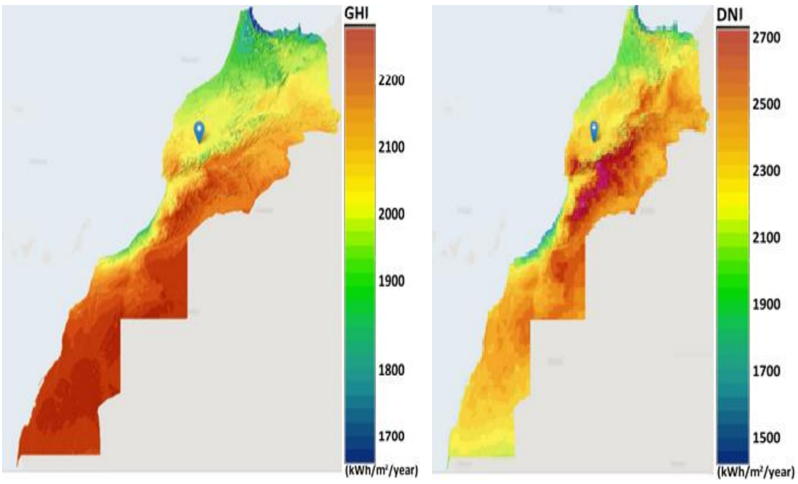
$$\mathrm{LOEE(MWh/yr)} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{M}} \mathrm{E_i} \quad (3)$$

where N is the total number of years used in the Monte Carlo simulation, M is the number of hours when the load is superior strictly to the global power available and E_i is the energy not supplied in MWh.

3. ELECTRICAL GENERATION OF CSP POWER PLANTS

3.1. Solar energy potential in Morocco

Morocco is distinguished by both a significant geographic position and intense solar radiation (an average irradiation of more than 5 kWh/m^2/day). With an intense solar radiation potential estimated by the Moroccan Agency for Sustainable Energy (MASEN) to be over 2,600 kWh/m^2/year under yearly sunlight durations (3,000 hours on average), it has an abundance of solar resources [5], [6]. It is one of the sunniest countries in the world, which makes it perfect for the large-scale development of CSP power plants. Figure 1 shows the Moroccan solar energy potential. Specifically, Figure 1(a) displays the global horizontal irradiation (GHI) for PV energy, while Figure 1(b) shows the direct normal irradiation (DNI) for CSP energy.



(a) (b)

Figure 1. Solar energy potential in Morocco [2], [3] (a) GHI and (b) DNI

3.2. Determination of DNI

The estimation of the CSP power is based on the solar radiation. To define this solar radiation, there are several solar resource data. In our research, we used the European Commission's PVGIS to extract hourly solar radiation from each CSP plant location. Figure 2 shows the evolution of the hourly DNI in W/m^2 and Table 1 gives the potential DNI for each location CSP plant.

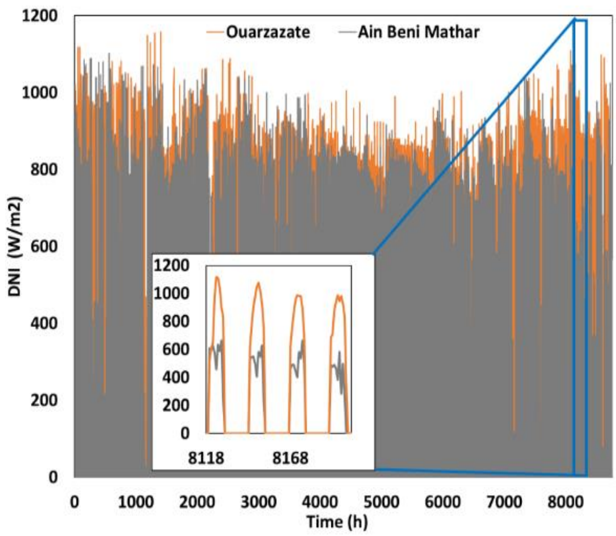


Figure 2. Evolution of DNI for localization CSP plants [30]

Table 1. Potential DNI of CSP plant localization

CSP plants localization	DNI (Wh/m²/day)	DNI (kWh/m²/year)
Ain Beni Mathar	6283	2293
Ouarzazate	6850	2706

3.3. Determination of CSP power

The system advisor model (SAM) software is used to calculate the hourly electricity generated by a CSP (with parabolic mirrors or a solar tower). Studies [31], [32] using the ambient temperature and the DNI extracted from the PVGIS database, the solar field area and the heat storage capacity of each CSP plant. In 2019, the operational CSP total installed power is 530 MW. Table 2 shows technical descriptions of these CSP plants and Figure 3 presents the evolution of the hourly electrical power of CSP plants.

Table 2. Technical descriptions of CSP plants [33], [34]

CSP plant	Installed Power (MW)	Technology	Solar field aperture area	Storage Capacity
Ain Beni Mathar	20	Hybrid, parabolic troughs	183 120 m^2	0 h
NOOR 1	160	Parabolic troughs and molten salt	1 308 000 m^2	3 h
NOOR 2	200	thermal energy storage	1 779 900 m^2	7 h
NOOR 3	150	Solar tower and molten salt thermal energy storage	1 312 000 m^2 7400 heliostats of 178m^2	7 h

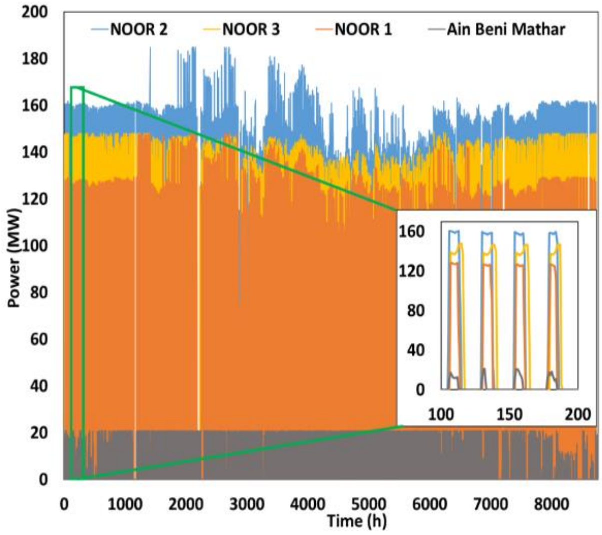


Figure 3. Evolution of the electrical power of CSP plants

4. ELECTRICAL GENERATION BY CONVENTIONAL POWER UNITS

The operational conventional generation units of Morocco in 2019 are also taken into account. The global installed power was then reaching 8746 MW (without considering the installed renewable power intermittent) dispatched between 6976 MW of thermal power, 1306 MW of hydraulic power and 464 MW of pumped-storage hydroelectricity [35]. In reality, the total power is the sum of the power generated by the conventional units and the renewable power including CSP plants examined during each constructed system state. Table 3 presents the Moroccan conventional generation park with the $EFOR_d$ corresponding.

Table 3. The conventional generating parks with $EFOR_d$ parameter [35], [36]

Conventional Park	Number of plants	Number of units	Installed power (MW)	$EFOR_d$ (%)
Hydro	31	68	1306	**7.73**
Thermal Coal	5	11	4116	**8.66**
Thermal Oil	2	6	600	**9.99**
Thermal Gas turbine	6	21	1110	**10.6**
Thermal Combined Cycle	2	2	834	**3.81**
Thermal Diesel	4	20	286	**7.23**
Pumped Storage	1	4	464	**5.39**

5. THE MOROCCAN EVOLUTION OF THE LOAD

This section aims to calculate the hourly electrical load of Morocco in 2019. For that, the actual monthly energy consumption of this year is used from the data of the higher planning commission. Figure 4 shows the monthly load of Morocco in 2019 and Figure 5 presents the evolution of the yearly peak load between 2013 and 2018.

We can note that the ratio between the hourly load and the average load of the day experiencing the annual peak is almost constant, so we can use it as a coefficient to estimate the hourly load in 2019. Based on these results of the monthly energy of 2019, the hourly load is determined assuming that the daily load is stable during each month; the hourly load of every month is calculated by multiplying the average hourly load and the coefficient of each hour of the day. The hourly load of 2019 is presented in Figure 6, the hourly peak load in 2019 is 6540 MW and the calculated one is 6526 MW, which validates this approach.

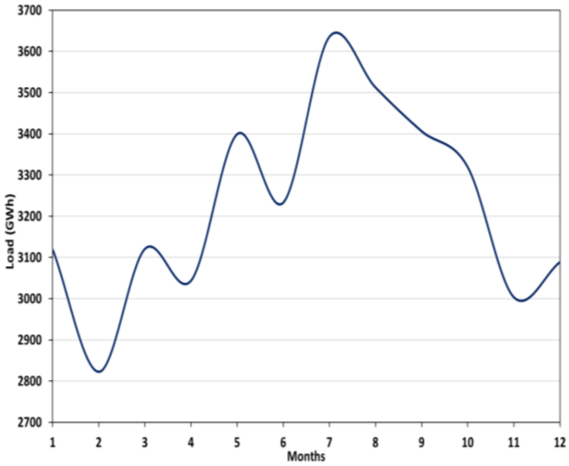


Figure 4. The monthly load in 2019

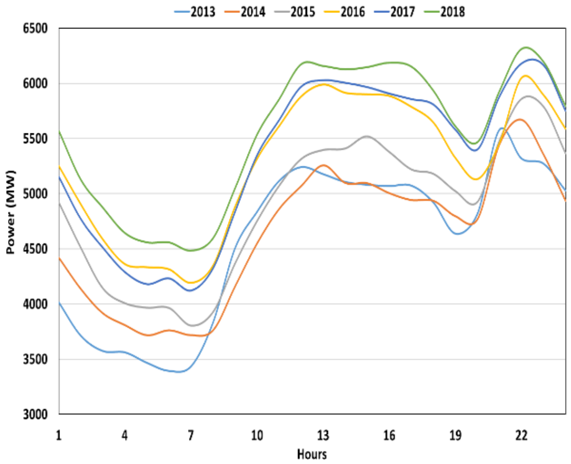


Figure 5. Evolution of the yearly peak load 2013-2018 [35]

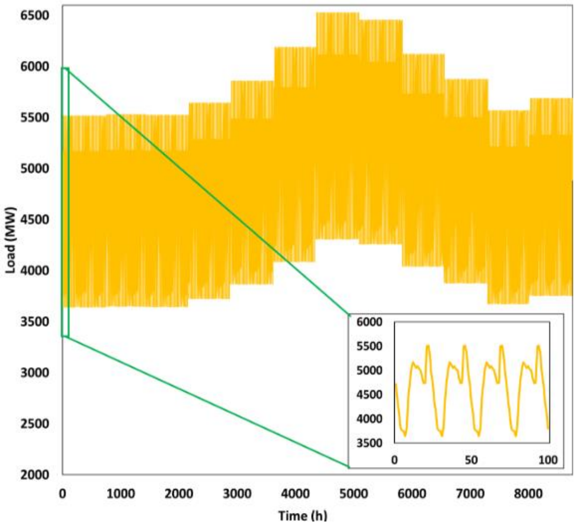


Figure 6. The evolution of the estimated hourly load of 2019

6. RESULTS AND DISCUSSION

6.1. The impact of replacing CSP by conventional generation

The purpose of this section is to investigate the impact of CSP in comparison with conventional power generation on the reliability of the Moroccan electrical system. To evaluate this impact, a Monte Carlo simulation is established, integrating CSP power (5%) into the conventional park described in Table 3 and replacing it with conventional generation (with the same load and installed power). The results of the simulation are presented in Figure 7 and Table 4.

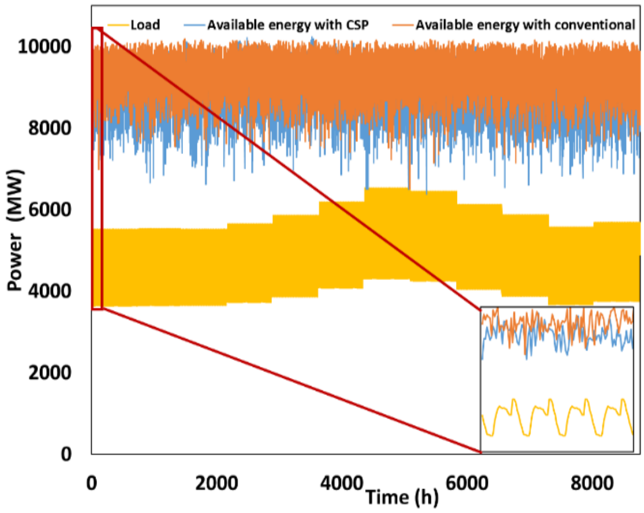


Figure 7. Evolution of available energy and load in 2019

Table 4. Results of replacement CSP power plants with conventional power

	With CSP power 5% (2019)	Replacement CSP with conventional power (2019)
Installed power (MW)	10677	
LOLP (10^{-7})	36	2.2
LOLE (hr/yr)	0.031	0.0019
LOEE (MWh/yr)	5.93	0.17
Load (GWh)	43679	
Available global generation (GWh)	77094	80179
Available CSP generation (GWh)	1551	0

From Table 4, we realize:

a. LOLP decreases significantly with replacement CSP by conventional power (LOLP =36 10^{-7} with CSP power LOLP = 2.2 10^{-7} with conventional power);
b. LOLE decreases from 0.031 to 0.0019 hr/yr;
c. LOEE decreases from 5.93 to 0.17 MWh/yr;
d. The available energy generated by the system with conventional units considerably exceeds the one with CSP power.

These results confirm that the reliability of the electrical system is influenced by the intermittency of CSP energy and this impact can be justified by the CSP production unpredictability and uncontrollability.

6.2. The impact of adding CSP generation

The second section aims to evaluate the reliability of adding CSP power (keeping the same load) and to determine at which CSP power added reliability indices reach the performance of conventional power. Based on Table 5, we note:

a. LOLP gradually decreases and begins to stabilize at 2.8 10^{-6} from 40% of CSP power added;
b. LOLE decreases and stabilizes at 0.024 hr/yr from 40% of CSP power added;
c. LOEE gradually decreases and begins to stabilize at 4.4 MWh/yr from 40% of CSP power added;
d. The available global and CSP generations of the system gradually increase when we add progressively CSP power.

In this part, we can conclude:

a. The reliability indices (LOLP, LOLE, LOEE) don't reach the performance of conventional units (2.2 10^{-7}) despite adding 100% of CSP power to the installed power of 2019;
b. The reliability indices (LOLP, LOLE, LOEE) improve by adding CSP power and stabilize from 40%;
c. The available global generation of the system exceeds that produced by conventional units from 10% of CSP power added; for this, it is essential to take into consideration interconnections with other countries and means of energy storage (pumped energy transfer station).

Table 5. Results of Monte Carlo simulation results by adding CSP power

% CSP power added	+10%	+20%	+40%	+60%	+80%	+100%
Installed power (MW)	11745	12812	14948	17083	19219	21354
LOLP (10^{-6})	3	2.9	2.8	2.8	2.8	2.8
LOLE (hr/yr)	0.026	0.025	0.024	0.024	0.024	0.024
LOEE (MWh/yr)	4.7	4.6	4.4	4.4	4.4	4.4
Load (GWh)			43679			
Available global generation (GWh)	80215	83340	89594	95847	102100	108352
Available CSP generation (GWh)	4678	7802	14057	20309	26562	32815

6.3. Impact of replacing conventional generation by CSP

The third section aims to determine the effect of gradually replacing the conventional power installed in 2019 (with the same load and the same installed power) with CSP power to verify that at any percentage of every renewable power the LOLE exceeds 3 hr/yr (the most reliability target required by the majority of European countries). In our research, we have chosen this reliability target because Morocco's grid is connected to the European electrical network.

From the results exposed in Tables 6 and 7, we can note that at 5% (2019) of CSP power LOLE is inferior to the reliability target. This result confirms that 5% is an appropriate percentage. However, from 16.5% of CSP power, LOLE exceeds this threshold; therefore, we have the margin and the capacity to replace conventional power with more CSP without exceeding the fixed value of reliability.

Table 6. The reliability target fixed by European countries [37], [38]

	France/Belgium/Great Britain/Greece	Netherlands	Portugal	Hungary/Ireland	Bulgaria
LOLE (hr/yr)	3	4	5	8	13

Table 7. Results of replacing conventional with CSP power

CSP power (%)	5% (2019)	10	15	16	17	18	19	20
LOLE (hr/yr)	0.031	0.26	1.8	2.7	3.9	5.5	7.9	10.6

7. CONCLUSION

In this research, we evaluated the impact of integrating the CSP power on the reliability of the Moroccan power grid using a non-sequential Monte Carlo simulation for the generation level (HLI). Firstly, when we replace CSP power in 2019 (5%) with conventional power (with the same load and power installed), the reliability indices (LOLP, LOLE, LOEE) decrease considerably and the available energy generated by the system with conventional units greatly exceeds that one with the CSP power. These results confirm that the electrical system's reliability is impacted by the intermittency of CSP power. Secondly, we note that the reliability indices (LOLP, LOLE, LOEE) improve when we add CSP power production and these indices do not reach the performance of conventional reliability indices even after adding 100% of CSP to the power installed in 2019; In terms of energy, Morocco's available production including CSP energy, is gradually increasing and exceeding the energy available on conventional from adding 10% of CSP; for this, it is essential to have interconnections with other countries and means of energy storage.

Ultimately, we conclude that 5% (2019) of CSP power is an adequate percentage because LOLE is below the reliability target set (3 hr/yr). However, when we gradually replace the conventional with CSP power, we can see that from 16.5% CSP power LOLE exceeds this threshold; therefore, we have the margin and the capacity to replace conventional with more CSP power without exceeding the fixed value of reliability. Considering the impact of intermittent renewable energy, including CSP energy, on the dependability of the Moroccan electrical system, what was found of our study can help policymakers and energy planners develop the equipment plan necessary to meet Morocco's National Energy Strategy towards 2030 target of 52% of the total renewable energy installed capacity in the electrical sector.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Taoufik Ouchbel	✓	✓	✓			✓		✓	✓	✓	✓			
Smail Zouggar				✓	✓	✓						✓	✓	
Mohamed Larbi Elhafyani				✓	✓	✓						✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the authors upon reasonable request.

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