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4 Theoretical evaluation of the evaporation rate of
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6 large-scale application potential

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21 **ABSTRACT**

22 2D solar-driven interfacial evaporation (2D SIE) is a low-cost, environmentally
23 friendly water treatment solution. Studies have improved the performance of single-stage
24 evaporation close to its upper bound in controlled environments. However, the most critical
25 parameter – the rate of evaporation – was only assessed by laboratory-scale measurements
26 and data are typically obtained under a specific set of conditions. Previous studies did not
27 evaluate or modeled evaporation rates in the case of changing environmental variables, for
28 example, temperature, humidity, or wind speed. To effectively utilize the 2D SIE technology
29 at real scale and understand its potential in different scenarios, the spatial and temporal
30 variability of environmental parameters must be considered. To preliminarily address this
31 issue, we propose the first model for assessing the evaporation rate of 2D SIE systems in real
32 environments. Based on this theoretical model, we thus explore the potential deployment of
33 the 2D SIE technology globally. This study provided a basis for further model development
34 and it discusses key information to guide further improvements of 2D SIE systems design and
35 its large-scale implementation.

36

37 **Keywords:** Interfacial evaporation; Solar desalination; 2D evaporator; Theoretical model;
38 Global assessment

39 **1. Introduction**

40 Evaporation is a natural process, ubiquitous in nature, which separates water of high
41 purity from contaminants and other substances (e.g., salts). However, heat utilization is
42 inefficient during so-called bulk evaporation, with only about 20% of the energy directed to
43 the phase change phenomenon, due to heat dissipation mechanisms [1]. Engineered
44 evaporation relying on environmentally friendly, low-cost energy sources, such as solar
45 energy, has gained momentum in the last decade within the overarching effort to provide
46 affordable water treatment systems powered by renewable energy [2-4].

47 To solve the problem of inefficient energy utilization, thermal localization strategies
48 have been proposed that effectively reduce heat loss and increase energy conversion by
49 selectively confining the heating to the surface where phase change happens, instead of the
50 entire water body [5]. Solar-driven interfacial evaporation (SIE) technology is the product of
51 this broad concept [2]. According to the structure of the evaporator, the SIE systems are
52 classified as 2D SIE and 3D SIE. Due to the advantages of simple structure, low cost, and
53 simple maintenance, the 2D SIE system is considered to have great potential in practical
54 application [6]. 2D SIE systems have shown outstanding success in the utilization of solar
55 heat and achieved highly efficient energy conversion, so much so that they have even begun
56 exceeding the apparent theoretical limit through mechanisms of absorption of the
57 environmental heat and reuse of the latent heat [7-10]. Evaporation efficiencies around 90%
58 have been shown with several materials, and higher water production rates than those
59 predicted from calculations based on the pure phase change ($\sim 1.5 \text{ kg m}^{-2} \text{ h}^{-1}$) have been

60 reported [11-14]. Also, the quality of the condensed product that has been produced starting
61 from waste liquid is typically high [14-16].

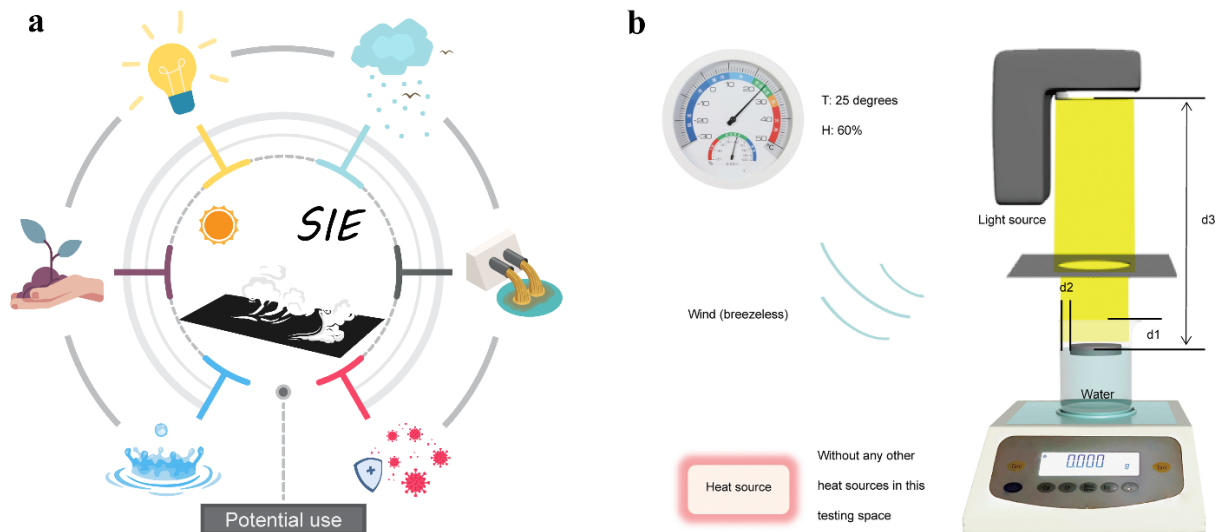
62 The availability of thermal positioning techniques and the efficiency leap driven by
63 the innovation in materials have greatly enhanced the possibility of implementing the SIE
64 technology at real scale. Nevertheless, the vast majority of research has so far stopped at the
65 laboratory stage, and most of the experiments simulating real environments have generally
66 been conducted at small-scale and for short durations, for demonstrative purposes only [11,
67 17]. Except for a few works, such as a recent one in which researchers have combined SIE
68 with solar panels to apply this technology in large-scale industries [9], relevant industrial
69 applications have not been reported. The current mainstream research trend in 2D SIE
70 technology largely consists of developing new materials to improve the evaporation
71 efficiency. This research commonly comprises small-scale characterization of new materials,
72 which is insufficient to understand the large-scale applicability of the technology [18], a topic
73 that has been not adequately explored so far. Also, differences in laboratory-scale
74 experimental methodologies complicate comparison of the data obtained by different research
75 efforts. Some researchers have provided experimental guidance to improve the availability
76 and usability of laboratory data [19]. In Table S1 of the Supporting Information, we
77 summarize the relevant data from some 2D SIE evaporators collected in the last four years
78 (2019-2022). It is clear that many studies lack reports of some necessary parameters to
79 understand the experimental conditions, highlighting the lack of standardization in the SIE
80 research field [15, 20-28], which in turn impairs the practical implementation of this process.

81 The prospect of placing SIE technology to practical industrial use has been discussed
82 in our previous article [29], where we reviewed the prospect of SIE technology in the field of
83 industrial wastewater treatment, mainly focusing on cost, pointing out that the SIE
84 technology is a competitive industrial water treatment solution under certain conditions.
85 Many reports have also preliminarily discussed the potential promising application of SIE in
86 other fields, such as high-quality water production and civil wastewater treatment [9, 13, 16,
87 29-31].

88 This study contributes to efforts aimed at increasing the feasibility of large-scale 2d
89 SIE. We hypothesize that the application of 2D SIE technology for water treatment solutions
90 can be adequately predicted taking into account variable environmental factors, thus
91 improving predictions of the evaporation rate by considering the installation environment. A
92 diagnostic model is designed and proposed, based on which the installation potential of 2D
93 SIE on a global scale is estimated. Based on this model, we point out the current potential and
94 needs of 2D SIE technology and research, including the need for accessible, interoperable,
95 and reusable data, as well as the necessity of large-scale, long-term 2D SIE pilot tests.

96

97



98

99 **Figure 1.** Potential applications of SIE technology and technical conventions employed in
 100 SIE research at this stage. (a) SIE technology has significant potential in areas including,
 101 from bottom left in the figure, desalination [15, 32], agricultural water improvement [29],
 102 solar steam power generation [9, 31], possible means on climate improvement [33], industrial
 103 wastewater treatment [29], and solar steam disinfection [1, 30]. (b) Some technical
 104 conventions for SIE experimental materials and systems under laboratory conditions,
 105 including specification of temperature, relative humidity, wind speed, and other conditions
 106 [Fig1.(b) revised with permission from ref [19]].

107

108 **2. Assessing the industrial application of 2D SIE technology: prediction on** 109 **evaporation rate**

110 Evaluations of cost and efficiency are required before the 2D SIE technology is rolled
 111 out on a large scale and to determine if stakeholders would consider this solution as an option
 112 for future applications. Detailed calculations of the cost of 2D SIE technology is complex and
 113 case-specific, as it requires considering all service costs, such as infrastructure inputs,
 114 materials transportation, labor, and many others. However, a preliminary conservative
 115 estimate in our previous work indicated that the cost of SIE technology might be significantly
 116 lower than that of conventional membrane/thermal-based technologies used in the same

117 desalination applications, specifically, below or around \$1 per cubic meter of product water
118 [29]. Here, we focus our attention on the issue of efficiency, namely, evaporation rate, the
119 other decisive factor in determining whether the technology may become a feasible one in the
120 portfolio of water treatment options.

121 **2.1 Calculation of evaporation volume and evaporation efficiency under laboratory** 122 **conditions**

123 The SIE efficiency under standard conditions (1 sun irradiation) is calculated with the
124 following equation [5, 15, 34-36]:

$$\eta = \frac{\dot{m}h_v}{C_{opt}P_0} \#(1)$$

125 where η denotes the evaporation efficiency, \dot{m} denotes the water vapor mass flux (unit
126 chosen as $kg \cdot m^{-2} \cdot h^{-1}$), h_v denotes the enthalpy of evaporation of water ($J \cdot kg^{-1}$), P_0
127 denotes solar radiation power of 1 sun ($1 kW \cdot m^{-2}$), and C_{opt} denotes the optical
128 concentration of the absorber surface.

129 As depicted in Fig. 1(b), laboratory experimenters follow certain general conventions
130 to artificially eliminate the effects of temperature, air humidity, wind [19]. While evaporation
131 efficiency is the best parameter to allow comparison of the performance of different systems
132 and materials investigated under laboratory conditions, evaporation rate is a better indicator
133 to evaluate the evaporation process in field scenarios and to obtain a more quantitative
134 prediction of the performance of SIE technology at large-scale, where wind and air humidity
135 significantly influence the net energy input.

136 **2.2 Evaporation prediction model for 2D SIE technology based on evapotranspiration**
137 **related theory and Penman formula extension**

138 The water evaporation process at the earth's surface, the transpiration of plant leaves,
139 and the sublimation of snow and ice are known collectively as evapotranspiration in the field
140 of meteorology [37-41]. The description of the evapotranspiration process may be used as a
141 blueprint for the description of the 2D SIE performance, since evaporation in a real
142 environment requires consideration of four main meteorological variables, namely, the wind
143 speed, atmospheric humidity, radiation, and air temperature, similar to natural evaporation
144 processes studied in meteorology and agriculture [40, 41].

145 To obtain an accurate description of the evaporation in the SIE technique, we make
146 certain extensions to the Penman formula for estimating evaporation from open water
147 surfaces and the Penman-Monteith formula for estimating evapotranspiration, both of which
148 are semi-empirical relationships for meteorological factors that have been verified by a large
149 amount of data and regarded as highly reliable [42, 43]. Our modified formula follows
150 Penman's consideration of energy conservation and heat and mass transfer relationships [42],
151 and proposes a correction for the specific behavior of 2D SIE with respect to natural
152 evaporation or plant transpiration. We express the theoretical evaporation rate with the
153 following equation:

$$ET = \frac{(\Delta \cdot R_n \cdot 0.9) + \frac{\rho c_p (e_s(T) - e)}{r_H}}{\lambda \cdot (\Delta + \gamma)} \times U_t \quad \#(2)$$

154 where ET denotes the theoretical evaporation rate, Δ denotes the slope of the saturation
155 vapor pressure-temperature relationship, R_n denotes the net radiation, ρ represents the
156 average air density at the ambient pressure corresponding to the evaporation process, c_p

157 denotes the specific heat capacity of air at constant pressure, $e_s(T)$ represents the saturated
158 vapor pressure at temperature T , e represents the actual vapor pressure in the air, r_H
159 denotes the aerodynamic resistance that is determined by the evaporation surface, λ denotes
160 the enthalpy of evaporation of water, γ denotes the humidity constant, and U_t is unit
161 conversion constant which depends on the units of each physical quantity chosen by the user
162 when using this formula. The derivation of Equation (2) can be found in the Supporting
163 Information (SI). The physical basis of the formula is the energy conservation equation of the
164 evaporating surface with the overall mass transfer characteristics of the turbulent boundary
165 layer.

166 All the parameters in Equation (2) can be each ultimately expressed as a functional
167 relationship of the same five input environmental variables,

$$ET = f(R_n, u_z, e, T, P) \quad \#(3)$$

168 where ET denotes the theoretical evaporation rate, R_n denotes the net radiation, u_z denotes
169 the wind speed measured at height z meters (a common meteorological parameter), e denotes
170 the actual vapor pressure in the air, T denotes the temperature of the air, P denotes the
171 atmospheric pressure. See SI for expressions of the specific dependency of each parameter on
172 the environmental variables, many of which are empirical in nature.

173 As outlined in the SI, we introduce the concept of “reference evaporation surface”
174 during derivation. This step is useful to simplify the choice among a wide variety of
175 evaporation surfaces characterized by specific heat transfer characteristics, heat loss caused
176 by long-wave radiation, shape and roughness, and other potentially diverse properties. The

177 “reference evaporation surface” is set by assigning values to a specific set of parameters
178 related to the device configuration and characteristics, mainly concerning the height of the
179 evaporation surface and the surface physical properties. In particular, the “reference
180 evaporation surface” represents here a material and configuration based on recent reports of
181 state-of-the-art porous media applied in 2D SIE. This surface is a relevant example for this
182 field, but may also be regarded as a reference basis for comparison o other materials and
183 systems that are being developed. If relevant, users can apply the model presented here to
184 different surfaces by adjusting the parameters related to the surface characteristics. See SI for
185 specific assumptions.

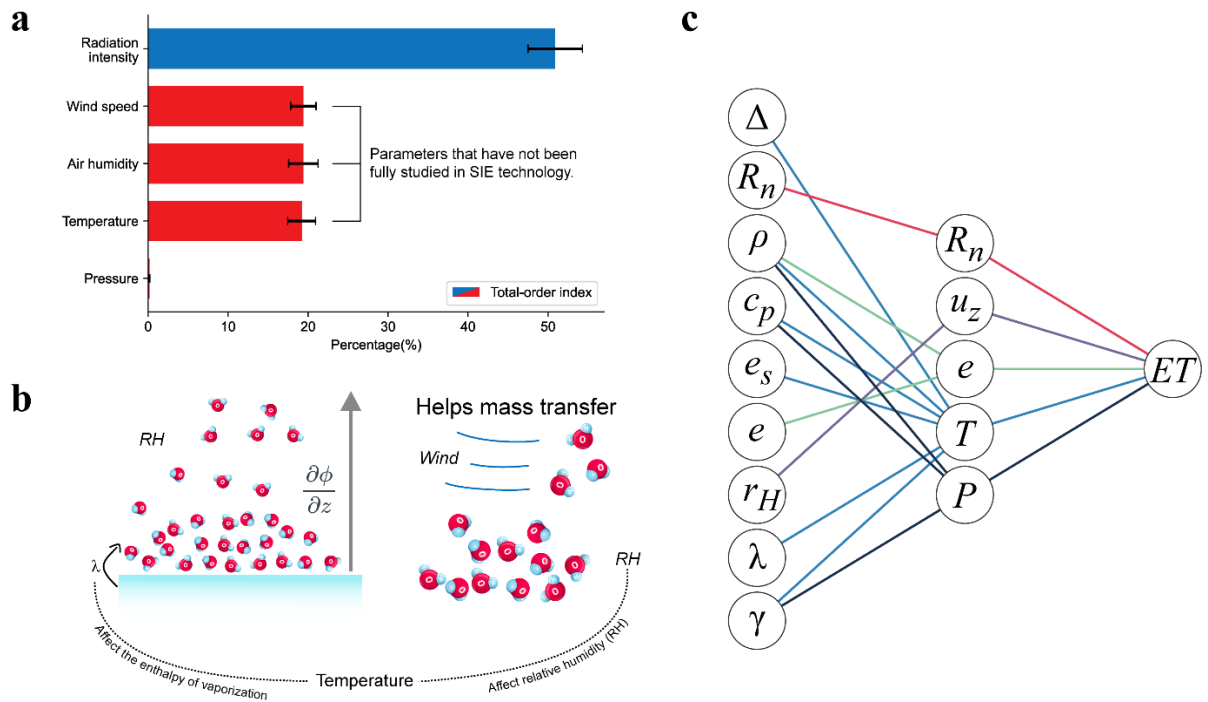
186 Different reference evaporation surfaces may be used in different calculation sets, as
187 long as the characteristics of the material and surface are known. Also note that changes in
188 water salinity will also slightly affect the evaporation rate, but this study did not introduce
189 this variable into the model. At the same time, we did not consider the reduction of latent heat
190 due to the coupling of the material to water. The properties of enthalpy changes in 2D
191 materials obey the descriptions of semi-empirical physical formulas. The salinity of the target
192 water body involved in the 2D SIE technology is typically large. However, for water bodies
193 with ultra-high salinity, a correction factor should be used, which depends on the actual salt
194 content [44].

195 **2.3 Sensitivity analysis and brief discussion of the model**

196 Modeling of the evaporation rate incorporates the consideration of energy
197 conservation and mass transfer processes in real situations, introducing several variables as

198 uncertainty factors (the changes of which affect the evaporation rate). To understand the
199 effect of variables and the robustness of the model, we first performed a sensitivity analysis
200 of the equations presented in Section 2.2. We used the Sobol method to perform a global
201 sensitivity analysis on our model, and the specific implementation of the analysis was
202 conducted with Python's SALib library [45]. We selected the parameters of atmospheric
203 pressure in the range of 80-103 kPa, temperature in the range of 0-40 °C, radiation in the
204 range of 0-1.5 sun, wind speed in the range of 0-3 m s⁻¹, and relative humidity in the range of
205 60%-100%.

206 Therefore, we obtained the first-order sensitivity index and total-order index, where
207 we found that about 50.9% of the output variance in the set analysis range is caused by the
208 radiation intensity, about 19.4% of the output variance is caused by the wind speed, about
209 19.4% of the output variance is caused by the change of air humidity, about 19.2% of the
210 output variance is caused by temperature, and only about 0.17% of the output variance is
211 caused by pressure.



212

213 **Figure 2.** The influence of multiple variables on evaporation. (a) Total-order index calculated
 214 within the range of parameters. (b) How environmental parameters qualitatively affect the
 215 evaporation process: The principle of evaporation is that water molecules have sufficient
 216 kinetic energy to escape the water surface. In SIE technology, the surface material directly
 217 provides kinetic energy for water molecules based on the heat energy obtained from the
 218 photothermal conversion process. At the same time, the air's capacity for water molecules is
 219 limited. If humidity reaches saturation, the evaporation process will stop. The air humidity is
 220 proportional to the concentration of water molecules, that is, the higher the concentration of
 221 water molecules, the higher the humidity. In the figure, ϕ represents the concentration of
 222 water molecules, and $\partial \phi / \partial z$ represents the concentration gradient of water molecules in
 223 the vertical direction. Wind can help water vapor transport away from the water surface,
 224 reduces the concentration of water molecules near the surface of the liquid, increases the
 225 concentration gradient, and enhances the mass transfer process. Temperature will affect the
 226 enthalpy of vaporization and the saturated vapor pressure of air (i.e., relative humidity). (c)
 227 There is a certain empirical relationship between the physical quantities in Equation (2) and
 228 Equation (3). Both forms can provide the predicted value of ET . The network diagram shows
 229 the functional relationship between related physical quantities. The specific functional
 230 relationship can be found in SI.

231

232 Fig. 2(c) schematically presents the functional relationship between the parameters

233 appearing in the model and the relationship between environmental parameters and ET. If

234 water vapor is not transferred away from the evaporation surface, the accumulation of water
235 vapor will negatively affect the evaporation process: air humidity and wind speed
236 significantly affect the water gradient at the surface-air interface, thus the overall evaporation
237 rate. Furthermore, local temperature affects the value of saturated vapor pressure and latent
238 heat of vaporization. The specific functional relationship is presented in the SI, but in general,
239 increasing temperature will increase the saturated vapor pressure and reduce the enthalpy of
240 vaporization. The lower the value of the enthalpy of evaporation, the easier it is for the water
241 to undergo phase change. The saturated vapor pressure represents the capacity of the air to
242 hold water vapor. If the saturated vapor pressure is higher, the evaporation process will be
243 more likely to occur. In this way, the temperature exerts an influence on the evaporation
244 process.

245 Note that wind speed, temperature, and air humidity together are more important than
246 radiation intensity in influencing evaporation rate and should not be overlooked. If
247 researchers can exploit environmental wind to enhance the mass transfer process at the
248 surface with a suitable design, or combine it with water-absorbing materials to change the
249 concentration of water molecules near the surface, the evaporation rate would increase
250 without additional energy input. We would like to underline that the complexity of the
251 evaporation process leads to the fact that its exact mechanism is not yet fully understood. In
252 addition to the inherent drawbacks in the derivation of the equations due to assumptions and
253 approximations, the model proposed in this study is phenomenological, thus its output
254 depends strongly on the accuracy of the estimation of the model parameters and other data

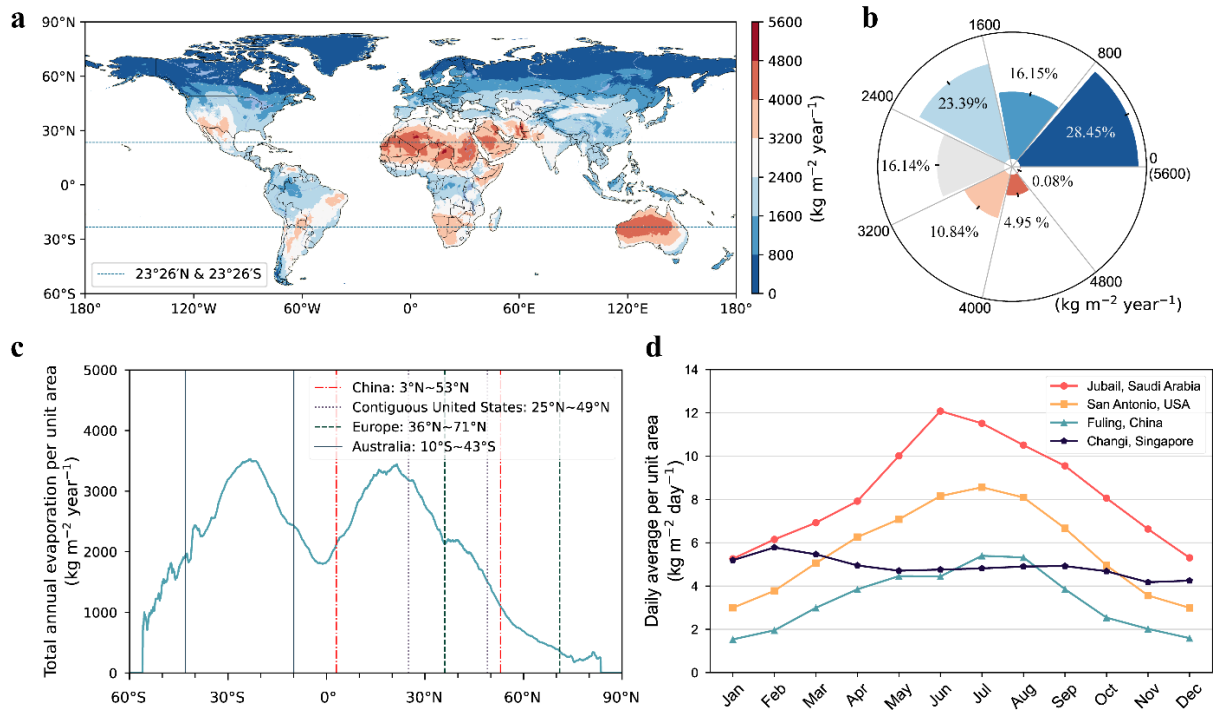
255 measurements. It should thus be regarded as a user-friendly first approximation of the
256 evaporation rate under different environmental conditions.

257

258 **3. Estimating the potential of 2D SIE technology on a global scale based on** 259 **theoretical formulas**

260 **3.1 Global Assessment**

261 Applying the model formulation as described above in Section 2.2, we used reanalysis
262 data provided by NASA [46], which has a spatial resolution of $0.1^\circ \times 0.1^\circ$ (equivalent to 5
263 million data points), a temporal resolution of one month, and involves a latitude range of 60°
264 S to 90° N. We used one year of data from the dataset for 2020, and obtained the model
265 outputs based on the 2020 weather conditions for the global-scale 2D SIE technical
266 evaporation potential. The results are presented in terms of total annual evaporation per unit
267 area in Fig. 3(a).



268

269 **Figure 3.** The global-scale 2D SIE technical evaporation potential prediction is calculated
 270 based on the theoretical model combined with global meteorological data for 2020 [46]. (a)
 271 The figure shows the global distribution of the predicted evaporation potential, calculated as
 272 the value of evaporation per unit area predicted to be generated in one year, with the
 273 evaporation unit as $\text{kg m}^{-2} \text{ year}^{-1}$. (b) Percentage of data volume of each evaporation data
 274 segment: 100% represents the total considered land area, covering almost all regions of the
 275 globe except for the continent of Antarctica and some islands south of 60°S latitude. (c) The
 276 total annual evaporation per unit area varies with latitude: the mean value is calculated as the
 277 average value of the estimated evaporation of all land at a certain latitude. There are two
 278 peaks in the curve, mainly indicating the latitudes corresponding to the tropics and
 279 encompassing Australia and North Africa. The graph also indicates the latitudinal span of
 280 China, the Contiguous United States, Australia, and Europe. (d) Trend of the recalculated
 281 daily average per unit area ($\text{kg m}^{-2} \text{ year}^{-1}$) in different months for four selected locations.

282

283 Evaporation shows greater potential in regions at or around the Tropic of Capricorn
 284 and the Tropic of Cancer, where the estimated evaporation rate per unit area is mostly
 285 concentrated in the interval of $3200\text{-}5600 \text{ kg m}^{-2} \text{ year}^{-1}$. According to our summary statistics,
 286 the map of the predicted evaporation shows the distribution reported in Fig. 3(b). This result
 287 indicates that the evaporation achievable applying the 2D SIE technology is considerable in a

288 significant portion of the globe but it requires wise site selection. Further, in Fig. 3(c) we
289 provide the relationship of the annual evaporation per unit area with latitude, and the curve
290 shows a very specific bimodal shape. We also indicate the approximate latitudinal ranges of
291 some countries or regions, namely, China, the Contiguous United States, and Australia, all
292 three having large evaporation potential, as well as Europe, which is associated with inferior
293 results due to its northerly location.

294 **3.2 Evaporation in four relevant locations**

295 Four locations were selected as examples and our model was used to computationally
296 estimate the evaporation rate of water using 2D SIE technology. Al Jubail, San Antonio, and
297 Fuling all have the need for brine desalination or wastewater treatment. Al Jubail in Saudi
298 Arabia has a need for desalination to produce drinking water; Fuling in Chongqing, China,
299 has a large amount of high-salinity squash wastewater that needs to be treated due to its
300 booming food industry; and San Antonio in Texas, USA is located in the Eagle Ford, a
301 famous shale gas producing area [47], where high salinity backwash from the shale gas
302 industry is also one of the target wastewaters treatable by this 2D SIE technology. The
303 climate of these three regions is somewhat different, another reason why they were chosen as
304 case studies for analysis. The fourth region, Singapore, was chosen to show how the
305 "depression" in the evaporation curve displayed in Fig. 3(c) is formed near the equator.

306 The estimated evaporation per unit area for the four regions as a function of month is
307 shown in Fig. 3(d), and the total annual evaporation rates per unit area are reported in Table 1.
308 The rates for three tropical locations, Al Jubail, San Antonio, and Fuling, are substantial.

309 Even in Fuling, where environmental conditions are less favorable, the unit area is still
 310 capable of handling about one ton of water per year. It should be emphasized that as specific
 311 technologies advance, actual yields will further increase from this conservative value,
 312 possibly making the 2D SIE technology even more competitive.

313

314 **Table 1.** General weather data for Jubail (Saudi Arabia), San Antonio (USA), Fuling (China),
 315 and Changi (Singapore) (the specific data are provided in the SI, Table S3). The final row of
 316 the table is the estimated annual water production per unit area ($\text{kg m}^{-2} \text{ year}^{-1}$).

317

Parameter	Jubail, Saudi Arabia	San Antonio, USA	Fuling, China	Changi, Singapore
Köppen climate classification [48]	BWh *	Cfa **	Cfa **	Af ***
Annual average wind speed (m s^{-1})	4.5	3.4	2.3	1.7
Annual average relative humidity (%)	59.00%	68.70%	75.10%	83.30%
Annual average temperature ($^{\circ}\text{C}$)	26.1	20.0	16.5	26.7
Annual solar radiation – horizontal ($\text{MJ m}^{-2} \text{ year}^{-1}$)	7332.85	6077.00	3949.30	5843.65
Annual water production per unit area ($\text{kg m}^{-2} \text{ year}^{-1}$)	3043	2077	1219	1780

318 Note:

319 * BWh: hot desert climates;

320 ** Cfa: humid subtropical climate;

321 *** Af: tropical rainforest climate.

322

323 Turning to the case of Singapore, the weather condition can be roughly understood
324 from Table 1, where we find that although Singapore has a notable annual average
325 temperature and radiation, its climate also corresponds to a high average humidity, which
326 directly limits the evaporation process. The area around 10 to 15 degrees near the equator is
327 mostly a tropical rainforest climate, a climate characterized by high temperatures, rain and
328 humidity throughout the year, according to the Köppen climate classification [48]. The high
329 humidity causes the depression of the predicted evaporation near the equator in the curve
330 displayed in Fig. 3(c).

331 **3.3 Interpretation of the numerical results**

332 Based on the results of the model, we were able to obtain an approximate but intuitive
333 understanding of the implementation potential of the 2D SIE technique, which shows an
334 axisymmetric bimodal structure with the change of latitude in space, with the areas near the
335 Tropics associated with higher processing water volumes. We suggest using this model
336 combined with field-specific meteorological data to calculate a more accurate evaporation
337 rate within acceptable errors. Also, it is important to point out that the numerical simulations
338 discussed in this work are based on the parameters identified for a "reference evaporation
339 surface". In order to obtain a suitable water supply in 2D SIE technology, porous media is
340 generally selected as the material for the evaporator. The parameters utilized for the
341 "reference evaporation surface" assumed that the evaporator consists of such porous medium.
342 Nevertheless, the model can be easily extended and adjusted, as it allows changing these

343 parameters to make predictions suitable for specific materials. Furthermore, estimations
344 based on different surfaces may be compared to those obtained with such “reference
345 evaporation surface” to understand their potential and behavior with respect to a common
346 standard.

347

348 **4 Outlook**

349 In order to achieve the global carbon neutrality in the second half of this century, it is
350 necessary to adjust the energy mix and to enhance the utilization of renewable energy sources.
351 2D SIE technology is a highly promising renewable energy-powered technology: means to
352 estimate pre-experimental evaporation rates for large-scale applications are important to
353 determine the preliminary feasibility of this technique. Detailed efficiency estimates would
354 involve site selection, site size, infrastructure input and costing, and many other aspects that
355 are critical to the longevity of on-site facilities and worthy of further study by researchers.
356 There are many factors in the evaporation process that are not fully understood for real
357 environment, such as turbulence. Laboratory research should be strengthened with
358 increasingly comprehensive and robust models, but in particular with real-world analysis,
359 ideally using data provided by actual installations on a large scale and over a long period of
360 time, a complex task that may require multidisciplinary cooperation.

361

362

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369

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