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Combining Stone Beds and Phase Change Materials in Passive Solar Stills: A Critical Review of Mechanisms, Design Variables, Modelling Practice and Field Lessons

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ABSTRACT

Passive basin solar stills can turn brackish or polluted water into drinking water with sunlight alone, but their output is small and stops soon after sunset. Thermal storage is the most common remedy. Sensible media such as stones, gravel, rock salt and cloth are cheap and stable, while phase change materials (PCMs) such as paraffin wax hold more heat per kilogram near their melting point. This review examines what is known about using the two kinds of storage together in one basin. It covers the heat-transfer mechanisms involved, the performance indicators used to judge stills, the reported gains of sensible, latent and combined storage, the design variables that matter most (water depth, size and amount of the sensible medium, PCM thickness and melting point), and the modelling tools now used to optimise such stills, namely response surface methodology, artificial neural networks and genetic algorithms. Reported yield gains over plain stills range from about 11% to 80% for single storage media and from 140% to 183% when storage is combined with reflectors or collectors. Lessons are then drawn from a field-tested pyramid still that combined granite stones in the basin water with a paraffin layer beneath a finned, CuO-coated absorber in a humid tropical climate. That still produced 85–149% more water by day than a conventional still and a night yield equal to 50–76% of its daytime yield, yet its paraffin never reached its melting range. The review closes with a design and testing workflow and a list of open research questions, chief among them matching the PCM melting range to the local climate and reporting night output and stored energy separately.

Keywords: Solar Still; Phase Change Material; Sensible Heat Storage; Granite Stones; Paraffin Wax; Night Productivity; Response Surface Methodology; Exergy

Abbreviations: ANN: Artificial Neural Network; BBD: Box–Behnken Design; CSS: Conventional Solar Still; GA: Genetic Algorithm; HSS: Hybrid Solar Still; PCM: Phase Change Material; RSM: Response Surface Methodology; TES: Thermal Energy Storage

Introduction

Safe drinking water remains out of reach for about two billion people, and the shortfall is most acute in rural, riverine and peri-urban communities that are far from piped supply [1]. Many of these communities lie in sunny regions, and many have access to water that is brackish, turbid or contaminated rather than to no water at all. For them, a device that can purify water using only sunlight, without fuel, electricity or skilled operation, has obvious value. The passive basin solar still is the simplest such device. Saline water in a blackened basin absorbs solar radiation, part of it evaporates, the vapour condenses on a cooler transparent cover, and the condensate runs into a collector [2]. The still has no moving parts and can be built from local materials, which explains why it continues to attract research effort more than a century after its first large-scale use. Other low-cost solar thermal devices built from local materials, such as a mixed-mode cabinet dryer for *Moringa oleifera* whose cabinet temperature and relative humidity were monitored through the day, have likewise been designed and tested under Nigerian conditions [3,4]. Its weakness is low output. A conventional basin still typically

produces 2–5 L of water per square metre per day, and nearly all of it while the sun is up [5,6]. Much of the solar input is lost through the cover and the base or is used to heat the water mass rather than to evaporate it, and once the irradiance falls in the late afternoon the basin cools quickly and production stops.

Many modifications have been proposed to address this: reflectors, external condensers, wicks, fins, nanoparticle coatings, collectors and, above all, thermal energy storage (TES) placed in or under the basin [5-8]. Storage works by absorbing part of the heat delivered around solar noon and returning it to the water later in the day and at night. Two broad kinds are used. Sensible media, such as stones, gravel, sand, metal scraps, rock salt and cloth, store heat by warming up; they are cheap, stable and easy to place [9]. Latent media, mainly PCMs such as paraffin wax, fatty acids and salt hydrates, store heat as they melt and release it at nearly constant temperature as they solidify [10-12]. Each kind has been studied widely on its own. Far fewer studies have examined stills that use both in one basin, and those that do usually change several features at once, so that the contribution of each medium, and whether the PCM actually melts under local weather, often remain unclear [7,8]. This review addresses that gap. It does not attempt a full survey of solar still technology, for which several reviews exist [5-9,12]. Instead it concentrates on combined sensible–latent storage in passive stills and asks five questions:

(i) By what mechanisms do the two kinds of storage interact

(ii) What yield and efficiency gains have been reported for each kind and for their combination

(iii) Which design variables control the benefit

(iv) How well do the statistical and machine-learning tools now used to optimise such stills perform, and what pitfalls arise in outdoor testing

(v) What can be learned from a field-tested still that used both media. The last question is answered with data from a pyramid still tested in the Niger Delta region of Nigeria [13]. A design and testing workflow and a list of research needs follow.

Scope and Approach of the Review

The review draws on peer-reviewed journal articles, review papers and standard texts on solar distillation, thermal storage and experimental design. Articles were identified from searches of major indexing databases for the period 2000–2025 using combinations of the terms solar still, phase change material, paraffin, sensible heat storage, stones, gravel, pebbles, night productivity, response surface methodology, neural network and genetic algorithm, and from the reference lists of the review papers cited above. Studies were retained when they reported measured or modelled performance of a basin-type still with at least one storage medium, or when they applied a formal optimisation method to a still. Reported gains are quoted as given by the original authors. Because each study measured its gain against its own reference still, under its own climate and over its own test period, the figures are used to show orders of magnitude and trends rather than to rank individual studies.

Working Principle and Performance Indicators

Energy Balance of a Basin Still

During the day, solar radiation transmitted through the cover is absorbed by the water, the absorber plate and any storage medium. The water exchanges heat with the inner surface of the cover by evaporation, natural convection and radiation, and the cover loses heat to the surroundings. The rate of evaporation is governed by the difference between the vapour pressure at the water surface and that at the cover. Dunkle's relations remain the standard description of this internal exchange [2,14]. The evaporative heat-transfer coefficient is

$$h_{ev} = 16.273 \times 10^{-3} h_{cv} \frac{P_w - P_{gi}}{T_w - T_{gi}} \quad (1)$$

where h_{cv} is the convective coefficient, P_w and P_{gi} are the saturation vapour pressures at the water temperature T_w and the inner-cover temperature T_{gi}. The vapour pressure itself rises steeply with temperature and is often written as [15]

$$P_w = \exp\left(25.317 - \frac{5144}{T_w}\right) \quad (2)$$

With T_w in K and P_w in Pa. Equations (1) and (2) explain why storage matters: a few kelvin of extra water temperature late in the day raise the saturation vapour pressure, and with it the evaporative driving force, by about 5% per kelvin, so heat returned to the water when the sun is low has a large effect on output.

Performance Indicators

The daily yield per unit basin area is the most common indicator. Studies of storage should report the daytime yield P_d (sunrise to sunset) and the night yield P_n separately, because storage moves production from the day to the night. The daily energy efficiency is

$$\eta_{th} = \frac{PL_{ev}}{\int Idt} \times 100 \quad (3)$$

where P is the yield (kg/m^2), L_{ev} the latent heat of vaporisation and $\int Idt$ the daily irradiation (J/m^2). Because the heat stored in a still is of low quality, the second-law (exergy) efficiency is a more demanding measure:

$$\eta_{ex} = \frac{PL_{ev}\left(1-\frac{T_a}{T_w}\right)}{\int Idt\left[1+\frac{1}{3}\left(\frac{T_a}{T_s}\right)^4-\frac{4}{3}\frac{T_a}{T_s}\right]}\times 100 \quad (4)$$

where the bracket in the denominator is the Petela factor for the exergy of solar radiation, T_a is the ambient temperature and $T_s \approx 6000$ K the apparent sun temperature [16,17]. The ratio $\theta = 1 - \frac{T_a}{T_w}$ is the Carnot factor of the basin water. Because θ is only 0.03–0.06 for water at 40–50 °C in a warm climate, exergy efficiencies of passive stills are typically only a few per cent, even when energy efficiencies are 20–40% [18,19]. Economic studies add the cost per litre of distillate and the payback period, and environmental studies add the CO_2 avoided over the service life. The same second-law and emissions reasoning is used to judge other systems that recover low-grade heat, for example organic Rankine cycles and turbine-based units that convert vehicle exhaust heat into useful work [20,21].

Heat Held in Storage

The sensible heat held by a medium of mass m and specific heat c_p, warmed from a reference temperature T_{ref} to T, and the latent heat held by a PCM of mass m_{pcm} and heat of fusion L_f are

$$Q_S = mc_p\left(T - T_{ref}\right), \qquad Q_l = fm_{pcm}\,L_f \quad (5)$$

where f ($0 \le f \le 1$) is the melted fraction. Equation (5) contains the most important practical condition for latent storage: Q_l is zero unless the PCM actually melts. A PCM whose melting range lies above the temperatures reached in the basin behaves as an ordinary sensible store with a modest specific heat (about 2 kJ/kg K for solid paraffin) and a low thermal conductivity (about 0.2 W/m K) [10,11].

Storage Configurations

Figure 1 shows the four configurations discussed in this review. In a sensible-bed still the medium lies in the basin water or beneath a thin liner (Figure 1b). In a latent still the PCM usually lies in a tray beneath the absorber, where it is insulated from the cover and does not reduce the water surface (Figure 1c). In a combined still both are present (Figure 1d). The position of each medium decides how it charges and discharges: a medium in the water charges and discharges with the water itself, while a medium beneath the absorber charges by conduction through the plate and returns its heat only when the water has become cooler than it.

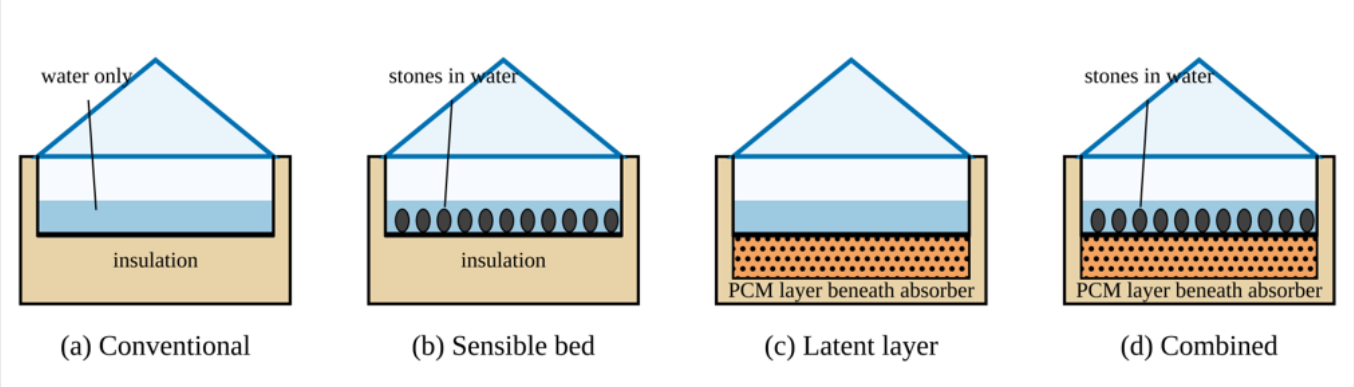


Figure 1: Storage configurations in a basin still:
a) Conventional still;
b) Sensible bed in the basin water;
c) PCM layer beneath the absorber;
d) Combined sensible bed and PCM layer.

Sensible Storage Media

Table 1 summarises representative studies of sensible storage. Natural stones are the most widely used medium because they are free or cheap, chemically inert in saline water and robust under thermal cycling [9]. Mohamed, et al. [22] used black basalt stones of 1, 1.5 and 2 cm in a single-basin still and raised its yield by 19.8–33.4%, with the largest stones giving the largest gain. Abdelmaksoud [23] found that natural stones alone raised the yield by only 11–32%, but that the same stones combined with a flat-plate collector raised it by 155–183%, which suggests that a sensible bed is limited more by the heat available to charge it than by its capacity. Dhivagar et al. [18] obtained 4.21 kg/m^2 per day, an energy efficiency of 32% and an exergy efficiency of 4.7% with gravel at a water depth of 1 cm. Attia et al. showed that the spacing [24] and size [25] of rock-salt balls in

a hemispherical still changed the gain from 13ss.84% to 49.0% and from 21.9% to 45.6%, respectively, and that flint stones placed on the absorber of a conical still raised its yield by 53.57% and its exergy efficiency by 190.64% [26]. Kalidasa Murugavel et al. [27] examined a double-slope still operated at minimum basin depth with several energy-storing materials. Three points emerge from these studies. First, the gains of passive sensible beds are moderate, mostly 10–55%. Second, the result depends on the size, spacing and placement of the elements, not only on the mass: elements change the absorbed radiation, the area exposed to the water and the shading of the absorber, as well as the heat capacity. Third, a large sensible bed can lower the daytime output, because it takes heat that would otherwise evaporate water in the morning; Bilal et al. [28] observed exactly this with pumice, where the night output rose but the daytime output fell as the stone mass increased. The value of a sensible bed therefore lies in shifting production, and its net effect depends on whether the extra night water outweighs the lost day water.

Table 1: Representative studies of sensible storage media in solar stills.

Study	Still and Medium	Variable Examined	Main Reported Result
Sakthivel, et al. [53]	Single slope; regenerative jute cloth	With and without medium	Yield about 20% higher
Mohamed, et al. [22]	Single basin; black basalt stones	Stone size 1–2 cm	Yield +19.8% to +33.4%
Bilal, et al. [28]	Single slope; pumice stones	Stone mass 0–10 kg	Daytime yield fell, night yield rose with mass
Dhivagar, et al. [18]	Single slope; gravel	Water depth	4.21 kg/m² per day; η_{th} 32%, η_{ex} 4.7% at 1 cm
Attia, et al. [24]	Hemispherical; rock-salt balls	Ball spacing 3–6 cm	Yield +13.84% to +49.0%
Attia, et al. [25]	Hemispherical; rock-salt balls	Ball size 0.5–2.0 cm	Yield +21.9% to +45.6%
Abdelmaksoud [23]	Basin; natural stones, with and without collector	Stone type; collector	+11% to +32% (stones); +155% to +183% (with collector)
Attia, et al. [26]	Conical; flint stones	Placement on absorber	Yield +53.57%; η_{ex} +190.64%

Latent Storage with Phase Change Materials

PCMs store heat at a nearly constant temperature, and paraffin wax is by far the most common choice in stills because it is inert, does not corrode steel, shows little supercooling and is cheap [10,12]. Its main drawbacks are low thermal conductivity and a melting range that, for common commercial grades, lies between about 50 °C and 65 °C. El-Sebaii, et al. [29] modelled a single-basin still with stearic acid beneath the liner and found that, on a summer day, the daily output rose from 4.998 to 9.005 kg/m^2 as the PCM mass increased, mainly through production after sunset, while the daytime output fell. Kabeel, et al. [30] placed paraffin beneath the basin of a single-slope still and raised its daily output from 4.51 to 7.54 L/m^2 (67.18%). Kateshia, et al. [31] compared several fatty acids and found that the gain depended on the acid, chiefly through its melting point. Murali, et al. [32] obtained 60.37% more water and 68.29% higher efficiency with a nano-PCM composite, and Chaichan, et al. [33] improved a paraffin-assisted still further with Al_2O_3 nanoparticles. In pyramid stills, Mekki, et al. [34] showed that the benefit of a PCM layer depends on its thickness, and Malik, et al. [35] combined PCM with Fresnel lenses in spring and autumn tests. Two cautions apply to this literature. The first concerns melting. Many studies quote the latent heat of the wax when they explain their gains, but fewer show from measured temperatures that the wax actually melted, and how much of it. In hot, dry climates with strong irradiance, basin temperatures of 60–70 °C are common and the wax melts. In humid tropical climates, where irradiance is more diffuse and the air is warm and moist, the basin may never reach the melting range of standard grades; the PCM then adds only sensible capacity. The second concerns conductivity. A thick paraffin layer with a conductivity near 0.2 W/m K charges slowly, so its outer part may stay cool even when the plate above it is hot. Fins, metal matrices, nanoparticles and stones embedded in the wax are used to overcome this [32,33,36].

Combined Sensible and Latent Storage

Why Combine the Two Media

The two kinds of storage have complementary properties. Stones and other dense sensible media have a higher conductivity than paraffin (about 2–3 W/m K for granite against 0.2 W/m K) and charge quickly, but they lose heat quickly as well. A PCM charges slowly but, once melted, releases its heat at a steady temperature over a longer period. Zhang, et al. [36] showed in a laboratory store that granite stones embedded in paraffin accelerated melting by 108% and raised the exergy storage rate by 246%, mainly because the stones conducted heat into the wax. In a still the two media can also be placed in different positions, a sensible bed in the water and a PCM beneath the absorber, so that each works at the temperature level that suits it: the bed smooths the water temperature during the day, and the PCM, insulated beneath the plate, returns heat after sunset.

Reported Combined and Multi-Feature Stills

Combined storage has rarely been tested on its own. In most reported stills it is one of several modifications. Abdelgaied, et al. [37] combined a CuO-doped black absorber coating, reflective mirrors and a PCM with pin fins in a pyramid still and obtained 140.1–142% more water, 138.1–140.1% higher energy efficiency and 243.6–252.9% higher exergy efficiency than a plain pyramid still. Anika, et al. [38] integrated a hybrid nano-PCM with black sand and sponge in a pyramid still and assessed it on exergo-economic and sustainability grounds. Handawy et al. [39] compared marble, basalt and gravel in a pyramid still and optimised it with artificial intelligence, and Dubey, et al. [40] combined PCM with an evacuated-tube collector under forced circulation. CuO coatings on the absorber or in the PCM have also been studied on their own [41,42]. Table 3 lists these studies. Their common limitation is that several features change together, so the effect of the storage, and the share of the stored heat held by each medium, cannot be isolated. Figure 2 brings together the reported gains of Tables 1–3. Single sensible media lie mostly between 11% and 55%, single latent media between 60% and 80%, and stills that add reflectors or collectors to storage reach 140–183%. The field-tested stone–paraffin still discussed below sits between the latter two groups by day without any active or optical aid, and above them when its night output is counted.

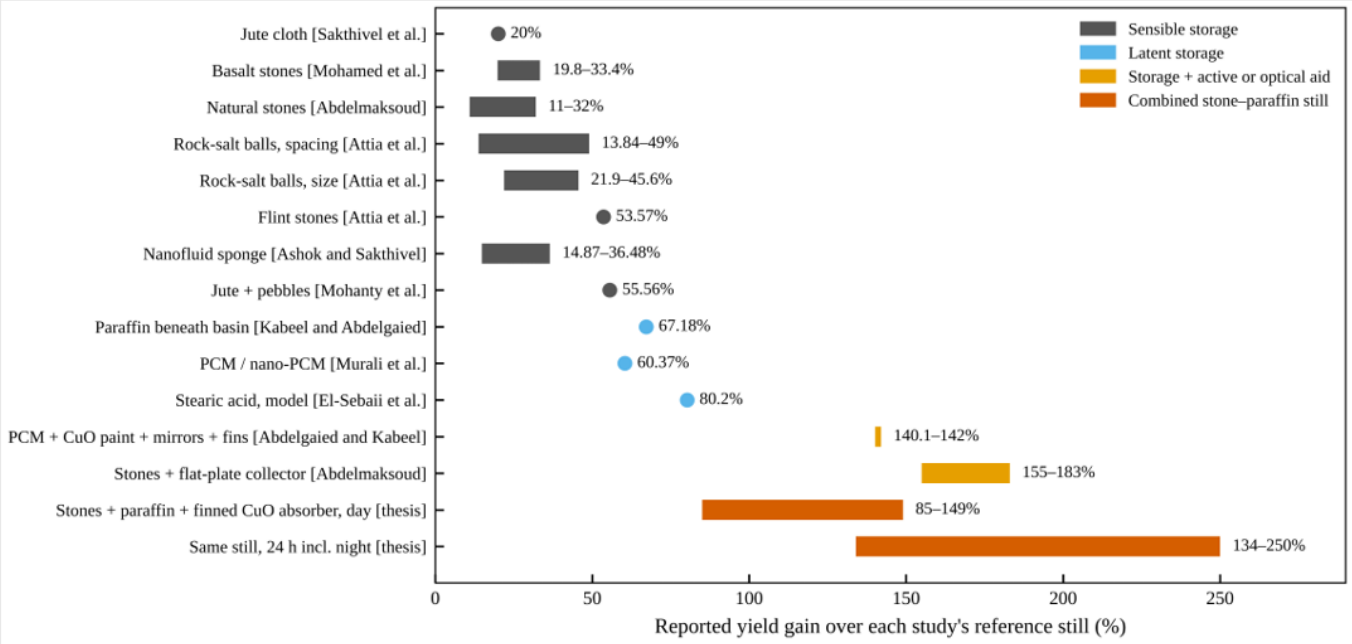


Figure 2: Yield gains reported for storage-assisted solar stills. Bars show the reported range and dots single values; each gain is measured against the study's own reference still, so the figure indicates orders of magnitude rather than a ranking.

Table 2: Representative studies of latent (PCM) storage in solar stills.

Study	Still and PCM	Variable examined	Main reported result
El-Sebaii, et al. [29]	Single basin; stearic acid beneath liner	PCM mass (model)	4.998 to 9.005 kg/m^2 per day; daytime output fell
Kabeel and Abdelgaied [30]	Single slope; paraffin beneath basin	With and without PCM	4.51 to 7.54 L/m^2 per day (+67.18%)
Kateshia and Lakhera [31]	Single slope; fatty acids	Type of acid	Gain depended on melting point of the acid
Chaichan and Kazem [33]	Single slope; paraffin with Al_2O_3	Nanoparticle addition	Further gain over plain paraffin
Murali, et al. [32]	Basin; PCM and nano-PCM composite	Composite type	Productivity +60.37%; efficiency +68.29%
Mekki, et al. [34]	Pyramid; PCM layer	Layer thickness	Benefit depended on thickness
Yousef and Hassan [17]	Single slope; PCM	Energy and exergy	Energy and exergy assessed with and without PCM

Table 3: Combined storage and multi-feature stills.

Study	Still and features	Method	Main reported result
Zhang, et al. [36]	Laboratory store; granite stones in paraffin	Charging tests	Melting 108% faster; exergy storage rate +246%
Abdelgaied and Kabeel [37]	Pyramid; CuO paint, mirrors, PCM with pin fins	Comparative test	Yield +140.1% to +142%; η_{ex} +243.6% to +252.9%
Anika, et al. [38]	Pyramid; hybrid nano-PCM, black sand, sponge	Exergo-economic and sustainability analysis	Combined storage assessed on 4E basis
Handawy, et al. [39]	Pyramid; marble, basalt or gravel	Experiment with AI optimisation	Storage material compared and optimised
Dubey and Arora [40]	Hybrid still; PCM with evacuated-tube collector	Forced circulation	Active charging of PCM
Present field study [13]	Pyramid; granite stones in water, paraffin beneath finned CuO-coated absorber	Box–Behnken design (17 runs), ANN, GA, energy balance	Day +85% to +149%; night 50–76% of day yield (see field lessons below)

Heat-Transfer Enhancement Alongside Storage

Storage only helps if heat reaches it. Fins on the absorber enlarge the area in contact with the water and conduct heat into a PCM beneath the plate; nanoparticle coatings raise the absorptance of the plate; and nanoparticles dispersed in a PCM raise its conductivity [33,41,43]. In combined stills these features interact with the storage media. A finned absorber between a sensible bed and a PCM layer, for example, carries heat both into the water above and into the wax below, and the size of the elements in the bed controls how much of the plate is shaded and how much area is exposed to the water. These interactions mean that the storage and the heat-transfer features should be designed together rather than added one at a time.

Design Variables

Water Depth

Water depth is the most studied variable. A shallow basin heats quickly and evaporates fast by day but stores little heat; a deep basin stores more but never becomes as hot. Most studies of stills without storage find the highest daily output at the smallest practical depth [6,27]. With storage present the optimum moves to an intermediate depth, because a thin water layer cannot use the heat returned by the store after sunset if it has already been lost through the cover in the afternoon. Statistical studies of pyramid and single-slope stills have confirmed water depth as a dominant factor [44,43].

Size, Amount and Placement of the Sensible Medium

For a sensible bed the relevant variables are the mass, the element size and the placement. At a fixed mass, smaller elements present more surface area per kilogram (the area per unit mass of spheres is $6/(\rho d)$), which speeds up heat exchange with the water, while larger elements store the same heat in fewer, hotter pieces and shade more of the plate. The direction of the effect is therefore not universal: Mohamed et al. [22] found larger basalt stones better, whereas the field still discussed below found smaller granite stones better. The difference probably reflects placement (stones on the plate in shallow water versus stones forming a porous absorber) and should be tested rather than assumed.

PCM Thickness and Melting Range

The amount of PCM is usually set by layer thickness. A thicker layer stores more heat but charges more slowly, and beyond a certain thickness the outer part never melts [29,34]. The melting range is at least as important as the amount. It should lie a few kelvin below the basin temperature reached on a typical day at the site; a range that is too high leaves the latent capacity unused, while one that is too low lets the PCM melt early and stay molten without returning much heat. Few studies report the melted fraction, which is the quantity that decides whether latent storage occurred.

Modelling and Optimisation Practice

Response Surface Methodology

Because the design variables interact, one-factor-at-a-time testing can miss the best combination. Response surface methodology (RSM) fits a second-order polynomial to the responses measured in a planned set of runs [45-47]:

$$y = \beta_0 + \sum_i \beta_i x_i + \sum_{i<j} \beta_{ij} x_i x_j + \sum_i \beta_{ii} x_i^2 + \varepsilon \quad (6)$$

where x_i are the coded factors and β the coefficients. The Box–Behnken design (BBD) needs only 15–17 runs for three factors [45] and has been used to optimise pyramid stills [43,48], single-slope stills [43], a nanofluid-infused sponge still [49] and a jute-and-pebble still [50]. Yuvaperiyasamy et al. [44] reported 2.585 kg/m^2 at 950 W/m^2, 50 °C inlet temperature and 4 cm depth; Ashok and Sakthivel [49] reported gains of 14.87–36.48%; and Mohanty et al. [50] obtained 55.56% more distillate with confirmation errors of 4.23% and 5.76%. Several responses can be optimised together with the desirability function [51]:

$$D = \left(\prod_{k=1}^{m} d_k \right)^{\frac{1}{m}}, \qquad d_k = \frac{\hat{y}_k - y_{k,\min}}{y_{k,\max} - y_{k,\min}} \quad (7)$$

Neural Networks and Genetic Algorithms

Artificial neural networks (ANNs) can capture nonlinear behaviour without assuming a functional form and have been used to predict still output from design and weather inputs [44,50]. With the small datasets typical of outdoor still tests (often fewer than 20 runs), they are prone to over-fitting and should be benchmarked against simpler models by cross-validation. Genetic algorithms, including the non-dominated sorting genetic algorithm (NSGA-II), search fitted models for the best compromise between competing objectives such as yield, efficiency and cost [50,52].

Pitfalls of Outdoor Experimental Designs

Three problems are common in outdoor statistical studies of stills and are seldom discussed. First, each run of a designed experiment usually takes place on a different day, so the daily irradiation and air temperature change with the run order. If the sunniest days happen to coincide with particular design points, the weather can masquerade as a design effect. Recording the weather of every run and testing it as a covariate, or blocking the design by test day, guards against this [47]. Second, a high coefficient of determination does not prove that a model describes the still. A sensor that detaches from a stone or is heated directly by the sun can produce smooth, well-fitted but physically meaningless response surfaces; each measured quantity should be checked for plausibility before it is modelled, and duplicate sensors should be used in each storage medium. Third, energy and exergy efficiencies divide the output by the input and are therefore partly normalised for weather, whereas yield and temperatures are not, so the choice of response affects how strongly weather contaminates the result.

Lessons from a Field-Tested Stone–Paraffin Still

The Still and the Test Programme

The lessons in this section come from a passive pyramid still with granite stones in the basin water and a paraffin layer beneath a finned, CuO-coated absorber, tested outdoors at Effurun, Nigeria (5.57° N), a humid tropical site [13]. The basin measured 0.7 m × 0.7 m (0.49 m^2) under a 4 mm low-iron glass pyramid at 30°. Water depth (10–30 mm), stone diameter (10–20 mm, 1 kg per run) and paraffin thickness (40–50 mm, melting range 56–60 °C) were varied in a 17-run Box–Behnken design, and a still of the same geometry without fins, coating, stones or paraffin was run at three depths as a reference. Day and night distillate were collected separately. Figure 3 shows the line diagram of the still and the positions of its thermocouples, and Figure 4 shows the test bank and the night distillate collected from the hybrid and conventional stills. Table 4 summarises the main results.

Table 4: Main results of the field-tested stone–paraffin pyramid still [13].

Quantity	Result
Daytime yield, 17 runs	1.21–1.73 L/m² (centre point 1.694 L/m²)
Night yield, 17 runs	0.64–1.08 L/m², equal to 50–76% of the daytime yield
Daytime gain over conventional still	85–149% (reference still 0.68–0.92 L/m²)
Daytime energy efficiency	18.5–25.1% (reference still 11.0–14.2%)
Exergy efficiency	0.58–1.40% (reference still 0.011–0.050%)
Daytime yield model	Quadratic, R^2 = 0.986; interior optimum near 21 mm water, 14 mm stones and 45 mm paraffin
Agreement of RSM, ANN and GA optima	Within about 3 mm on each factor; confirmation run within 1.5% of prediction
Peak paraffin temperature (centre run)	55.5 °C at 15:00, below the 56–60 °C melting range
Heat held at 18:00 (centre run, above 18:00 air)	1.38 MJ: water 48.6%, paraffin 42.5%, steel 7.9%, stones 0.9%
Unit cost of water; payback	₦910–1,098 per litre; 3.1–5.7 years
Distillate quality	13 of 14 WHO-listed parameters within limits; coliforms from storage container

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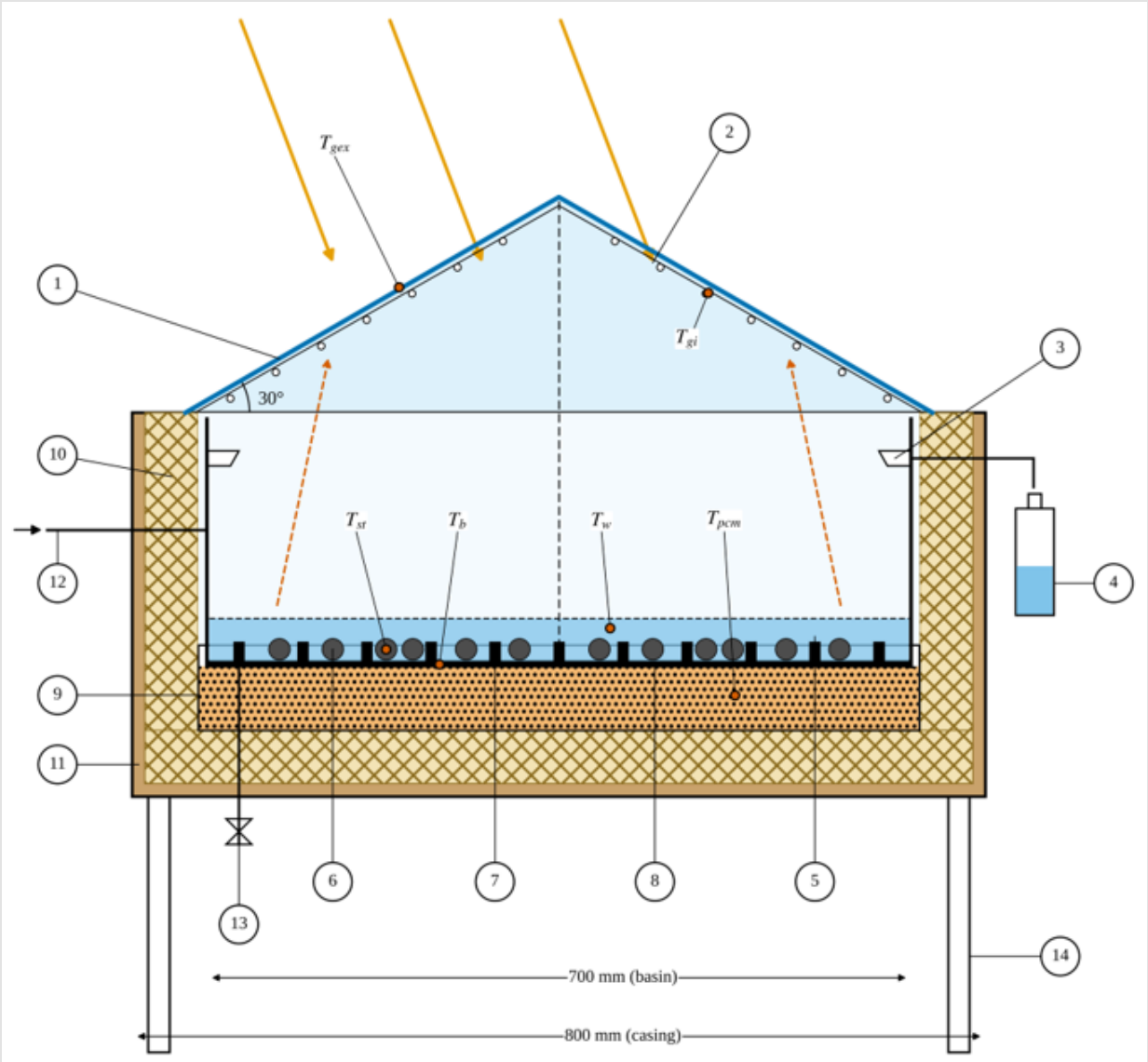


Figure 3: Line diagram of the field-tested hybrid still (vertical section, not to scale) [13]:

1. Low-iron glass cover (4 mm, 30°);
2. Condensate;
3. Collection channel;
4. Outlet and bottle;
5. Saline water (10–30 mm);
6. Black-painted granite stones (10–20 mm);
7. CuO-coated square fins;
8. Mild-steel absorber (700 mm × 700 mm);
9. Paraffin layer (40–50 mm);
10. Rock-wool insulation;
11. Casing;
12. Feed inlet;
13. Drain valve;
14. Stand. Orange dots mark the thermocouples.

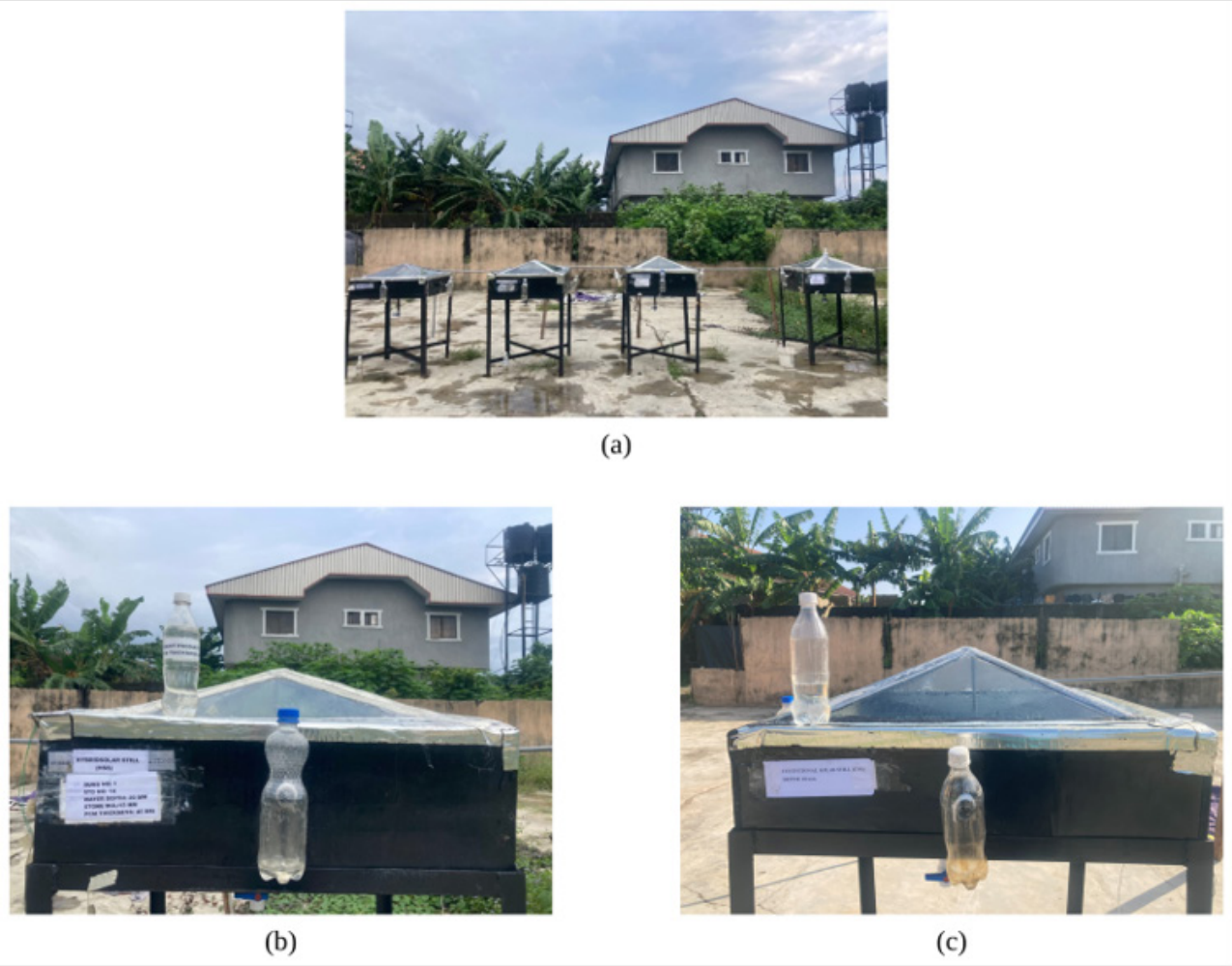


Figure 4: Field tests at Effurun, Nigeria [13]:
a) Test bank of three hybrid stills and the conventional still;
b) Night distillate collected from the hybrid still at the centre point (20 mm water, 15 mm stones, 45 mm paraffin);
c) Night distillate collected from the conventional still at 10 mm water depth.

Lesson 1: A Combined Store Can Raise Both Day and Night Output

The still produced 85–149% more water by day than the reference still, and its night yield, which the reference still largely lacked, equalled half to three-quarters of its daytime yield. Unlike the pumice and stearic-acid stills discussed earlier [28,29], the configurations that produced more water by day also produced more at night. The paraffin beneath the plate did not add to the water mass that must be heated each morning, so storage was gained without a daytime penalty. Figure 5 shows why. In the centre-point run the hourly yield rose steadily to a maximum at 16:00 and was still 91 mL/h at 18:00, when the irradiance had fallen to about 90 W/m^2, and all internal temperatures were still about 16 K above the air at sunset. Figure 6 compares the day, night and 24 h output of this still with those of the reference still: the hybrid still gave about 2.75 L/m^2 over 24 h against 0.78–1.18 L/m^2, and its night yield was 62% of its daytime yield against 15–38% for the reference still.

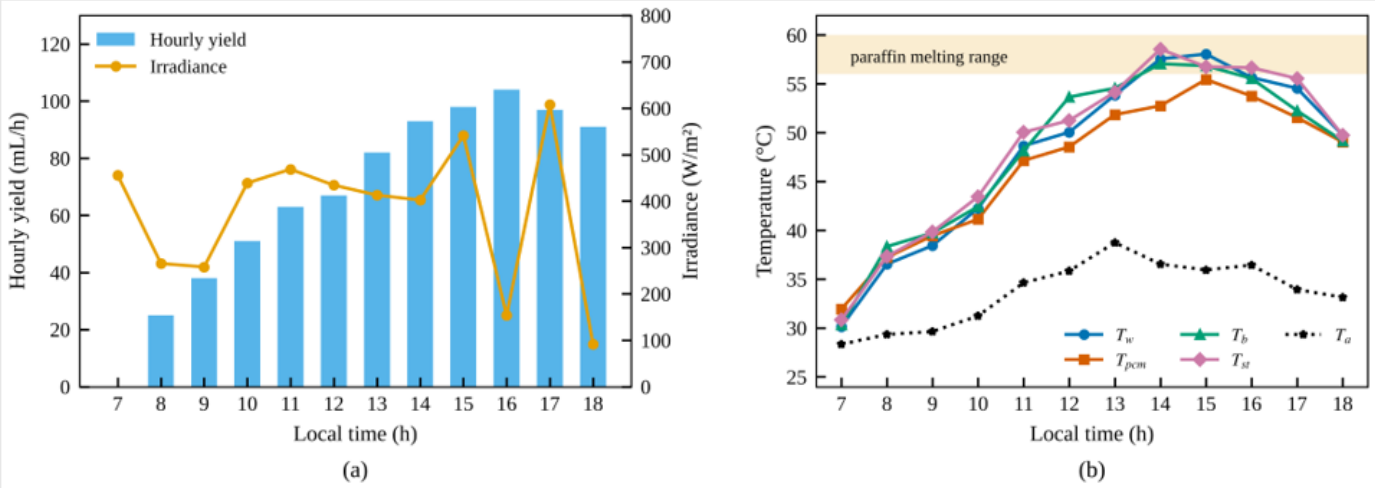


Figure 5: Hourly record of the centre-point run of the field-tested still [13]:
a) Irradiance and hourly distillate yield;
b) Temperatures of the water, paraffin, absorber, stones and air, with the nominal melting range of the paraffin shaded.

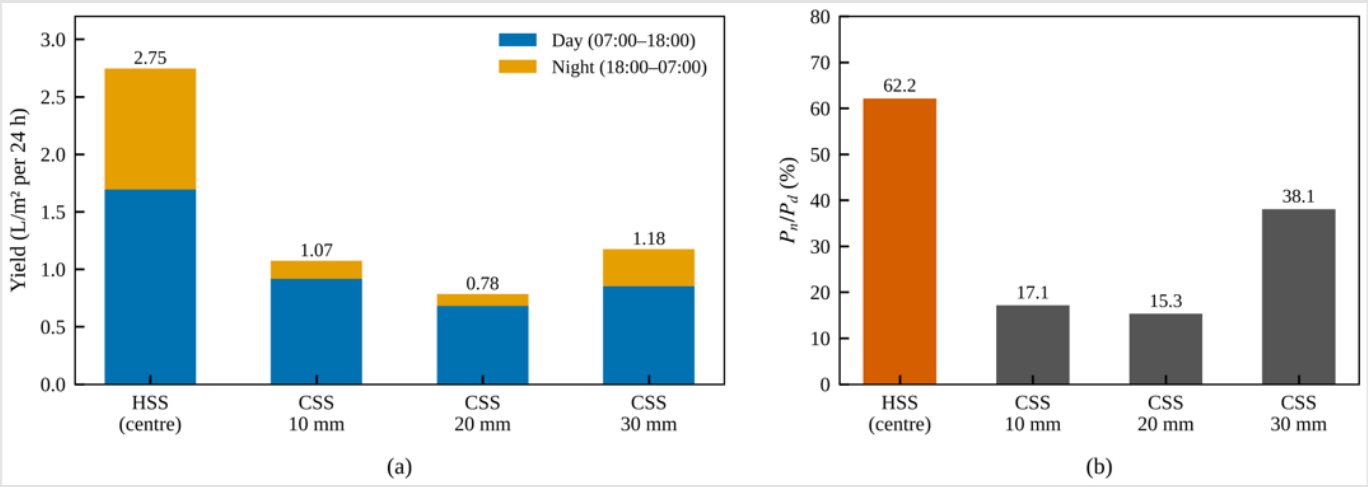


Figure 6: Hybrid still (centre point) and conventional still at three water depths [13]:
a) Daytime, night and 24 h yield;
b) Night-to-day yield ratio.

Lesson 2: Check Whether the PCM Melts

The paraffin never reached its melting range in any run (Figure 7a). Its daily mean temperature was 41.7–46.9 °C, and even in the warmest hour of the centre run it peaked at 55.5 °C. The paraffin therefore acted as a sensible store with a specific heat of about 2 kJ/kg K, and its latent capacity of 3.5–4.4 MJ per unit, two to three times the whole sensible store, was not used. This is likely to be common in humid tropical climates and is a direct argument for choosing a PCM with a melting range of roughly 45–50 °C at such sites. Any study that credits a PCM with latent storage should show from measured temperatures that it melted.

Lesson 3: The Sub-Basin Store Carries the Night

At 18:00 the centre-run still held about 1.38 MJ above the air temperature, and the night distillate removed about 1.21 MJ as latent heat of vaporisation (Figure 7b). The water alone held just over half of this demand; the remainder came from the paraffin and the steel

beneath the water, which cooled more slowly than the water because they were insulated from the cover. Across the 17 runs the night yield followed the paraffin temperature and the heat held by the paraffin, not the heat held by the water. In this design the stones held less than 1% of the stored heat, so their role was not storage capacity.

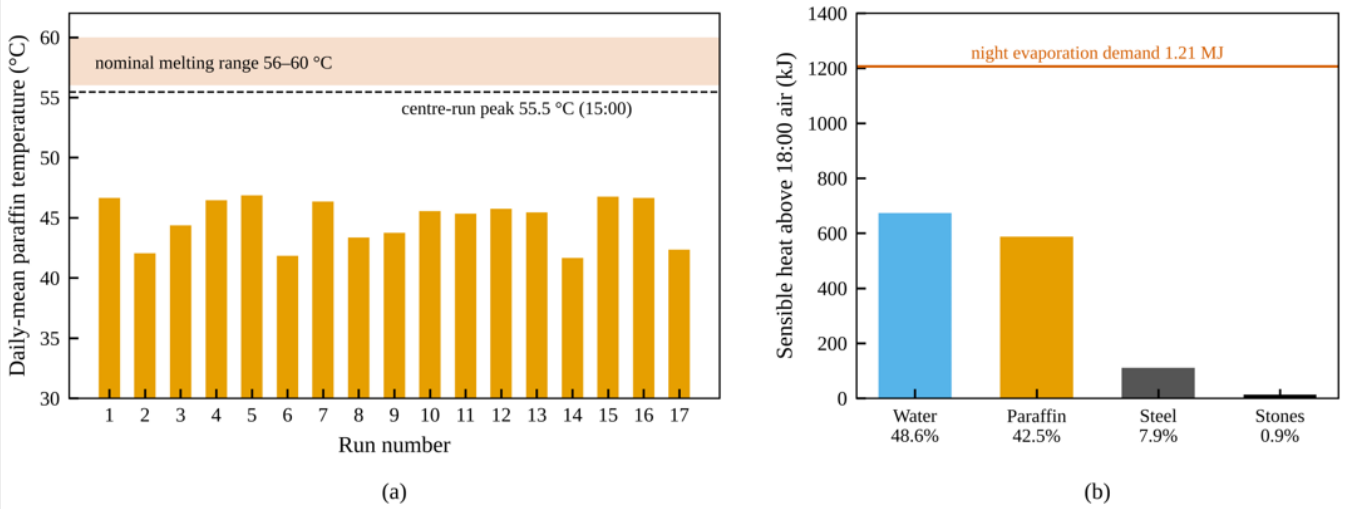


Figure 7: Field-tested stone–paraffin still [13]:
a) Daily-mean paraffin temperature in the 17 runs, with the centre-run peak and the nominal melting range;
b) Sensible heat held by each thermal mass at 18:00 in the centre run, compared with the heat carried away by the night distillate.

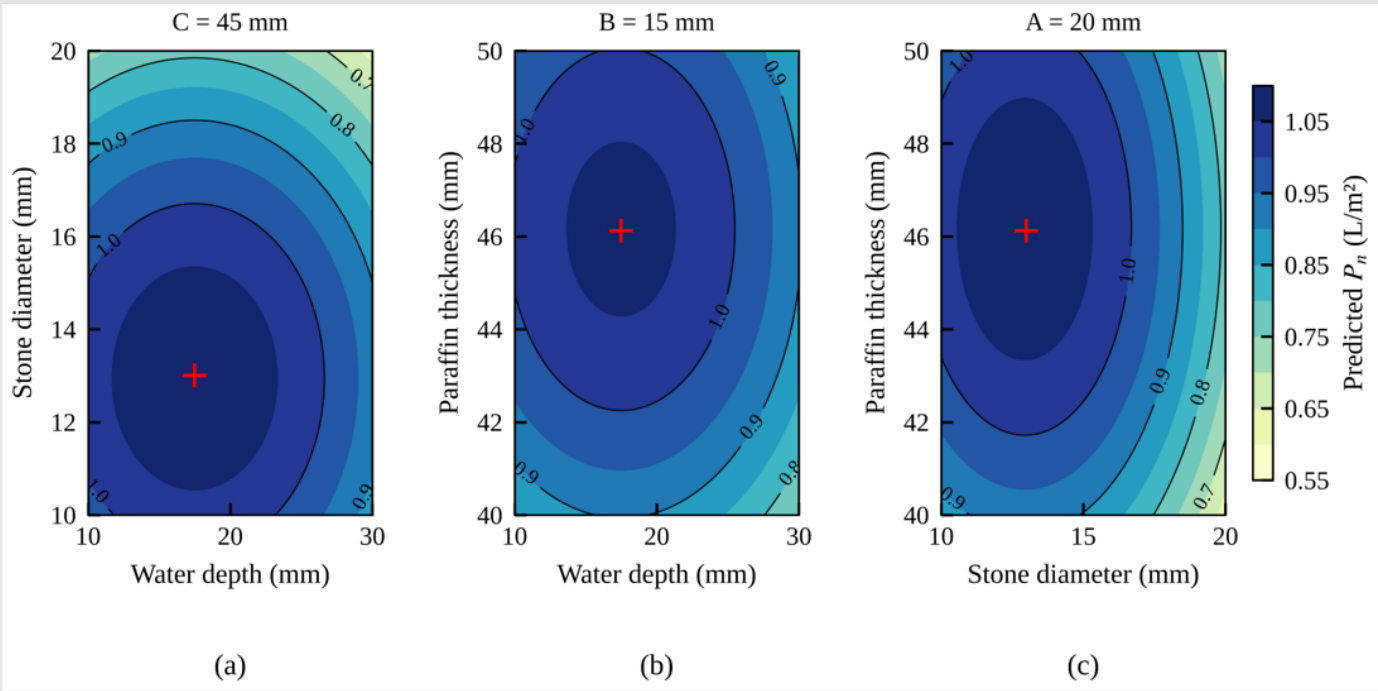


Figure 8: Predicted night yield of the field-tested still from a quadratic response-surface model of the 17 runs [13]:
a) Water depth and stone diameter at 45 mm paraffin;
b) Water depth and paraffin thickness with 15 mm stones;
stone diameter and paraffin thickness at 20 mm water. The cross marks the predicted maximum.

Lesson 4: Element Size of the Sensible Bed Matters Through Surface Area

At a fixed stone mass, smaller stones gave a warmer paraffin layer and more water by day and by night. With 1 kg of stones the heat capacity of the bed hardly changed with size, but the surface area per kilogram doubled from 20 mm to 10 mm stones. The stones therefore acted mainly as an extension of the finned absorber, passing absorbed radiation to the water and to the plate above the paraffin. Stone size should be treated as a heat-transfer variable as much as a storage variable. Figure 8 shows the response surfaces of the night yield fitted to the 17 runs: the predicted maximum, about 1.09 L/m^2, lay at roughly 17.5 mm water, 13 mm stones and 46 mm paraffin, and the night yield fell steeply as the stone diameter approached 20 mm.

Lesson 5: Second-Law Performance Depends on Keeping the Water Hot

The exergy efficiency of the hybrid still was 24–110 times that of the reference still. Writing it as the energy efficiency multiplied by the Carnot factor of the water (Equation 4) showed that the Carnot factor accounted for about 62% of the variation between runs. Design changes that keep the water hot late in the day, such as a sub-basin store and small stones, therefore raise the exergy efficiency more than changes that only increase evaporation. Figure 9 shows this hour by hour for the centre-point run: the exergy output peaked between 15:00 and 17:00, after the irradiance had passed its maximum, because the Carnot factor of the water stayed above 0.05 until sunset.

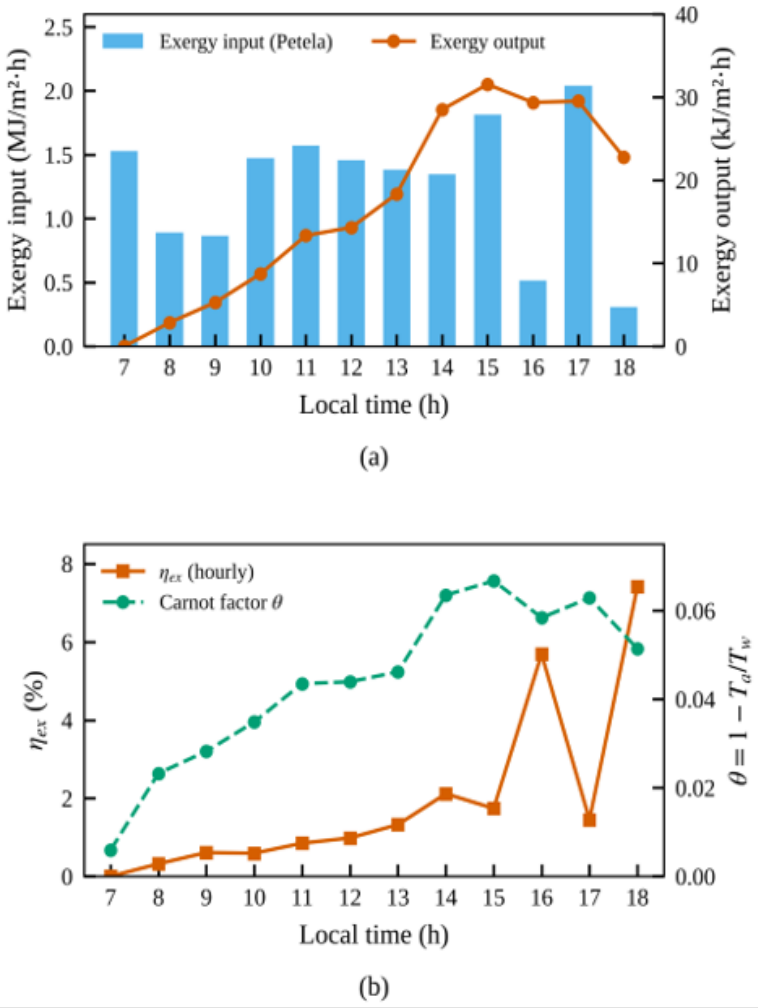


Figure 9: Centre-point run of the field-tested still [13]:
a) Hourly exergy input (Petela relation) and exergy output;
b) Hourly exergy efficiency and Carnot factor of the basin water.

Lesson 6: Screen Data and Weather Before Modelling

Of twelve quantities recorded in the design, eleven gave statistically significant quadratic models, but not all were physically meaningful. The stone thermocouple in one unit read close to air temperature while immersed in water at 46–50 °C, and the resulting stone-temperature model, which had the highest coefficient of determination of all, described the faulty sensor rather than the still. Daily irradiation was also partly aliased with the design because the sunniest test days fell on the centre-point runs. The effects of stone diameter and the curvature in paraffin thickness survived an adjustment for irradiation, but some water-depth effects did not. These problems would have gone unnoticed without a plausibility check of each sensor and an explicit weather test [53].

Research Gaps and Future Directions

Figure 10 proposes a workflow for designing and testing combined-storage stills that follows from the review and the field lessons. Several research needs stand out.

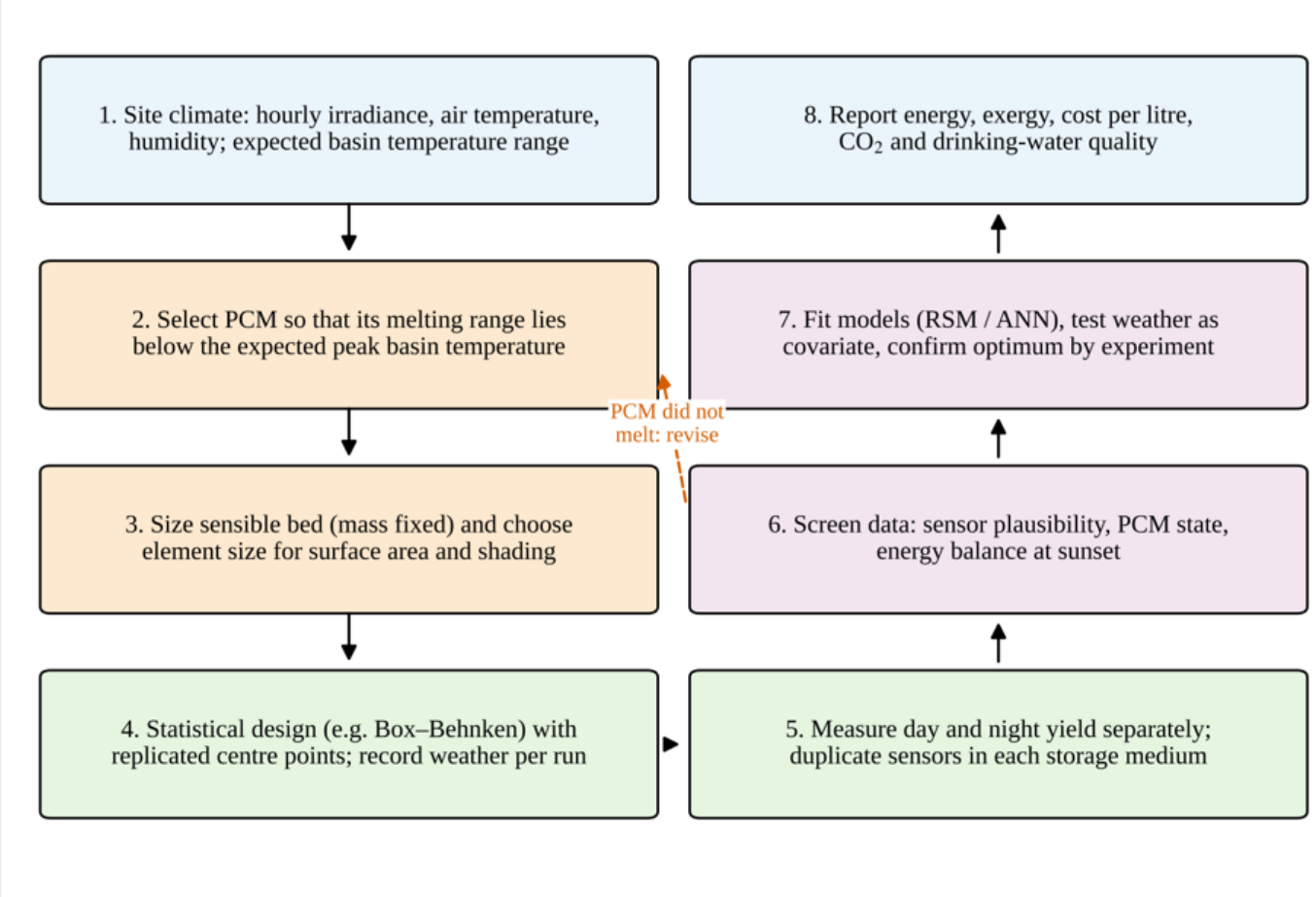


Figure 10: Proposed workflow for designing and testing solar stills with combined sensible and latent storage.

i. **Climate-Matched PCM Selection:** Studies should report the expected basin temperature at the test site and choose a PCM whose melting range lies below it. Comparative tests of paraffin grades or fatty acids with melting ranges between 40 °C and 55 °C in humid tropical climates are needed.

ii. **Four-Arm Experiments:** To establish whether se

iii. nsible and latent storage are more than additive, the same still should be tested with no storage, sensible storage only, latent storage only and both, under the same weather.

iv. **Separate Reporting of Night Output and Stored Energy:** Night yield, the heat held by each medium at sunset and the melted fraction of the PCM should be reported as standard, together with an energy balance showing that the night output is consistent with the stored heat.

v. **Robust Outdoor Statistics:** Designed experiments should record and test the weather of every run, block by test day where possible, replicate the centre point, and screen each response for sensor plausibility before modelling.

vi. **Heat Transfer into the PCM:** Low-cost ways of raising the conductivity of a sub-basin PCM layer, such as embedded stones, metal fins or locally available fillers, deserve systematic study.

vii. **Long-term Performance and Water Quality:** Few studies report the cycling stability of PCMs and stones over months, or the microbiological quality of the distillate under realistic collection and storage. Both matter for field use.

viii. **Economics and Scale-Up:** Cost per litre, payback and CO_2 savings should be assessed with local prices and with the night output included, and multi-unit installations should be tested in the communities they are meant to serve.

Conclusion

This review examined the use of sensible and latent storage together in passive solar stills. Single sensible media such as stones, gravel and rock salt typically raise the yield by 11–55%, single PCMs by about 60–80%, and stills that add reflectors or collectors to storage by 140–183%. Combining a sensible bed with a PCM is attractive because the dense, conductive medium charges quickly and can help to charge the poorly conducting PCM, while the PCM, insulated beneath the absorber, returns heat after sunset. Few stills have tested the combination on its own, and most reports change several features at once and do not show whether the PCM melted. Lessons from a field-tested stone–paraffin pyramid still in a humid tropical climate show that such a still can raise both day and night output (85–149% more water by day and a night yield of 50–76% of the daytime yield), that its sub-basin store rather than the water carries the night production, that stone size acts through surface area, and that a standard paraffin grade may never melt at such sites. Matching the PCM to the local climate, testing storage media separately and together, reporting night output and stored energy, and screening outdoor data for weather and sensor effects are the main steps needed to turn combined storage from a promising idea into a reliable design practice.

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Conflict of Interest

The authors declare no conflict of interest.

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Author Contributions

Okon Asukwo Emmanuel: conceptualisation, literature search, data curation, writing – original draft. **Olusegun David Samuel:** supervision, writing – review and editing.

Modestus Okechukwu Okwu: supervision, writing – review and editing.

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