Passive Airwell Irrigation System

Business Plan, Technical Specification, and Installation Guide

A fully passive, zero-energy water harvesting and irrigation system using radiative dew condensers, buried cisterns, and honeycomb subsurface dripline.

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Reference Site	Fort Collins, CO (5,000 ft / 1,530 m)
Comparison Site	Decatur, GA (1,000 ft / 305 m)
Target Climate	Semi-arid to humid subtropical

Contents

1. Executive Summary

This document describes a fully passive water harvesting and irrigation system that requires zero energy input and has no moving parts. The system chains proven technologies into a practical configuration: a dew/fog condenser feeding a buried cistern, with collected water distributed through a subsurface honeycomb dripline lattice.

Two condenser designs are presented. **Design A (Radiative Cooling)** uses a lightweight, high-emissivity panel tilted at 30 degrees that radiates infrared heat to the cold night sky through the 8-13 micrometer atmospheric transparency window. The surface cools 5-15 degrees C below ambient without any connection to ground thermal mass. This is a proven, well-documented approach, with field data from sites worldwide showing yields of 0.1-0.5 L/m2/night. **Design B (Ground-Coupled Air Loop)** draws ambient air through a buried pipe where it cools below the dew point, and condensate collects in a cistern at the low point. This requires a passive wind-driven intake (no electric fan) and is better suited to sites with reliable breezes.

> **System summary:** Condensing surface (radiative or ground-cooled) harvests atmospheric moisture. Condensate drains into a buried cistern. Cistern gravity-feeds a honeycomb subsurface dripline. Every stage is passive. Every flow is gravity-driven.

The system is designed for incremental deployment: individual units are inexpensive (~$50-150 each for Design A), and arrays scale linearly by adding units to a shared dripline lattice. Performance is climate-dependent, with optimal yield on clear nights with moderate humidity (40-70% RH). An optional self-powered smart valve, using thermoelectric generation from the cistern's ground-to-surface temperature differential, can provide soil-moisture-responsive irrigation control with zero external power.

2. Business Plan

2.1 Value Proposition

This system does not compete with municipal water on cost. Its value lies in providing irrigation where conventional water supply is unavailable, unreliable, or prohibitively expensive to install. Key differentiators:

- **Fully passive** — zero energy consumption, zero moving parts, zero operating cost.
- **Infrastructure-independent** — works where there is no water hookup, no electricity, and insufficient rainfall for rain harvesting.
- **Self-sustaining** — once installed, requires no ongoing input. No consumables, no filters, no degradation of core components.
- **Incrementally scalable** — add units to increase yield without redesigning the system.
- **Permanent infrastructure** — no consumables, no filters, no degradation of core components (copper, concrete, aluminum).

2.2 Target Markets

The system is best suited for applications where water access is the binding constraint:

Segment	Need	Scale
Off-grid homesteads	Supplemental irrigation without well or utility	5-20 units
Land restoration / reforestation	Establish vegetation on arid unserviced land	50-500 units
Desert permaculture	Passive water source for food forests	10-50 units
Remote agriculture	Irrigation for sites with no infrastructure	20-200 units
Emergency / humanitarian	Water in disaster zones with no power	Modular kits

2.3 Unit Economics

Bill of materials per unit (radiative panel + cistern share):

Component	Full Retail	Salvage
High-emissivity foil (2 sq m)	$10-20	$5-10

Panel frame (angled support)	$15-30	$10-15
Gutter + drain fitting	$10-15	$5-10
Cistern allocation (HDPE drum)	$40-60	$20-30
Dripline share (per unit)	$10-15	$10-15
Misc (fittings, sealant)	$10-15	$5-10
Total per unit	$95-155	$55-90

2.4 Array Configurations

System yield depends on climate, humidity, and array size. In Fort Collins, productive condensation occurs on roughly 10-12 nights per month during summer (post-thunderstorm evenings when dew points spike above the ground temperature threshold). Effective season-averaged yield is ~0.15 L/unit/night. The following table uses this conservative Fort Collins figure.

Plot Size	Plant Type	Units	Monthly Yield	Material Cost
10 sq m	Xeriscaping	10	45 L	$1,150 - $2,300
10 sq m	Drought-tolerant	22	99 L	$2,530 - $5,060
25 sq m	Xeriscaping	24	108 L	$2,760 - $5,520
25 sq m	Drought-tolerant	54	243 L	$6,210 - $12,420
50 sq m	Xeriscaping	48	216 L	$5,520 - $11,040
50 sq m	Drought-tolerant	108	486 L	$12,420 - $24,840

Table: Array sizing for Fort Collins at ~0.15 L/unit/night (season average). More humid sites yield 2-3x more.

Note: These figures are conservative for Fort Collins. In climates with higher nighttime humidity (coastal, subtropical), per-unit yield can reach 0.4-0.8 L/night, reducing unit counts by 50-75%. Always validate with a 2-3 unit trial before scaling.

2.5 Competitive Landscape

System	Energy	Water Source	Operating Cost	Infrastructure
This system	None	Ambient humidity	None	None required
Fog nets	None	Fog only	Net replacement	Mesh + frame

Rain barrels	None	Rainfall	None	Gutters + roof
Solar pump + well	Solar	Groundwater	Pump maintenance	Well + panels
Municipal water	Grid	Utility	Monthly bill	Pipes + meter

The system occupies a unique niche: it requires neither rainfall, nor groundwater, nor fog, nor infrastructure. Its only requirement is atmospheric humidity and a meaningful day-night temperature differential.

3. Technical Specification

3.1 System Overview

The system comprises three subsystems connected in series, all driven by gravity and passive radiative cooling:

- **Condensing surface** — a tilted, high-emissivity panel that radiates infrared heat to the cold night sky through the 8-13 micrometer atmospheric transparency window. The surface cools below the dew point, and ambient humidity condenses on its exterior. Condensate drains by gravity into the cistern. (See Section 4 for alternative collection approaches.)
- **Cistern** — a buried water storage vessel at 2-3m depth, at stable ground temperature (~10-12 degrees C in Fort Collins). Provides water storage, buffers productive nights against dry periods, and provides a thermal differential for optional Seebeck power generation (see Section 5).
- **Dripline lattice** — a subsurface honeycomb drip irrigation network, gravity-fed from the cistern through a valve (manual, float, or self-powered smart valve).

> **Design philosophy:** Every stage uses gravity or passive physics. No pumps, no fans, no electricity. The only optional active component is a self-powered smart valve that generates its own electricity from the cistern's temperature differential.

3.2 Cistern

Parameter	Value	Notes
Depth (center)	2.0 - 3.0 m	Below frost line, stable temp zone
Volume (minimum)	2,000 L	Per unit or shared
Ground temperature	~10-12 C (Fort Collins)	Varies by region; measure locally
Material	Concrete / HDPE / ferrocement	Waterproof, durable
Thermal capacity	8.36 MJ/K (at 2,000 L)	Increases with fill level
Insulation	None (ground contact desired)	Ground is the heat sink

For arrayed installations, individual cisterns (200-500L each) connected via the dripline lattice are simpler to install than a single large cistern. Each unit gets its own small buried tank, installed using a post-hole auger. Ground temperature is a key site parameter — it determines the thermal differential available for optional Seebeck power generation and the cold-side temperature for Design B (ground-coupled air loop) condensation.

3.3 Altitude and Pressure Effects

At Fort Collins elevation (~5,000 ft / 1,530 m), atmospheric pressure is approximately 84 kPa — 83% of sea-level pressure. This affects the system in two ways:

Solar intensity (increased load)

At altitude, the thinner atmosphere transmits approximately 15-20% more solar radiation than at sea level. Fort Collins receives ~10.7 hours of sunshine per day in July. This increases the daytime thermal load on the condensing panel, which can cause re-evaporation of dew collected during the night. Recommendations: orient panels with a slight north-facing bias to reduce direct solar exposure, and plan collection timing around pre-dawn hours when accumulated dew is at maximum before sunrise evaporation begins.

Radiative cooling performance

Lower atmospheric pressure and lower absolute humidity at altitude mean the 8-13 micrometer atmospheric window is more transparent than at sea level. This improves radiative cooling performance — the condensing panel can radiate heat to the sky more efficiently. The low humidity that makes Fort Collins a marginal site for total dew yield also makes it an excellent site for radiative cooling efficiency per unit area.

Parameter	Sea Level	Fort Collins (5,000 ft)
Atmospheric pressure	101.3 kPa	~84 kPa

Atmospheric window transparency	Baseline	Improved (lower humidity)
Solar intensity	Baseline	+15-20%
Radiative cooling efficiency	Baseline	Improved
Net effect on dew yield	Baseline	Mixed (better cooling, less moisture)

3.4 Airwell Condensing Surface

Parameter	Value
Surface area	2.0 sq m per unit
Geometry	30-degree tilted panel with gutter
Material	High-emissivity PE or PETG foil on insulated frame
Cooling mechanism	Radiative emission through 8-13 um window
Cooling power	25-100 W/m2 (clear night sky)
Temp. reduction	6-8 C below ambient (blackbody emitter)
Insulation	Polystyrene backing to isolate from ground radiation
Orientation	Sky-facing, slight north bias to reduce morning solar

The condensing panel uses radiative cooling to reach sub-ambient temperatures. A polystyrene or foam backing insulates the panel from upward ground radiation, while the sky-facing foil surface emits infrared radiation through the atmospheric window. The 30-degree tilt is a well-validated compromise between maximizing sky view angle, minimizing wind effects, and enabling gravity drainage of condensate.

3.5 Subsurface Dripline Lattice

The dripline network uses a honeycomb (hexagonal) geometry for uniform coverage. This pattern is decomposed into three sets of parallel trenches at 60-degree angles, matching the capabilities of standard trenching equipment.

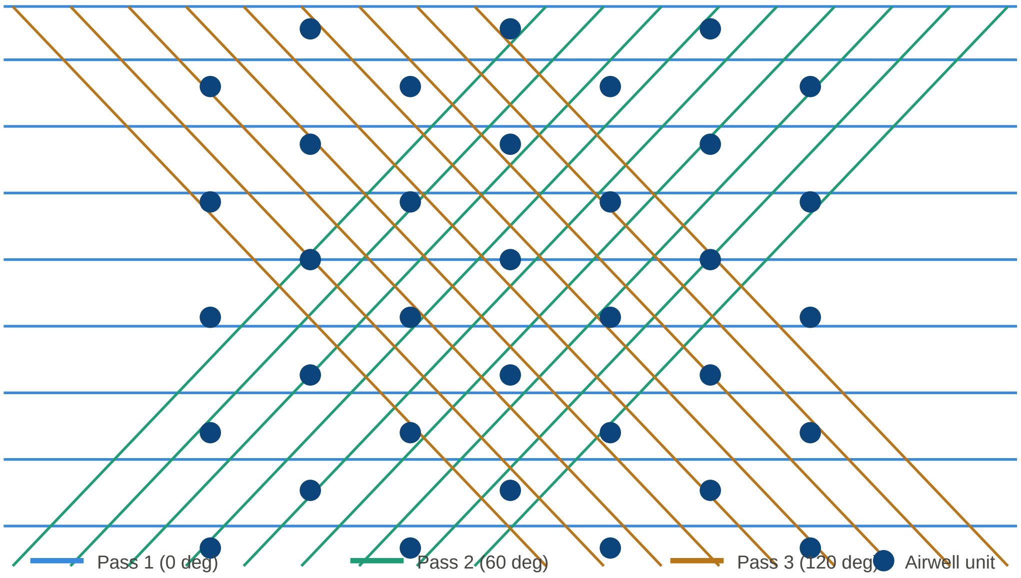

Figure 2: Top-down view of the three-pass trenching pattern. Intersections form the hex lattice; dots show airwell unit positions.

Parameter	Value
Emitter spacing	70 cm along each line
Hex row spacing	~61 cm between parallel lines
Coverage per emitter	~0.42 sq m
Trench depth	15 - 30 cm (dripline only)
Material	Standard drip tubing or porous pipe (jute)
Feed pressure	Gravity (cistern at depth)
Control	Float valve or manual valve per unit

3.6 Performance Modeling

Performance depends primarily on the relationship between nighttime dew point and stable ground temperature at cistern depth. The system can only condense water when it can cool the airwell surface below the dew point. Since the cold source is the ground (~10-12 degrees C in Fort Collins), condensation occurs only when the dew point is below approximately 10 degrees C. The following model assumes: 15 degrees C night air temperature (Fort Collins July avg low), 10 degrees C ground temperature at 2.5m depth, and natural convection (h = 10 W/sq m/K) at the airwell surface.

Condition	Value
Ground temp (cold source)	10-12 C (Fort Collins at 2.5m)
Night air temp (July avg low)	~15 C
Radiative cooling power	25-100 W/m2 (clear sky)
Achievable surface temp	6-8 C below ambient (~7-9 C)
Condensation condition	Surface temp must be below dew point
Documented yield (semi-arid)	0.1-0.5 L/m2/night
Productive nights/month (FC)	~10-15 (clear sky nights)
Season-averaged yield (FC)	~0.15 L/unit/night (2 m2 panel)
Monthly yield per unit (FC)	~4.5 L/month

Key constraint: Radiative cooling can achieve 6-8 degrees C below ambient on clear nights. In Fort Collins, with July nighttime lows of ~15 degrees C, the panel surface can reach ~7-9 degrees C. Condensation occurs when this surface temperature drops below the dew point. On typical dry nights (dew point 5-8 degrees C), the margin is slim but viable. On humid post-storm evenings (dew point 10-13 degrees C), the panel may not cool below the dew point at all. Clear, dry nights with moderate humidity (40-55% RH) are optimal.

3.7 Humidity Sensitivity

The following table shows system performance at varying nighttime relative humidity levels, holding night air temperature at 15 degrees C (Fort Collins July avg low). Radiative cooling achieves approximately 7 degrees C below ambient on clear nights, giving an achievable surface temperature of ~8 degrees C.

Night RH	Dew Point	Margin (Surface-DP)	Yield/m2/night	Assessment
25%	-4.9 C	12.9 C	0.50 L	Excellent

35%	-0.3 C	8.3 C	0.43 L	Excellent
45%	3.2 C	4.8 C	0.25 L	Good
55%	6.0 C	2.0 C	0.05 L	Marginal
65%	8.5 C	-0.5 C	0.00 L	No condensation
75%	10.6 C	-2.6 C	0.00 L	No condensation

Key finding: Condensation requires the radiative-cooled surface temperature (~8 degrees C at Fort Collins night temps) to be BELOW the dew point. At 25-45% RH, dew points are well below the surface temp, giving good margin. Above ~65% RH, the dew point approaches the achievable surface temperature and condensation becomes marginal. Clear skies are essential — clouds block the infrared atmospheric window and can eliminate the radiative cooling effect entirely.

3.8 Fort Collins Site Assessment

Fort Collins, Colorado (elevation ~5,000 ft / 1,530 m) presents a specific set of conditions for this system. This section summarizes the site-specific parameters and their implications.

Parameter	Fort Collins Value	Impact
Elevation	5,000 ft (1,530 m)	Improved radiative cooling efficiency
Station pressure	~84 kPa (83% sea level)	More transparent atm. window
Ground temp (2.5 m)	~10-12 C year-round	Good for TEG, Design B marginal
July avg high / low	31 C / 14 C	Strong day-night delta (~17 C)
Summer avg RH	~45-48%	Marginal to moderate
Summer dew points	5-8 C typical	Usually below ground temp (good)
Post-storm dew points	10-13 C	Above panel surface temp — no condensation
Annual sunshine	~300 days	High solar load, needs insulation
Monsoon (Jul-Sep)	9+ rain days/month	Best collection window
Annual precipitation	404 mm (16 in)	Supplemental, not primary

Seasonal productivity estimate

Based on Fort Collins climate data, the system has three distinct operating modes through the year:

- **Peak season (July-September):** Clear nights with 35-55% RH are the most productive. The radiative panel cools to ~8 degrees C, and dew points at these humidity levels (0-6 degrees C) sit comfortably below the surface temperature. Post-thunderstorm evenings with elevated humidity (>65% RH) and cloud cover are actually unproductive because clouds block the infrared atmospheric window and dew points exceed the achievable surface temperature. Expect ~10-15 productive clear nights per month. Season-averaged yield: ~0.15 L/m2/night.
- **Shoulder season (May-June, October):** Cooler nights with variable humidity. Some productive nights, but shorter duration and lower yields. ~5-10 productive nights/month.
- **Off season (November-April):** Freezing night temperatures. System is dormant. Cistern water may freeze near the surface. No damage expected if properly constructed (HDPE tolerates freeze-thaw), but no collection occurs.

> **Honest assessment:** Fort Collins is at the marginal end of this system's effective range. The low humidity is actually favorable (low dew points give good thermal margin), but the total number of productive nights per year is limited. This system is best suited as supplemental irrigation for xeriscaping or native plants — not as a primary water source. A 2-3 unit trial over one summer is strongly recommended before any larger investment.

3.9 Decatur, GA Comparison Site

Decatur, Georgia (metro Atlanta, elevation ~1,000 ft / 305 m) provides a useful contrast to Fort Collins. Its humid subtropical climate inverts most of the constraints that apply in semi-arid Colorado.

Parameter	Fort Collins, CO	Decatur, GA
Elevation	5,000 ft (1,530 m)	1,000 ft (305 m)
Atm. pressure	~84 kPa	~101 kPa (near sea level)
July avg high / low	31 C / 15 C	33 C / 22 C
Day-night delta	~16 C	~11 C
Summer avg RH	~45%	~69-74%
Summer dew points	5-8 C	18-22 C
Ground temp (2.5 m)	~10-12 C	~16-18 C
Annual precipitation	404 mm (16 in)	1,321 mm (52 in)
Clear sky frequency	~300 days/yr	~218 days/yr
Cloud cover (summer)	Low	Moderate (partly cloudy)

Design A (Radiative cooling) in Decatur

Radiative cooling performs poorly in Decatur. At nighttime lows of 22 degrees C, a radiative panel achieves ~15 degrees C surface temperature. But summer dew points are 18-22 degrees C — well above the achievable surface temperature. The panel cannot cool below the dew point on most summer nights. Additionally, higher cloud cover frequency blocks the 8-13 micrometer atmospheric window more often than in Fort Collins. Radiative panels may be productive in spring and fall when dew points are lower, but summer collection would be minimal.

Design B (Ground-coupled air loop) in Decatur

The ground-coupled approach is far more promising in Decatur. Ground temperature at depth is ~16-18 degrees C, and summer dew points are 18-22 degrees C. Air drawn through buried pipes cools to ground temperature, and since the dew point is above ground temperature, condensation occurs reliably. The high absolute humidity means each cubic meter of air carries substantially more moisture than in Fort Collins. With passive airflow (wind-driven or solar chimney), this design could produce meaningful yields on most summer nights.

TEG performance in Decatur

The smaller day-night temperature differential (~11 degrees C vs. ~16 degrees C in Fort Collins) and warmer ground temperature reduce the TEG delta-T. However, daytime surface temperatures can still exceed 50 degrees C in direct sun, giving a delta-T of ~32-34 degrees C against the 16-18 degrees C cistern. TEG performance would actually be comparable or better than Fort Collins during peak daytime hours.

> **Key insight:** Fort Collins and Decatur require opposite collection strategies. Fort Collins (dry, clear skies) favors Design A (radiative cooling). Decatur (humid, partly cloudy) favors Design B (ground-coupled air loop). The cistern, dripline lattice, and self-powered smart valve are effective in both climates. Site selection determines which collection method to deploy — the storage and distribution layers are universal.

	Fort Collins, CO	Decatur, GA
Best collection method	Design A (radiative)	Design B (earth tube)
Productive season	May-Sep (clear nights)	Apr-Oct (humid nights)
Est. productive nights/month	10-15	20-25
Est. yield per unit per night	0.1-0.3 L/m2	0.2-0.5 L/unit *
Season-averaged yield	~0.15 L/m2/night	~0.3 L/unit/night *
Primary constraint	Low humidity	Cloud cover / airflow
Secondary benefit	Rain barrels useless	Rain barrels also viable

** Decatur yields for Design B depend heavily on airflow volume through earth tubes and are less well-documented than radiative panel yields. Figures are estimates.*

4. Alternative Collection Configurations

This section evaluates passive mechanisms for cooling a condensing surface below the dew point, comparing their feasibility, yield, cost, and suitability for different climates. As shown in the site assessments (Sections 3.8-3.9), the optimal collection method depends on local humidity and sky conditions.

4.1 Radiative Sky Cooling (Design A)

Earth's atmosphere has a transparency window at 8-13 micrometers wavelength that coincides with the peak thermal radiation of surfaces at ambient temperature (~300K). A sky-facing surface with high emissivity in this band radiates heat directly to outer space (~3K), cooling itself 6-15 degrees C below ambient without any ground coupling, electricity, or moving parts. This is the mechanism used by all successful modern passive dew collectors.

Parameter	Value
Mechanism	Infrared radiation through 8-13 um window
Cooling power	25-100 W/m2 (clear sky, nighttime)
Temp. reduction	6-8 C below ambient (blackbody emitter)
Documented yield	0.1-0.5 L/m2/night (semi-arid)
Theoretical max	~0.5 mm/night (~0.5 L/m2/night)
Material	Modified PE foil (OPUR), polycarbonate, or PETG
Material cost	< $10/m2
Geometry	30 degree tilted panel with gutter at base
Constraints	Clear sky required; clouds block IR window
Fort Collins fit	Excellent — 300 days sunshine, clear nights

This is the recommended primary collection method. The International Organization for Dew Utilization (OPUR) has deployed radiative foil condensers across multiple continents with consistent results. The foil is inexpensive, lightweight, and requires no precision assembly. Condensate drains by gravity from the tilted surface into a gutter, then into the cistern. Fort Collins' abundant clear skies are ideal for radiative cooling, and the low humidity (which limits total yield) also means the atmospheric window is maximally transparent, improving cooling efficiency.

Verdict: PRIMARY RECOMMENDATION. Proven, cheap, simple, and well-suited to Fort Collins climate. Use as the main collection method.

4.2 Ground-Coupled Air Loop (Design B)

Ambient air is drawn through buried pipes (earth tubes) at 1.5-3 m depth where stable ground temperature (10-12 degrees C in Fort Collins) cools it. If the air cools below its dew point, moisture condenses on the pipe walls and drains to a collection point. This approach was used in the Airdrop water harvester (Linacre, 2011) and has historical precedent in the Courneya apparatus (1982).

Parameter	Value
Mechanism	Air cooled by ground thermal mass in buried pipe
Pipe diameter	100-150 mm, smooth-walled PVC or metal
Burial depth	1.5-3.0 m (stable temperature zone)
Ground temp (FC)	10-12 C year-round
Condensation condition	Incoming air dew point > ground temp
Air circulation	Wind-driven intake, solar chimney, or natural convection
Material cost	$50-150 per 10m run
Yield	Variable; depends on airflow volume and humidity
Constraints	Requires airflow; pipe hygiene; marginal at low humidity
Fort Collins fit	Marginal — dew points often below ground temp

The challenge in Fort Collins is that typical summer nighttime dew points (5-8 degrees C) are already BELOW the ground temperature (10-12 degrees C), meaning the air cannot be cooled to its dew point by the ground alone. Condensation only occurs on post-thunderstorm evenings when dew points spike to 10-13 degrees C. Additionally, fully passive air circulation (no fan) limits throughput. Natural convection through earth tubes is possible using a solar chimney (heated vertical pipe creates updraft pulling air through buried horizontal pipes), but flow rates are modest.

> **Verdict: SUPPLEMENTARY.** Can complement radiative panels on high-humidity nights, but not reliable as a primary method at Fort Collins humidity levels.

4.3 Massive Thermal Inertia Condenser

The historical approach: large stone or concrete structures that radiate heat to the night sky, cool down, and maintain a cool surface into the early morning hours for dew collection. This includes the Zibold condenser (1912, Crimea) and Chaptal's pyramid (1929, France). The cooling mechanism is actually radiative (same as Design A), but the thermal mass was intended to buffer cool temperatures through the morning hours.

Modern analysis has shown these were largely unsuccessful. The high thermal mass that was supposed to help actually HINDERS performance: the massive structure cannot cool below the dew point because its thermal inertia prevents rapid temperature drops. Lightweight radiative panels with low thermal mass outperform stone condensers significantly.

Verdict: NOT RECOMMENDED. Historically interesting but outperformed by lightweight radiative panels in every documented comparison.

4.4 Desiccant Sorption/Desorption Cycle

A hygroscopic material (metal-organic framework, silica gel, or salt-based desiccant) absorbs moisture from ambient air during cooler/humid periods, then solar heat regenerates it during the day, driving off concentrated water vapor which condenses on a cooler surface within a sealed chamber. MIT recently demonstrated a passive, window-sized panel using a hydrogel-desiccant combination that harvests drinking water from desert air without electricity.

The key advantage is that this works at ANY humidity level, including below 30% RH, because the desiccant concentrates moisture over time. It decouples collection from the dew point constraint entirely. The disadvantage is lower yield per cycle and the need for specialized sorbent materials (though common silica gel works, advanced MOFs perform better). Fort Collins' 300 days of sunshine provides excellent solar regeneration conditions.

Verdict: PROMISING FOR FUTURE ITERATION. Best option for very low humidity conditions. More complex than radiative panels but works in conditions where nothing else can. Consider as a Phase 2 enhancement after validating the radiative panel baseline.

4.5 Recommended Configuration: Radiative Panel + Cistern + Dripline

The recommended system uses radiative cooling panels as the primary collection method. The architecture:

- **Collection:** Tilted high-emissivity foil panels (OPUR-style or equivalent), ~2 m2 each, at 30 degrees slope facing sky. Condensate drains via gravity through a gutter into the cistern inlet.
- **Storage:** Buried cistern at 2-3m depth. Provides water storage and buffers productive nights against dry periods. Also provides thermal differential for optional Seebeck power generation (see Section 5).
- **Distribution:** Honeycomb subsurface dripline lattice (unchanged). Three-pass trenching at 60-degree angles, gravity-fed from cistern.
- **Control:** Optional self-powered smart valve using thermoelectric generation from cistern temperature differential (see Section 5).

Revised bill of materials (per unit)

Component	Cost	Notes
High-emissivity foil (2 m2)	$10-20	PE/PETG film, OPUR-type
Panel frame (angled support)	$15-30	Wood, aluminum, or PVC pipe
Gutter + drain fitting	$10-15	Standard rain gutter
Cistern allocation	$40-60	Shared HDPE drum or concrete
Dripline share	$10-15	Per-unit allocation of lattice
Total per unit	$85-140	Simple hardware-store materials

> **Key advantage:** The radiative panel design uses no specialty materials (no copper pipe, no vacuum pump, no brazing), is based on globally-deployed technology, and requires only basic hand tools for assembly.

5. Self-Powered Instrumentation (Seebeck Effect)

The buried cistern creates a persistent temperature differential between the cool underground water (~10-12 degrees C) and the warm surface above (up to 30+ degrees C on summer days). This differential can be harvested via the Seebeck effect to generate small amounts of electricity — enough to power sensors and actuators that upgrade the system from fully passive to self-powered smart.

5.1 Thermoelectric Generation from Cistern Delta-T

The Seebeck effect generates voltage when two dissimilar conductors experience a temperature difference: V = S x Delta-T, where S is the Seebeck coefficient. A standard bismuth telluride (Bi2Te3) thermoelectric generator (TEG) module contains ~127 thermocouple pairs in series.

Parameter	Value
Seebeck coefficient (Bi2Te3)	~200-250 uV/K per couple
Standard TEG module	~127 couples, 40 x 40 mm
Voltage at Delta-T = 8 C (night)	~200-250 mV per module
Voltage at Delta-T = 20 C (day)	~500-630 mV per module
Power at Delta-T = 20 C	~20-40 mW per module
Module cost	$3-8 each (Bi2Te3, commercial)

5.2 Power Budget and Applications

A single TEG module clamped between a solar-heated surface plate (warm side) and the cistern lid or a pipe carrying cistern water (cold side) produces ~20-40 mW during peak daytime Delta-T of ~20 degrees C. Over 8 hours of useful differential, that accumulates roughly 160-320 mWh (576-1152 J) per day per module.

Application	Power Needed	Modules Required	Feasibility
Soil moisture sensor	~0.1 mW (sleep mode)	1	Easily feasible
MCU (ATtiny/MSP430)	~0.5-3 mW (duty-cycled)	1	Feasible
Small solenoid valve	~200 mW (pulsed)	1 + supercapacitor	Feasible
Wireless transmitter	~10-50 mW (burst)	1-2	Feasible

Small DC fan (80mm)	~1000 mW (continuous)	50-100	Impractical
Earth tube ventilation fan	~2000 mW	100+	Not viable passively

The key insight is that TEG power at these modest temperature differentials is unsuitable for driving fans or pumps, but is more than sufficient for low-power electronics: sensors, microcontrollers, and solenoid valves. This shifts the value proposition from 'generate meaningful energy' to 'self-power the instrumentation layer.'

5.3 Smart Dripline Control

The most practical application of Seebeck generation in this system is a self-powered smart irrigation valve. The concept:

- **Energy harvesting:** One TEG module on the cistern lid (warm sun-side up, cool cistern-side down) feeds a boost converter (e.g., LTC3108 or BQ25504) that charges a small supercapacitor or LiFePO4 cell.
- **Sensing:** A capacitive soil moisture sensor at a representative point in the dripline lattice is read by a low-power MCU (MSP430, ATtiny, or RP2040 in dormant mode) every 15-30 minutes.
- **Actuation:** When soil moisture drops below a threshold, the MCU pulses a small latching solenoid valve open on the cistern outlet. When moisture is adequate, it pulses closed. Latching solenoids draw power only during state transitions (~200 mW for ~50 ms), not while holding a position.
- **Self-regulating feedback:** On hot, sunny days the TEG produces more power (larger Delta-T) — which is precisely when the soil dries fastest and the valve needs to open most frequently. On cool, cloudy days when plants need less water, the TEG produces less power and the system naturally throttles back. The energy supply correlates with irrigation demand.

Component	Cost
TEG module (Bi2Te3, 40x40mm)	$5
Boost converter board (LTC3108)	$3
Supercapacitor (1F, 5.5V)	$2
Microcontroller (ATtiny85 or MSP430)	$2-4
Capacitive soil moisture sensor	$3-5
Latching solenoid valve (12mm)	$8-15
Thermal paste + mounting hardware	$3
Total	$26-37

Design philosophy: Rather than trying to generate enough Seebeck power to run a fan (impractical at these temperature differentials), use it to make the system intelligent. A $30 self-powered smart valve replaces a passive float valve and provides soil-moisture-responsive irrigation with zero external power — true to the system's fully autonomous design intent.

6. Installation Guide

This guide covers installation of the recommended configuration: radiative cooling panels draining into buried cisterns, with a honeycomb dripline lattice and optional self-powered smart valve.

6.1 Site Assessment

Before installation, verify the following site conditions:

- **Climate data:** Obtain local nighttime RH averages (prefer > 30% during growing season). Check day-night temperature differential (prefer > 10 degrees C). Note average cloud cover — clear skies are essential for radiative cooling.
- **Sky exposure:** The radiative panel needs unobstructed sky view. Avoid locations under trees, eaves, or near tall structures that block the sky hemisphere. South-facing slopes are acceptable if the panel faces upward.
- **Ground temperature:** Measure or estimate stable ground temperature at 2-3m depth. In Fort Collins this is ~10-12 degrees C year-round. Relevant for cistern sizing and optional TEG performance.
- **Slope and drainage:** Identify natural slope. Place cisterns upslope of the planting area if possible to maximize gravity feed pressure.

6.2 Tools and Materials

For single prototype unit

- Post-hole auger or hand auger (for cistern bore, 45-60 cm diameter)
- High-emissivity foil: 2 m2 (OPUR-type PE film, or PETG sheet)
- Panel frame: wood or aluminum angle, cut to support foil at 30 degrees
- Rain gutter section + end caps + downspout fitting
- HDPE barrel (200-500 L) for cistern
- PVC pipe fittings for cistern inlet/outlet
- Basic hand tools, saw, drill, level

Additional for array installation

- Walk-behind trencher (rental) — for dripline lattice
- Drip tubing: 16mm poly drip line with inline emitters at 70 cm spacing
- Tee and cross fittings for lattice intersections
- Float valve or smart valve assembly (see Section 5.3)

Optional: self-powered smart valve

- TEG module, boost converter, supercapacitor, MCU, soil sensor, latching solenoid
- See Section 5.3 for complete BOM (~$30 total)

6.3 Phase 1: Cistern Excavation

Use a post-hole auger to bore to 2.5-3.0 m depth, lower an HDPE drum, and backfill. Pre-drill inlet port (for condensate from panel gutter) and outlet port (for dripline feed). Leave cistern lid accessible for optional TEG mounting.

> **Tip:** A standard 55-gallon (208 L) HDPE drum fits a 60 cm bore and provides adequate per-unit storage. If using the TEG option, paint the lid flat black to maximize solar absorption on the warm side.

6.4 Phase 2: Radiative Panel Installation

- 1. Build the frame: a simple A-frame or angled support that holds the foil at 30 degrees from horizontal, with the low edge facing the cistern.
- 2. Stretch the high-emissivity foil taut over the frame. Secure with clips or adhesive. Avoid wrinkles (condensate needs to sheet-flow downward).
- 3. Attach a rain gutter along the low edge to catch condensate runoff.
- 4. Connect the gutter downspout to the cistern inlet via PVC pipe. Ensure positive slope for gravity drainage.
- 5. Position the panel with maximum sky exposure — no trees, walls, or overhangs obstructing the upward-facing surface. North-facing tilt bias helps avoid direct midday sun in summer.
- 6. Verify condensate drainage: pour a small amount of water at the top of the panel and confirm it sheets down into the gutter and drains to the cistern.

6.5 Phase 3: Dripline Lattice (Trenching)

Three-pass trenching at 0/60/120 degrees, lay drip tubing, connect at intersections, connect to cistern outlet, pressure test, backfill. See Section 3.5 for detailed specifications and hex lattice diagram.

6.6 Phase 4: TEG and Smart Valve (Optional)

- 1. Mount the TEG module on the cistern lid: apply thermal paste to both faces. Clamp the module between the lid surface (cold side, in contact with cistern water) and a small black-painted aluminum plate (warm side, facing sun).
- 2. Wire the TEG output to the boost converter input. Set the boost converter output to 3.3V.
- 3. Connect the supercapacitor to the boost converter output as an energy buffer.
- 4. Wire the MCU, soil moisture sensor, and latching solenoid valve to the boost converter output.
- 5. Flash the MCU with a simple threshold program: read soil moisture every 15-30 minutes; pulse valve open if dry, pulse closed if wet.

- 6. Install the solenoid valve on the cistern outlet pipe (replacing the float valve).
- 7. Bury the soil moisture sensor at drip emitter depth (~20 cm) at a representative location in the dripline lattice.

> **Note:** The smart valve is entirely optional. A simple float valve or manual valve works fine for initial trials. Add the TEG system in a later phase once you have baseline yield data and want to optimize water distribution.

6.7 Commissioning and Testing

- 1. Fill the cistern with an initial water charge (100-200 L for a single unit). This provides starting water for the dripline and thermal mass for TEG operation.
- 2. Check for condensation: on the first clear night with suitable humidity (> 40% RH), inspect the panel surface at dawn. You should see condensation droplets or wet streaks on the foil.
- 3. Measure yield: place a graduated container at the cistern inlet for several nights to establish baseline condensation rate.
- 4. If using TEG: verify voltage output with a multimeter during peak afternoon sun. Expect 400-600 mV from a single module. Verify the boost converter is charging the supercapacitor.
- 5. Open the dripline valve and verify uniform drip at all emitter points.
- 6. Monitor cistern water level over 2-4 weeks to confirm net positive accumulation (collection > irrigation draw).

6.8 Scaling to Full Array

After validating a single prototype unit, scale to the full array incrementally:

- **Trial phase (2-3 panels):** Install a small cluster draining into a shared cistern. Run for one full summer. Total cost: ~$200-400 with basic materials.
- **Expansion phase:** Based on measured yield per m2, calculate panel area needed for your target irrigation area. Add panels and cisterns, connecting to the existing dripline.
- **Lattice extension:** The honeycomb dripline can be extended in any direction by adding new trench passes. New cisterns connect to the existing grid at intersection points.
- **Smart upgrade:** Once baseline yield is established, add TEG smart valves to optimize water distribution based on actual soil moisture.

> **Recommended trial:** Start with 2-3 radiative panels (4-6 m2 total) sharing a single cistern. Measure actual yield over July-September. This provides the real-world data needed to size a full installation. Total trial cost: approximately $200-400.

Annotated References

The following sources were used to validate the technical claims in this document. Each annotation describes what the source confirms and where it applies.

Radiative sky cooling (Section 3, 4.1)

- **Beysens et al., "Application of passive radiative cooling for dew condensation," Energy, 2006** — "Dew yield is effectively limited to 0.5 mm/night." Also: "The dew yield is restricted by the cooling power, which lies in the range of 25-100 W/m2 for clear evening skies." Establishes the theoretical ceiling for passive dew collection. [ScienceDirect]
- **Khalil et al., "A review: dew water collection from radiative passive collectors," Sustainable Water Resources Management, 2016** — "A 1 m2 radiative condenser yields between 0.3 and 0.6 L/day of dew water in arid and semi-arid regions." Key validation of the yield range used in array sizing calculations. [Springer]
- **Maestre-Valero et al., "Comparative analysis of two polyethylene foil materials for dew harvesting in a semi-arid climate," Journal of Hydrology, 2011** — Year-long field study in semi-arid Spain using 1 m2 OPUR-standard and low-cost black PE foils tilted at 30 degrees. Validates the panel geometry and foil material choices recommended in Design A. Reports that a low-cost agricultural PE foil performed comparably to the OPUR standard. [ScienceDirect]
- **Muselli et al. (2002), cited in multiple reviews** — 30 m2 OPUR condenser in Corsica: 214 dewy nights over 478 days, average 0.12 mm/night, maximum 0.38 mm/day. Largest documented long-term passive dew collection deployment. Validates that the technology works at multi-year timescales.
- **Clus et al.; Lekouch et al.; various OPUR field deployments** — Consistent results from Grenoble (France), Ajaccio (Corsica), Jerusalem (Israel), Bordeaux (France), and Mirleft (Morocco). Yields 0.05-0.5 L/m2/night depending on climate. Confirms that the technology is globally validated across diverse climates.
- **Raman et al., "Radiative sky cooling: Fundamental principles, materials, and applications," Applied Physics Reviews, 2019** — "Radiative sky cooling cools an object on the earth by emitting thermal infrared radiation to the cold universe through the atmospheric window (8-13 um). It consumes no electricity." Cooling power up to 140 W/m2 at ambient temperature. Comprehensive physics review. [AIP Publishing]
- **"A review of clear sky radiative cooling," ScienceDirect, 2018** — "A near blackbody emitter attains up to 120 W/m2 radiative heat flux and the minimum attainable temperature is 6-8 degrees C below ambient." Validates the temperature reduction and cooling power figures in Section 4.1 table.
- **Comparison of surface foil materials in Kenya, Agricultural and Forest Meteorology, 2019** — Year-long field study with multiple foil types. Cumulated yields 18.9-25.3 mm over the study period, with OPUR and PVC performing comparably. Confirms that inexpensive foils are viable alternatives to the OPUR standard.

Ground-coupled air loop / Airdrop (Section 4.2)

- **Linacre, Airdrop Irrigation System (2011 James Dyson Award winner)** — "Air is channeled underground through a network of piping that quickly cools the air to soil temperature. This process creates an environment of 100-percent humidity, from which water is then harvested." Prototype produced ~1 L/day. Validates the ground-coupled air condensation concept. [newatlas.com; jamesdysonaward.org]
- **Khalil et al. (2016) review** — "The airdrop can harvest 11.5 ml of water for every cubic meter of air." Also notes the system uses wind-powered turbine and solar battery backup. Confirms the yield-per-volume-of-air figure. [Oxford Academic]
- **Wikipedia, "Ground-coupled heat exchanger"** — "Buried 1.5 to 3 m underground where the ambient earth temperature is typically 10 to 23 degrees C all year round in temperate latitudes." Also: "Passive ground-coupled heat exchange drives circulation using pressure differences caused by wind, rain, and buoyancy-driven convection." Validates the earth tube parameters and confirms passive (no-fan) operation is possible. [en.wikipedia.org]
- **Wikipedia, "Air well (condenser)"** — "One method is to use the ground as a heat sink by drawing air through underground pipes ... Designs of this type require air to be drawn through the pipes by a fan, but the power required may be provided (or supplemented) by a wind turbine." Confirms the approach and its limitation regarding airflow. [en.wikipedia.org]

Desiccant sorption/desorption (Section 4.4)

- **MIT News, "Window-sized device taps the air for safe drinking water" (2025)** — "A passive device that harvests clean drinking water from desert air without electricity. The window-sized panel uses a hydrogel-desiccant combo absorbing vapor at night and releasing it via sunlight-driven condensation — no batteries, fans, or power needed." Validates the fully passive desiccant approach. [news.mit.edu]

Thermoelectric energy harvesting (Section 5)

- **"Energy Harvesting from Natural Temperature Difference Between Soil Surface and Soil Depth by Thermoelectric Generation," JSDEWES** — From a 3.05 degrees C temperature difference, a TEG module generated maximum 27 mW daytime and 6.3 mW nighttime, with average 550 uW. Directly validates the power figures in Section 5.2 for similar temperature differentials. [sdewes.org]
- **"Battery-Less Environment Sensor Using Thermoelectric Energy Harvesting from Soil-Ambient Air Temperature Differences," PMC, 2022** — Demonstrates TEG-powered IoT sensor nodes using soil-air temperature differential. Validates the concept of self-powered environmental sensing from ground thermal gradients. [PMC/NIH]
- **"Environment-Monitoring IoT Devices Powered by a TEG," Sensors, 2021** — "TEG is a suitable solution for powering energy harvesting nodes. TEG can also be used to extend the battery life of devices by generating power from waste heat." Confirms TEG viability for sensor applications. [MDPI Sensors]
- **Analog Devices, LTC3108 datasheet and FAQ** — "The LTC3108 provides a complete power management solution for wireless sensing and data acquisition. The step-up topology operates

from input voltages as low as 20 mV." Also: "These parts target applications that require a low average power (in the milliwatt range or less)." Validates the boost converter selection and confirms the power range is matched to our TEG output. Confirmed operable from as little as 1 degree C temperature differential. [analog.com]

- **Digi-Key, "Ultra-Low Voltage Energy Harvester Uses Thermoelectric Generator for Battery-Free Wireless Sensors"** — "The output power varies from hundreds of microwatts to tens of milliwatts over a Delta-T range of 1 to 20 degrees C." Validates the power budget figures in Section 5.2. [digikey.com]

Fort Collins climate data (Section 3.8)

- **USDA, Official Series Description — FORT_COLLINS Series** — "Mean annual soil temperature: 8 to 13 degrees C (47 to 55 degrees F.)." Validates the ground temperature range used throughout the document. [soilseries.sc.egov.usda.gov]
- **Weather-and-Climate.com, Fort Collins** — "Nighttime temperatures range from 15 degrees C (59 degrees F) in July to -10 degrees C (14 degrees F) in December." Also: "Sunshine peaks in July at around 10.7 hours per day." Validates the nighttime temperature and solar exposure figures. [weather-and-climate.com]
- **Weather-US.com, Fort Collins** — "June, August and September, with an average relative humidity of 45%, are the least humid months." Validates the summer humidity baseline. [weather-us.com]
- **NWS Denver/Boulder, Pressure Readings** — Fort Collins station pressure ~840 hPa / 24.8 inHg at ~5,016 ft elevation. Validates the atmospheric pressure figures used in the altitude calculations. [forecast.weather.gov]

Decatur, GA climate data (Section 3.9)

- **Weather-and-Climate.com, Decatur** — "The city experiences its highest humidity in August, reaching 75%. Throughout the year, the average humidity in Decatur is 68%." Also: nighttime temperatures of 21 degrees C (70 degrees F) in July. Validates the humidity and nighttime temperature figures. [weather-and-climate.com]
- **Weather-US.com, Decatur** — "July is the warmest month with average temperature varying between 71.6 degrees F (22 degrees C) and 90.7 degrees F (32.6 degrees C)." Also: "July and August, with an average relative humidity of 69%, are the least humid months." Validates the temperature range and summer humidity floor. [weather-us.com]
- **Weather2Visit.com, Decatur July** — July averages: daytime 31.2 degrees C, nighttime 20.4 degrees C, humidity 74%, 9.3 hours sunshine, 126 mm rainfall over 12 rainy days. Validates the complete July climate profile used in the comparison table. [weather2visit.com]
- **MyPerfectWeather.com, Atlanta** — "In Atlanta, the air can feel uncomfortably humid during the summer months from June to August. This occurs when dewpoint temperature is above 65 degrees F." Confirms that summer dew points regularly exceed 18 degrees C (65 degrees F), validating the 18-22 degrees C dew point range used in the comparison. [myperfectweather.com]
- **BestPlaces.net, Decatur** — "Decatur has a humid subtropical climate. The area receives an average of about 50 inches of rainfall annually." Also: "218 sunny days per year." Validates the

annual precipitation and clear sky frequency figures. [bestplaces.net]

End of document. This specification is released for open development and prototyping. No warranty is expressed or implied. Build, test, measure, iterate.