Potential of Water-Responsive Materials to Harvest Energy from Evaporation

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ABSTRACT

Water-responsive materials swell/shrink in response to changes in relative humidity (RH) and can potentially harvest energy from evaporation. Here, we theoretically investigate harvesting energy from naturally evaporating water due to varying weather conditions. We model the effects of energy harvesting on evaporation rate and the resulting power output and intermittency. Calculations over a range of locations across the United States predict power productions with reduction in evaporative losses. Non-steady state calculations at three test locations predict that power output is robust against daily and yearly variations in power demand & weather conditions. We find that this system can potentially surpass the energy density of wind-based approaches with lower intermittency than solar systems. These results suggest that further research into water-responsive materials could supply devices that surpass existing energy platforms.

Keywords: water, alternative energy, stimuli-responsive materials, hydrology, environment

1 INTRODUCTION

Evaporation, the flow of latent energy from a higher to lower potential, is a powerful energy flow at the Earth's surface. It is estimated that the global energy flux due to evaporation is 80 W/m^2 [1] (Figure 1). Water-responsive materials in nature, powered by evaporation, achieve a diversity of vital tasks, such as plant movement and molecular transport. Several biologically inspired materials have been developed and investigated that mimic materials observed in nature [2, 3].

With growing interest in water conservation and alternative energy, we are motivated to investigate the effect that water-responsive materials have on evaporation. These materials swell/shrink upon sorption/desorption of water and are performing work to undergo these changes in shape. It may be possible to use these materials in a system to harvest work from evaporation through a cycle of water sorption/desorption.

The power output of this system depends on the evaporation rate E and the amount of work done per unit of evaporating water w, which is determined by the load on the water-responsive material. Here, we investigate the potential of harvesting energy from naturally evaporating water due to natural weather conditions. We model the effects on evaporation rate, the resulting power output, and intermittency concerns by using a method developed by Penman [4]. Steady state calculations over a range of locations across the United States predict the average energy flux and net water savings. Non-steady state approaches at three test locations predict daily and yearly variations in power output.

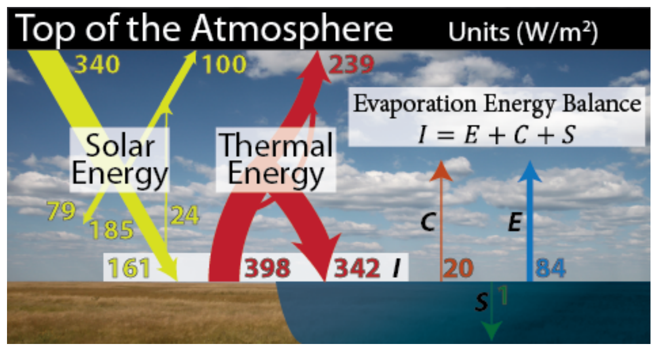

Figure 1: Energy Balance of the Atmosphere & Surface. Adapted from [1]

2 THE MODEL

The rate of evaporation is governed by the mass and heat transfer characteristics of the atmosphere and the energy balance between incoming energy from solar radiation, and heat losses due to conduction, convection, and thermal radiation. Penman's combination equation synthesizes the mass and energy balance to predict evaporation rates from meteorological data for the steady state condition. This equation has been modified to predict evaporation rates from plants [5] and soil [6] where evaporation is restricted. As a result of restriction, vapor pressure at the evaporating surface drops below saturation level. This reduction is determined empirically in the case of plants and soil.

However, in the presence of energy conversion devices, the vapor pressure is determined by the amount of work w done for a unit amount of evaporating water. This allows us to relate the work load w to the evaporation rate E. Figure 2 presents an illustration of the proposed model scheme.

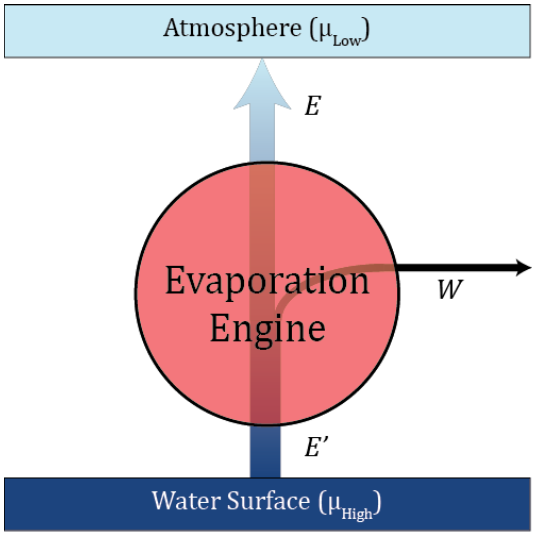

Figure 2: Scheme of an evaporative energy engine.

3 STEADY-STATE PREDICTIONS

Assuming that over sufficiently long periods of time the average temperature of an evaporating body of water remains constant, we can determine the effort that ambient weather conditions will have on the potential for evaporative energy harvesting.

3.1 Energy Availability of Typical Weather

Here, we calculated the evaporation rate, power density, and surface temperature that would result from evaporative energy harvesting as a function of the load on a potential evaporative energy harvester for mild weather conditions (Figure 3). As the work load increases, the rate of evaporation declines as the surface temperature rises. Evaporation ultimately stops at a certain work load, at which point heat is transmitted back to air entirely in the form sensible heat. Importantly, the energy flux extracted from evaporation peaks at a certain work load.

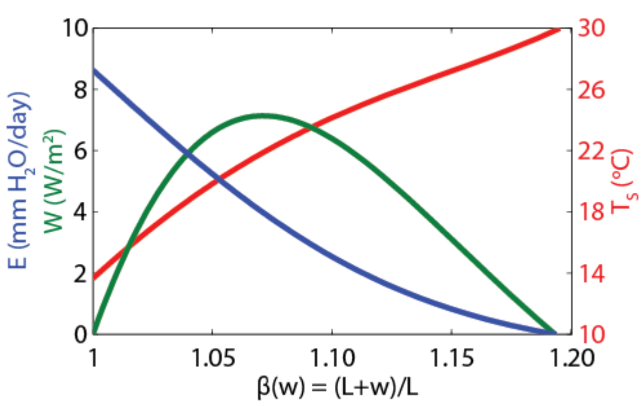

Figure 3: Predictions for Surface Temperature (red), Evaporation Rate (blue), and Power Density (green) as a function of work load for mild weather conditions.

3.2 Annual Steady State Prediction in Daggett-Barstow, CA

This calculation is expanded to give us insight into the variability in energy availability over a year. Using appropriate data for Daggett-Barstow, CA [7], we can predict the maximum power output and corresponding water savings for each day in the dataset (Figure 4). We see that during the warm, dry months of the summer, energy densities of 15 – 20 W/m² are available.

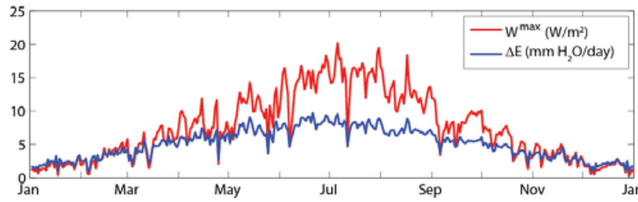

Figure 4: Maximum Daily Power Generation and Corresponding Water Savings in Daggett-Barstow, CA.

4 INTERMITTENCY & THE NON-STEADY STATE

Intermittency frequently challenges renewable energy platforms, where insufficient power is available due to external constraints such as variable demand and changing environmental conditions. To explore this challenge, we modeled a dynamically controlled non-steady state power generator subject to varying power demand and weather.

4.1 Variable Power Delivery

Each simulation model is run for three simulation years to confirm adequate stabilization and memory loss of initial conditions. Figure 5 illustrates the final year of a simulation at Daggett Barstow, CA. For clarity, the results for surface temperature and evaporation rate are excluded. In this low power density demand regime, the model matches scaled power demand over 99% of the time, exhibiting some power failure in winter days where global horizontal irradiance is low and relative humidly is high.

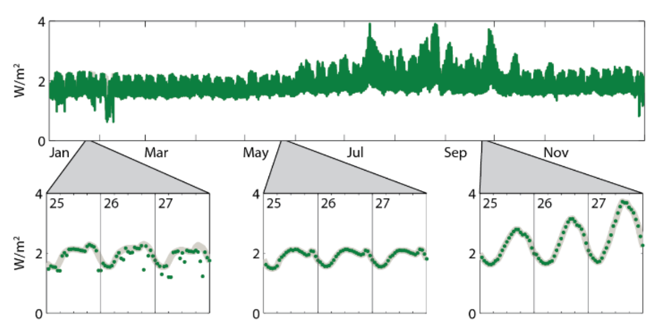

Figure 5: Power output (green) varying to match power demand (grey) during a simulation year. Matches demand over 99% of the time in Daggett Barstow, CA.

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4.2 Comparison of 3 Test Locations

We observe that for each test location, the model system eventually saturates and provides no more power output with increasing power demand. A comparison of these test locations is shown in Table 1. From these results, we see that evaporative energy harvesting has the potential to provide up to 8 W/m^2 of power density along with 81% capacity with appreciable water savings.

Location	<PD> W/m^2	W^{max} W/m^2	CF @ 95% %	ΔE^{min} mmH_2O/day
CA	11791	8.08	66.9	4.62
TX	12541	5.05	80.9	3.32
NY	6292	2.46	64.8	2.05

Table 1: Comparison of Test Locations in CA, TX, & NY.

5 RENEWABLE ENERGY POTENTIAL

Another question of interest is how this model compares to wind and solar technologies. Table 2 compares this evaporative energy harvesting method to two prevalent renewable technologies, wind power and photovoltaic (PV) solar power. Data from this table is extrapolated from DOE technical reports [8-11]. The power density that can be realized by this model is squarely in the range of current renewable energy technologies, with the added benefit of increased capacity factor compared to PV solar and wind.

Clean Energy Technology	W^{peak} W/m^2	W^{gen} W/m^2	CF %
Evaporation	21.5	5.20	> 60
Wind	8.24 [8]	2.90 [9]	30 – 52 [11]
PV Solar	44.9 [8]	8.06 [10]	16 – 30 [11]

Table 2: Comparison of Evaporation Energy Harvesting Results to Wind & PV Solar Systems.

6 CONCLUSION

Evaporation across the contiguous United States can potentially provide power densities higher than current wind power plants and comparable to current solar power plants. The development of water responsive materials allows for the potential to harvest energy from evaporation. This model relates the change in evaporation rate due to work load and generates predictions based on typical weather conditions. This model predicts that harvesting energy from evaporative water flows may be possible and could provide water savings. These results suggest that further research into water responsive materials could result in novel energy harvesting devices.

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