Proceedings of the 10th World Congress on Mechanical, Chemical, and Material Engineering (MCM'24)
Barcelona, Spain –August 22-24, 2024
Paper No. HTFF 273
DOI: 10.11159/htff24.273

Important Parameters for the Characterization of Rain as an Energy Source

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Abstract – Rainfall is an often overlooked source of renewable energy due to its relatively low energy density. However, this does not automatically imply that rain energy has no practical applications. Predicting the power potentially harnessed from rainfall nonetheless requires a basic formulation of its energy content in terms of the simple relevant parameters in a manner that has generally been done for characterizing other renewable energy resources such as solar and wind energy. In this paper, it is shown that the power potential of rainfall is a function of both its kinetic and mechanical potential energy. More specifically, the power contained in rain is proportional to the rate of rainfall, the square of the impact velocity, and the collector height. Additionally, the power output of a rain energy conversion device is proportional to collector area due to the linear relation between rate of rainfall and the volume of rain collected. With a capture device that is able to harness both the kinetic and potential energy in falling rain, the energy potential of a given geographic region can thus be determined. In this paper, a case study on the Amazon Rainforest was conducted for which it was determined that a 10,000 square meter collector at a height of 10 m has an energy potential of approximately 815 kW-hr per year.

Keywords: Renewable energy, Rainfall, Rain Collection, Energy Generation, Alternative Energy

1. Introduction

In climates with significant amounts of rain, the potential exists for harnessing the kinetic and/or potential energy present in the raindrops. Given the small amount of energy contained within rainfall compared to other renewable energy resources, however, rain energy devices are generally less developed than for other renewable energy sources, making large scale production unlikely. Nonetheless, implementation of rain energy can still have numerous practical applications. The focus of this paper is to investigate and characterize rain as a renewable energy source in an effort to enhance the discussion around the topic and further inform potential applications strategies.

Various methods for capturing rain energy currently in development are descried in the literature. These are typically one of two types, those capturing the kinetic energy inherent in rainfall and those that harness the potential energy of rain collected at some height above the ground. As an example of the former, researchers in France have created a piezoelectric device that vibrates when impacted by falling droplets [1]. The vibrational energy is then converted into a small amount of useful power. The system is constructed out of a PVDF (polyvinylidene fluoride) polymer that contains embedded electrodes that can recover up to 12 milliwatts of power from a single large raindrop [1]. According to studies on this system, the amount of energy that can be recovered depends on the size of the piezoelectric membrane, droplet diameter, impact velocity, and the frequency of the rainfall [1-2].

Once a raindrop reaches terminal velocity, the kinetic energy within the drop remains constant since it no longer accelerates. Though the terminal velocity can vary significantly, the literature commonly cites the value to be approximately 9 m/s [3]. Because of this limitation, only a small amount of kinetic energy is available for capture with a reasonable efficiency. Other designs utilizing the gravitational potential energy of collected rain have therefore been proposed.

Carter et. al proposed a such a system in which rainfall is collected at an average height of six metres and then allowed to run down through a microturbine [4]. The system mimics many of the same principles that are seen in hydroelectric power generation Notwithstanding the turbine design, power output for the system was reported to depend on the rainfall intensity [4]. Given that the amount of potential energy in water depends on its height above ground and that turbines tend to have greater efficiencies than piezoelectric devices in nature, the energy capture potential for systems of this sort appear more promising than piezoelectric devices that harness only kinetic energy, especially those in which rainfall can be collected at significant height [4].

Of course, any type of rain energy device will only be useful in a climate with a substantial amount of rainfall. This makes rainforests an ideal candidate for this application. For this paper specifically, the focus will ultimately be directed towards the rain energy potential in the Amazon Rainforest which typically receives somewhere between 1,500 – 3,000 millimetres (59 – 118 inches) of rainfall in a year [5].

2. Rain Energy Characterization

Given the vast differences between finite and renewable energy resources, and the enormous differences between various renewable energy resources themselves, a working knowledge of the basic variables contributing to a potential green energy resource is required before responsible implementation of an energy conversion scheme can be applied. The local nature of renewable energy makes this especially important since periods of a year or longer are often required for energy prospecting before the suitability of a particular site can be accurately assessed [6]. To that end, information akin to that given in Table 1 in which renewable energy sources are characterized in terms of the relevant variables, power relationships, and time variability, are particularly useful. This section aims to characterize rainfall as an energy resource in a similar manner.

Table 1: Characterization of various renewable energy resources (adapted from [6])

Source	Major Periods	Relevant Variables	Power Relationship	Comments
Direct solar	24 hours, 1 year	Direct solar irradiation, G_D; angle of incidence θ	$P \propto G_D(\cos\theta)$	Daytime only
Indirect solar	24 hours, 1 year	Indirect solar irradiation $G_{d,}$ cloud cover	$P << G_d$	Energy still significant
Wind	1 year	Wind speed V_m, turbine hub height above ground z	$P \propto V_m^3$	High fluctuation
Ocean wave	1 year	Significant wave height H_S; wave period T	$P \propto H_S^2 T$	High power densities of ~50 kW/m of wavefront
Ocean tidal range	12.42 hours	Tidal range R; contained area A; estuary length L and depth h	$P \propto R^2 A$	Enhanced tidal range if $L/\sqrt{h} = 36{,}000\ \text{m}^{1/2}$
Ocean tidal current	12.42 hours	Reservoir height H; water volume flow rate Q	$P \propto V_c^3$	Similar to wind
Ocean temperature gradient	Constant	Temperature difference between sea surface and "deep" water ΔT	$P \propto (\Delta T)^2$	Tropical locations have $\Delta T \sim 20°\text{C}$; harnessable with low efficiency
Hydro		Reservoir height H; water volume flow rate Q	$P \propto HQ$	Well established resource

2.1. Rain Energy Types

Three sources of energy can be identified in falling rain. First, kinetic energy is present due to a mass m of rain traveling with a known velocity v. Second, the potential energy of a rain drop at any time during its descent is proportional to its elevation h. Initially, rain falls from high altitudes (> 1000 m) and this potential energy is partially converted into kinetic energy as it falls. However, the rain quickly reaches its terminal velocity due to high air resistance, and the potential energy is irreversibly dissipated. The rain subsequently travels with near constant velocity for the majority of its descent. Finally, rain also represents a potential heat sink given that droplet temperature may be different than that of the ambient. When rain initially forms, it is in the much cooler upper atmosphere. As it falls, the temperature may drop further due to evaporative cooling in altitude zones that are not at fully saturated conditions. Due to the very high surface area to volume ratio for a raindrop, however, droplets rapidly adjust to ambient temperatures. For these reasons, the thermal energy in rain is simply acknowledged as a consideration but not investigated, as any potential temperature differences are small and difficult to assess.

The total energy of falling rain is therefore considered a combination of two mechanical energy sources, kinetic energy and potential energy. These forms of energy relate to the available power output that can be captured and utilized as a green energy source. Characterizing energy sources to determine the parameters that relate to power potential is an important first step in any sort of energy discussion. Therefore, this will be the focus of the next section.

Characterizing the kinetic energy of a single rain drop starts by considering the kinetic energy formula of a particle,

$$E_k = \frac{1}{2} m v^2, \tag{1}$$

where E_k is kinetic energy, m is the mass of a water droplet, and v is the velocity. It is important to note that for this analysis, raindrops are assumed to travel at their terminal velocity so that v is Eq. (1) is a constant. Given that rain reaches terminal velocity quickly after forming high in the atmosphere, this assumption should be valid for a collector device at any reasonable elevation. Piezoelectric devices represent one available technology that has been employed to capture kinetic energy.

The total potential energy of a raindrop can be expressed as

$$E_p = mgh \tag{2}$$

where E_p is the potential energy, g is the acceleration of gravity, and h is the height above ground. Potential energy collected in rainwater can be captured via a number of existing devices akin to those commonly used in hydroelectric facilities.

Since the potential energy in Eq. (2) is proportional to elevation, the advantage of collecting rainwater at as large a value of h as possible is evident. The kinetic energy in Eq. (1), however, does not change so that devices designed to harness kinetic energy are unaffected by collector elevation. Equating Eqs. (1) and (2) and assuming a terminal velocity of 9 m/s shows that at a collection height of h = 4.13 m, the potential energy is the same as the kinetic energy. Thus, a device designed to make use of both forms of mechanical energy has twice the total energy available when a collector is placed at a modest elevation compared to devices harnessing only kinetic energy.

For continuous rainfall, Eq. (1) can be modified to reflect the rate of kinetic energy passing a given horizontal area. Since the kinetic energy per unit mass of rain is $v^2/2$, kinetic energy per unit time is

$$P_k = \frac{1}{2} \dot{m} v^2, \tag{3}$$

where P_k is the power in rain from kinetic energy and $\dot{m}$ is the mass flow rate of rainwater. The corresponding potential energy equation per unit time can be written in a similar fashion as

$$P_p = \dot{m} gh, \tag{4}$$

where P_p is the power in rain from potential energy. Hence the total power from potential and kinetic energy in rainfall with a known mass flow rate $\dot{m}$ is

$$P = \dot{m}\left(\frac{v^2}{2} + gh\right). \tag{5}$$

Equation (5) shows that the power contained in falling rain can be fully characterized by knowing three specifications: the mass flow rate, the impact velocity, and the height of the collector. It is also important to note that although the datum for h in Eq. (5) is assumed to be the ground, the important parameter for an energy conversion device is the elevation difference between the rainwater collection height and the outflow reservoir.

2.2. Effect of Rainfall Intensity

As seen in the last section, the mass flowrate of the rainfall needs to be taken into account in order to fully characterize the power. Several methods are described in the literature to quantify the mass flow of rain falling on various types of surfaces and on land, the latter generally being calculating via storm runoff flow rates. Assuming that the collector has a solid, impermeable surface, however, simplifies the process. Figure 1 shows a schematic diagram of a potential collector with a control volume defined for the analysis.

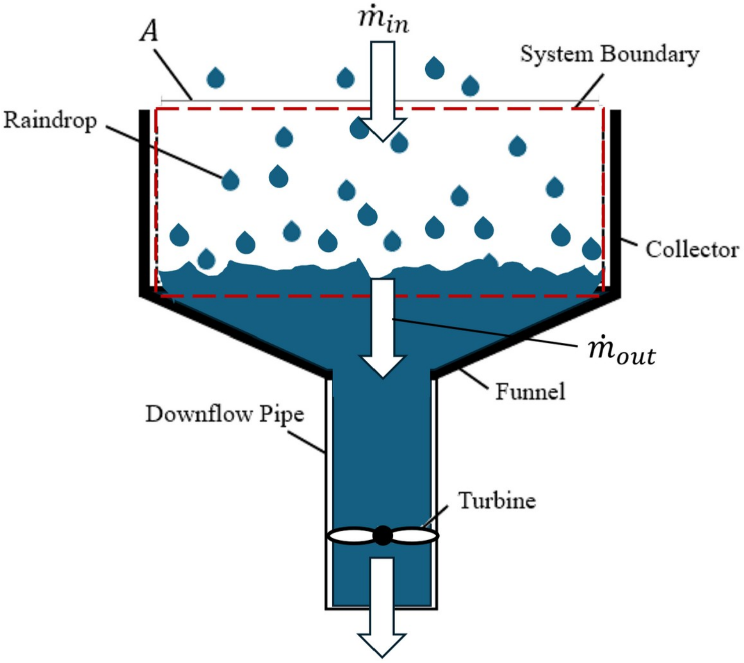

Figure 1: A potential rainfall collector that includes a large collection area, a funnel, downflow pipe, and microturbine. A system boundary is defined where A is the cross-sectional area of the collector, $\dot{m}_{¿}$ is the mass flow rate into the system, and $\dot{m}_{out}$ is the mass flow rate out of the system.

Assuming steady conditions, the application of conservation of mass to this system yields

$$\dot{m}_{¿}=\dot{m}_{out}, \tag{6}$$

where both mass flowrates account for the mass of liquid water only. Hence, the same mass flow of rain entering the system leaves the system and ultimately goes through the turbine. For an incompressible fluid with a flat velocity profile, mass flowrate can be calculated from

$$\dot{m}=\rho vA, \tag{7}$$

where ρ is fluid density, v is fluid velocity, and A is the cross-sectional area. For the purposes here, the fluid velocity in Eq. (7) can be interchanged with rainfall intensity, defined as the height of a volume of rain collected in a rain gage per unit time. Published values are typically reported in units of mm/hr. With this substitution, rainfall mass flowrate is written as

$$\dot{m}=\rho iA, \tag{8}$$

where i is the rainfall intensity. Finally, incorporating this flowrate into Eq. (5) gives the power relationship for rainfall as

$$P=\rho iA\left(\frac{v^2}{2}+gh\right). \tag{9}$$

Equation (9) shows that the power contained in rain is proportional to rainfall intensity, the square of the impact velocity, and the height above ground. Apart from the parameters inherent in rainfall itself, the power output of a rain energy device is also proportional the collector area.

2.3. Variability of the Resource

Rainfall is a resource that depends on a variety of factors. In some geographical locations, rain is abundant throughout most of the year, while other locations may not receive any appreciable rainfall in a given year. Yearly rainfalls can range from less than 2.5 cm to over 1.2 m [7].

In general, the heaviest amount of rainfall occurs close to the equator and decreases towards the poles [8]. Local geographical factors such as the presence of mountains can also play a role. On the windward side of mountains, the amount of rainfall tends to be larger than on the leeward side, and coastal regions typically receive more precipitation than inland regions [8]. Global winds are an additional complicating factor. Furthermore, rainfall can be seasonally dependent, as many locations receive more rainfall during the summer months [9]. With these considerations, the characterization of rain as an energy source is relatively well defined. Table 2 gives the complement to Table 1 for rain as a renewable energy source.

Table 2: Properties of rainfall as an energy source

Source	Major Periods	Major Variables	Power Relationship	Comment
Rain	Annual	Rainfall intensity i; impact velocity V; height h; collector area A	$P \propto iA\left(\frac{V^2}{2}+gh\right)$	Relatively low amounts of energy available, geographically dependent

Table 3 provides generally accepted rainfall classifications based on US Geological Survey standards [10]. Assuming a terminal velocity of 9 m/s, the energy intensity per square meter was estimated for each rainfall type at a height of 0, 10 m, and 50 m. These heights were chosen since they represent reasonable estimates of potential collector heights. This range could reflect the heights of a ground-based collector, a collector on the rooftop of a common building, or a collector on a dedicated tall structure.

Table 3: Rainfall energy intensities using the maximum rainfall rate for each level of classification and assuming that the rainfall terminal velocity of 9 m/s and the density of 997 kg/m^3.

Classification	Rainfall Rate	Maximum Energy Intensity $\left(\frac{J}{hr \cdot m^2}\right)$		
		$h=0\,m$	$h=10\,m$	$h=50\,m$
Slight Rain	¿$0.5\ \frac{mm}{hr}$	20.2	69.1	264.7
Moderate Rain	$0.5-4\ \frac{mm}{hr}$	161.5	552.7	2117.6
Heavy Rain	$4-8\ \frac{mm}{hr}$	323.0	1105.5	4235.3

As is evident from Table 3, rainfall rates can vary significantly from as little as 0.5 mm/hr to more than 8 mm/hr. This influences design of energy collection systems both in terms of energy output, and their design regarding rain flow rates. For example, a turbine might need to be designed to function at anywhere from 6% – 100% of its rated capacity depending on the rainfall intensity.

Finally, in addition to rainfall intensities being highly variable, rainfall drop size is also variable. Common raindrops can range from a vanishingly small \diameter to a maximum diameters on the order of 5 mm. One of the major effects this has on the rain's energy is that the rain drops diameter is closely related to its terminal velocity. As shown in Fig. 3, smaller raindrop diameters can have significantly lower terminal velocities than larger raindrop diameters, which in turn results in smaller total energy content [11].

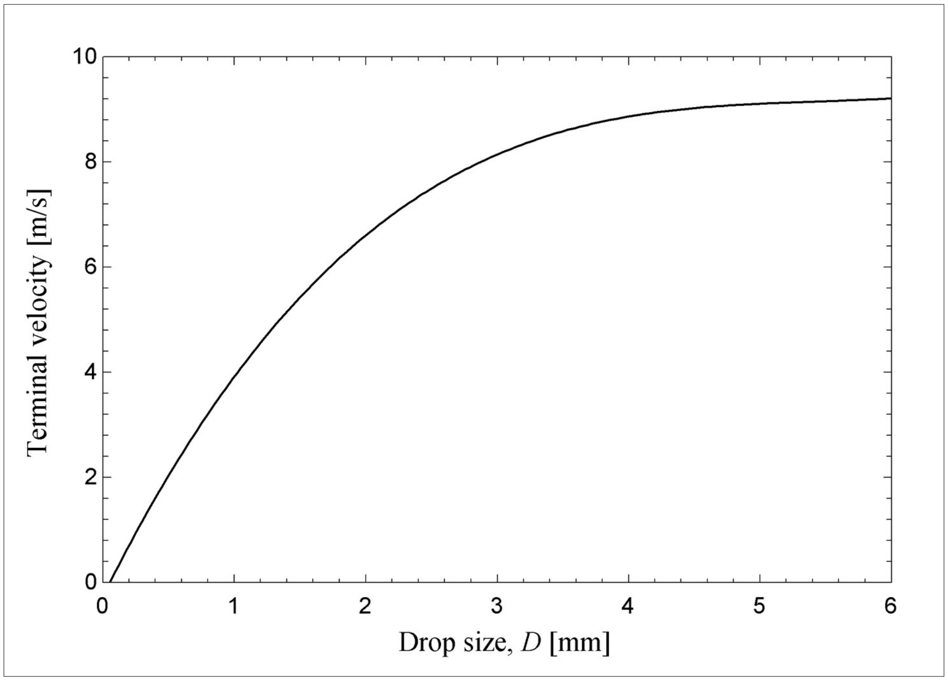

Figure 3: Effect of raindrop size on terminal velocity. Adapted from [11].

The distribution of raindrop size is site specific and challenging to measure. Furthermore, ambient weather such as temperature and wind have significant effects on terminal velocity as well. Because of this, it was chosen to consider the often cited 9 m/s average to be the terminal velocity of raindrops from this study, while recognizing that real world situations would almost certainly vary in power generation potential.

3. Amazon Rainforest Case Study

With the technical background established, a case study on the energy potential of rainfall in the Amazon Rainforest was completed. This location was chosen due its large rainfall rates and the perceived potential for the region to benefit from an additional renewable energy source.

The Amazon Rainforest receives around 1,500 mm to 3,000 mm of rainfall on a yearly basis [5]. Rainfall in the Amazon River Basin follows a yearly pattern, with significant regional variations in precipitation within the basin's centre [12]. Due to these variations, this analysis assumes an annual precipitation rate of 2117 mm/year, which was an average based on a 2005 study [13]. Furthermore, it was decided that it was important to quantify expected power outputs given average precipitation intensities/rates. During rainy periods, the rainfall rate can average from 2-2.5 mm/hr [14]. It should be mentioned that most regions only experience rain 10-20% of the time, so rainfall is not considered a continuous energy source but rather an intermittent one. This analysis also assumes that a combined potential and kinetic energy collector would be located on a rooftop of a large warehouse-type facility. The roof height was estimated to be at a height of 10 m, and the area was assumed to be 10,000 square meters. Further, it was assumed that rain would first strike a piezoelectric-type device, capturing kinetic energy, and then flow off the roof through a turbine-style potential energy collector similar to a hydroelectric dam. Based on these findings and previous mathematical models, the following values shown in Table 4 can be calculated.

Based on these results, it is important to consider the level of impact this energy would create. Assuming 100% conversion efficiency, 815 kW·hr/yr could be collected by this system at most. This amount of energy is very small for such a large are, with more solar energy striking this area in an hour than this device collects in an entire year. This is exacerbated by the fact that high conversion efficiencies are unlikely based on existing technology. However, if implemented in remote areas under unique circumstances, there is the potential to supply a small amount of off-grid energy. Finally, some areas average almost twice as much annual rainfall, with intensities reaching 8 mm/hr or more, which would increase power output to a maximum of almost 4 kW in select locations.

Table 4: Hypothetical rainfall energy analysis in the Amazon Rainforest

Energy Type	Power Output per Unit Area $\left(\frac{W}{m^2}\right)$	Total Power Output (W)	Annual Energy per unit Area $\left(\frac{kW \cdot hr}{m^2}\right)$	Total Annual Energy $(kW \cdot hr)$
Kinetic	0.0281	281	0.0238	238
Potential	0.0681	681	0.0577	577
Total	0.0962	961	0.0815	815

4. Conclusion

Though its energy content is small, the potential for capturing energy from rain exists. The power potential for rain as an energy source includes both its kinetic and potential energies, and is proportional to the rainfall intensity, impact velocity, collector height, and collector area. As a result of the very low energy density relative to other existing technologies such as solar, with energy densities that are serval orders of magnitude larger, rain is unlikely to be a practical option for producing significant amounts of energy for most applications. Nonetheless, if rain energy technology is implemented on a small scale, there could be applications in climates receiving significant amounts of yearly rainfall with large intensity, such as the Amazon Rainforest. The conversion schemes with the best potential for success are those that include the conversion of both kinetic and potential energies.

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