Complex model of AirHES

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The previous articles on AirHES [1][2][3] were aimed at addressing some of the critical problems that arose in the discussion of the project. For example, when writing an article on a feasibility study, I proceeded from known data on fog collection systems, although my subsequent calculations for mesh optimization showed that the effectiveness of meshes can actually be 2-3 times lower than the indicated 50%. Also, in the feasibility study calculations, I was guided by the aerostatic balance of forces, assuming that free hanging the mesh would automatically avoid significant aerodynamic loads, leaving behind the brackets a significant reduction in performance when tilting the mesh. The same problem arises when using blown kites instead of mesh, which must also change the angle of attack or the surface area of the collector to prevent excessive aerodynamic loads. It's time to collect a complex model of AirHES, suitable for parametric optimization.

Initial data and optimization parameters:

1 Estimated lifetime, LT, years

It is estimated at about 10 years according to data for similar devices. For example, in [4] such an estimate is given for fog collection systems, and in [5] for sails of sea vessels. It should be noted that this value is used only for extensive criteria of model and for intensive target functions (for example, for the payback period) is not affected.

2 Average wind speed, Va, m/s

It is estimated based on meteorological data for the estimated altitude and the expected location of the AirHES. For example, according to GOST R 53460 - 2009 [6] (table 149, page 184), the average speed of a scalar wind at an altitude of 2 km in St. Petersburg in the summer is estimated at 2.7 m/s. While the average annual wind speed over Europe in [7] is estimated at 6.8 m/s. At the same time, one can also find an estimate of 10 m/s at an altitude of 2 km, for example, in surveys [8] on wind generation. This velocity is used in simple calculations of the mean annual moisture flux in the clouds or in more complex calculations to determine the Weibull distribution coefficients [9][10][11][12].

3 Maximum wind speed at a fixed angle of attack, Vm, m/s

This is the calculated wind speed at which AirHES must still withstand wind loads at a predetermined angle of attack of its sails with a given margin of safety. Of course, the actual wind speed can significantly exceed this speed, but it is assumed that the loads will be automatically controlled by reducing the angle of attack of the sails or by other methods, as described in [2].

4 Maximum wind speed at a fixed area, Vs, m/s

This is the calculated wind speed at which AirHES should still withstand wind loads at a predetermined area of its sails with a given margin of safety. It is assumed that the wind loads will be controlled by reducing the sail area, or the descent of the entire AirHES.

5 Estimated liquid water content of clouds, LWC, g/m3

It is estimated on the basis of weather data for the lower cloud layer, suitable for AirHES. For example, in [13] for different types of clouds the range 0.25-0.45 g/m3 is indicated. If one is guided by data for stratus clouds, then in [14] an estimate of 0.28-0.30 g/m3 is given. On the other hand, it is well-known that the water content of the cloud increases significantly from the base of the clouds. This can be estimated from the graphs of water content in the section of the cloud in [15] (pages 7-8), which show that the maximum water content is reached approximately at an altitude of 1 km from the base of cumulus clouds and is ~ 1 g/m3. Since AirHES can choose the optimum height for receiving moisture, the distribution of water content can also be used to optimize the height.

6 Cloud cover factor, CCF, %

It is estimated on the basis of meteorological data for the lower cloud layer. Approximately correlates with the level of precipitation. In general, over the planet it is 67% [16]. For a proper territory can be obtained from NASA satellite data [17].

7 Area of meshes or sails for receiving moisture, S, m2

It is the calculated value of the surfaces for the intake of moisture. Determines the performance of AirHES. It is chosen taking into account the design demand for water and electricity.

8 Initial angle of attack, Avm, deg

The design parameter, which determines the initially fixed angle of inclination to the horizon of the meshes or sails of the AirHES. When the maximum design wind speed ***Vm*** is reached, this angle will automatically decrease to reduce wind loads under the conditions of providing the estimated strength of the rigging.

On the one hand, this parameter determines the water productivity, corresponding to the wind projection of the sails, on the other hand it determines the aerodynamic lift corresponding to this wind force and the total balance of forces, i.e., determines the aerodynamic quality [18] and the basic geometric angle of blow-by in kite design of AirHES. Usually for kites it is ~ 15 degrees.

9 Coefficient of drag Cx

Cx is mainly a function of the properties of the material (the permeability of the mesh or the sail) and the angle of attack. This factor allows you to calculate the horizontal force exerted on the mesh or sail by the wind pressure. A constant value for a given material can be used if the angle of attack is fixed. At small angles of attack a, one can use the approximation $Cx \sim Cx0 + Kx * a^2$, where ***Cx0*** depends on the aspect ratio, and ***Kx*** is calculated from the given value of ***Cx*** for a given angle of attack (see [2][19]). For the proposed design [20] of AirHES sails, we can use the ***Cx0*** value from 0.0066 (for a flat elongated plate) to 0.025 (CFD calculation).

Here we must point that the ***Cx*** values obtained in [3] in the case of two-dimensional CFD modeling are purely evaluative, since they do not take into account the longitudinal (vertical) structures of the mesh or the sail fabric. In particular, this is evident from the fact that ***Cx*** for a double mesh remains practically constant up to very small angles of attack, since the mesh elements almost do not overlap each other in the wind projection.

10 Coefficient of lift Cy

Cy is also a function of the properties of the material (the permeability of the mesh or the sail) and the angle of attack. This factor allows you to calculate the vertical lift force generated by the wind pressure. A constant value for a given material can be used if the angle of attack is fixed. At small attack angles ***a***, one can use the linear approximation ***Cy ~ Ky*a***, where ***Ky*** is calculated from the given ***Cy*** value for a given angle of attack.

As stated above, the ***Cy*** values obtained in 2D CFD modeling are purely evaluative, since they do not take into account the longitudinal (vertical) structures of the mesh or the sail fabric. In particular, this is clear from the fact that ***Cy*** for a double mesh does not have asymptotic stability up to very small angles of attack (ie, it should practically be taken as zero). Thus, in-situ measurements and further studies are needed to refine all aerodynamic characteristics.

11 Efficiency of the mesh or sail to receive moisture, X, %

This is the most important parameter that shows how much of the atmospheric droplet moisture settles on the receiving surfaces of the AirHES in the corresponding wind projection. It is also a function of the material properties (the permeability of the mesh or the sail) and the angle of attack, since the efficiency is calculated not by the total area of the mesh or sail, but only by the area of the wind projection. According to data from the high-mountain fog collection systems, this efficiency can reach 50-70%, although the integrated efficiency usually does not exceed 25%. In my laboratory experiments, I also received a value of up to 50%. My CFD calculations for conventional fog collection systems with perpendicular double-mesh flow also show values of ~ 20%. For sail of kites, these values can be significantly higher at the appropriate angles of attack ~ 15 degrees, but it should be remembered that the wind projection of such a kite is only about 26% of its area.

As mentioned above for the aerodynamic coefficients ***Cx*** and ***Cy***, the ***X*** values obtained in the two-dimensional CFD simulation are purely evaluative, since they do not take into account the longitudinal (vertical) structures of the mesh or the sail fabric.

12 Specific weight of mesh or sail, CSW, kg/m2

13 Specific price of material of mesh or sail, CSP, $/m2

14 Coefficient of weighting of mesh or sail, CWF

Specifies the weighting of the mesh or sail material due to the accumulation of moisture, as well as additional rigging and drainage. Used for calculating the weight of the mesh or sail, and also affects the angle of attack with free hanging the mesh. Usually it is assumed ~ 2 and above.

Generally speaking, the model of AirHES can contain several different types of surfaces for both moisture intake and aerodynamic support - then, for each type of surfaces, points 7-14 must be repeated with their values.

15 Length of hose/rope (maximum head), L, m

This is the very important parameter that determines the maximum lift height of the AirHES, and also significantly affects its cost. It must correlate with the corresponding meteo data for the lower cloud layer at a given location. Theoretically, for maximum water and energy productivity, it must ensure that the receiving surfaces are elevated to the maximum water content of the cloud (0.5 to 1 km above the cloud base), taking into account wind drift for all suitable weather conditions. Taking into account that the height of the cloud base can vary greatly, being a function of temperature and the dew point (Ferrel formula [21]), the choice of ***L*** is an additional optimization problem.

16 Hydraulic losses in the hose, HL, %

An important optimization parameter when using AirHES for power generation. It allows to find a balance between the efficiency of AirHES and the weight of water in the hose. Usually it is assumed ~ 10%. (To this, in calculating the efficiency of the AirHES, losses in the turbogenerator are added, which depend on many factors, but usually also amount to ~ 10%.) For the production of water only, this parameter is assumed to be 100%, i.e., the water loses all its potential energy in Hose, moving with the maximum possible speed for this flow, ensuring a minimum weight of water in the hose.

17 Hydraulic loss factor (Darcy friction factor) in the hose, DFF

If we do not use specialized algorithms for hydraulic calculations [22] and limit ourselves to the Darcy-Weisbach formula [23], the best match for a plastic smooth hose is obtained at a coefficient of ~ 0.00762 (unless special hydrophobic coatings are used).

18 Hydraulic margin of safety, HMS

This is the margin of safety that is used in calculating the wall thickness of the hose from Dyneema under hydrostatic pressure at the lowest (most stressed) point at the maximum possible hydraulic head (which is determined by the length of hose in the vertical position). The estimated safety margin is ~ 5.

19 Aerodynamic margin of safety, AMS

This is the margin of safety that is used to calculate the wall thickness of the hose from the Dyneema (or the total cross-section of the ropes and hose) under the longitudinal stress of the total weight, aerostatic and aerodynamic forces at the top point (most stressed) of attachment of this hose (or ropes and Hose). The basis is the safety factor used in aircraft construction, which is usually 1.5 [24]. For AirHES it is recommended to take this value ~ 2.

20 Balloon Volume factor, BVF

This parameter specifies an excessive aerostatic lift (buoyancy) as compared to the aerostatic balance at which it is 1. Excess aerostatic force can be used to optimize the aerodynamic lift to ensure the required height of the intake of moisture and optimize the head and power of the AirHES.

21 Coefficient of drag for aerostat, Cax

For an ideal aerostat, this value is ~ 0.03, for a real ~ 0.06-0.08. Usually, the drag of the balloon is negligible compared to meshes or sails and, in the first approximation, may not be taken into account in engineering calculations.

22 Specific price of Dyneema, DSP, $/кг

One of the most important parameters, since the cost of the hose and ropes from Dyneema is usually several times higher than the cost of the remaining elements of the AirHES. The price of the raw material (polyethylene), from which Dyneema is made, is usually ~ $1/kg, while the price of Dyneema is ~ $100/kg (minimum ~ $50/kg). A reduction of up to ~ $10/kg could significantly improve the feasibility performance of AirHES, which seems quite achievable in mass production.

The general ideology of optimization of AirHES

The main idea of AirHES is to get water and hydro power anywhere from drip clouds, using fog collection technology. Accordingly, the main task and problem is how to keep the surfaces collecting cloudy moisture (meshes or blown fabrics) at the required height with real wind loads up to the hurricane winds.

Three main directions of the solution of this problem were considered:

1) Freely hanging meshes that will automatically deviate when the wind load increases, with the proper aerostatic hold.
2) Blown fabric sails (kites) that will automatically or controllably change the angle of attack for sustained aerodynamic hold.
3) Controlled change in active aerodynamic area of meshes or sails.

Obviously, with different initial data, we can optimize either of these schemes, or a combination of them. Thus, the complex model should describe all possible variants and combinations of design solutions, and the optimization calculation should simply automatically find the necessary design solutions and optimized parameters for the specified optimization criterion for the given initial data.

The ideology of such optimization is to maximize the positive results and minimize the adverse negative factors as much as possible. The main positive result of the work of AirHES is the receipt of water and, related to it, hydro power. The main negative is the cost under the given operating conditions.

Thus, the optimal AirHES should provide the maximum flow of water at a minimum cost. Calculations show that whatever type of AirHES we have not considered, the main costs are the cost of the hose and ropes from Dyneema at the current market value for this material. In turn, these costs are determined by those horizontal wind loads that affect the meshes and sails of the AirHES, since vertical aerodynamic or aerostatic forces should be correlated with them to maintain the required height of the collection of moisture from the clouds.

So, it comes down to the following basic ratio:

Criterion of optimality $\sim (LWC*CCF*Va*S*\sin(a)*X)/(Cx*S*\rho*Va^2/2) \sim X*\sin(a)/Cx/Va$

It demonstrates the obvious conclusions that the surfaces of the AirHES should have the maximum efficiency of collecting moisture in the wind projection at the minimum drag, and that the relative profitability of AirHES increases with the decrease in the average wind speed (for example, it corresponds to the conditions of the equatorial zone).

Consider, for example, how this optimality criterion for materials calculated in CFD modeling changes (see the appendix in [3]).

Va, m/s	a, o	Cx	X, %	X*sin(a)/Cx/Va
CFD calculations for a double-layered Raschel mesh				
5.000	15.0	0.364	46.200	**6.570**
10.000	15.0	0.320	84.600	**6.843**
15.000	15.0	0.424	76.500	**3.113**
20.000	15.0	0.346	83.800	**3.134**
5.000	30.0	0.671	22.700	**3.383**
10.000	30.0	0.600	25.300	**2.108**
15.000	30.0	0.511	33.600	**2.192**
20.000	30.0	0.531	36.400	**1.714**
5.000	45.0	0.731	29.000	**5.610**
10.000	45.0	0.698	39.900	**4.042**
15.000	45.0	0.551	47.100	**4.030**
20.000	45.0	0.609	47.400	**2.752**
5.000	60.0	0.767	11.200	**2.529**
10.000	60.0	0.687	15.400	**1.941**
15.000	60.0	0.687	19.000	**1.597**
20.000	60.0	0.566	21.200	**1.622**
5.000	75.0	0.715	7.000	**1.891**
10.000	75.0	0.694	9.900	**1.378**
15.000	75.0	0.665	9.900	**0.959**
20.000	75.0	0.593	10.100	**0.823**
5.000	90.0	0.784	17.300	**4.413**
10.000	90.0	0.745	26.000	**3.490**
15.000	90.0	0.682	28.900	**2.825**
20.000	90.0	0.540	28.400	**2.630**
CFD calculations for a single-layered Raschel mesh				
8.000	5.0	0.136	18.100	**1.450**
8.000	10.0	0.160	46.000	**6.240**
8.000	15.0	0.186	58.900	**10.245**
8.000	30.0	0.290	18.700	**4.030**
8.000	45.0	0.317	13.600	**3.792**
8.000	60.0	0.328	10.200	**3.366**
8.000	75.0	0.371	9.900	**3.222**
8.000	90.0	0.351	8.900	**3.170**
CFD calculations of permeable kite fabric (sail)				
8.000	1.0	0.030	46.000	**3.345**
8.000	2.0	0.047	48.100	**4.465**
8.000	3.0	0.059	44.500	**4.934**
8.000	4.0	0.075	44.800	**5.208**
8.000	5.0	0.093	43.700	**5.119**
8.000	10.0	0.183	39.200	**4.650**
8.000	15.0	0.315	37.800	**3.882**

In reality, many different conflicting factors influence the optimization of AirHES, so this criterion only shows the main trend that must be taken into account when designing. More complex technical and economic calculations, which will be discussed in the next section, show that the problem of optimizing AirHES can not be reduced to one simple formula.

Algorithm for calculating the complex model of AirHES

This algorithm is based on previous numerical calculations of individual AirHES systems and assumes that for the optimization problem one can confine ourselves to engineering approximations of the exact calculations made earlier. This allows to conduct targeted feasibility studies in the usual form of spreadsheets (where engineering calculations are fulfilled in macros) or to optimize the AirHES variants by using the Java/C class.

1 Calculation of water productivity

The simplest version of the calculation assumes that the mesh or sail set at the specified initial angle of attack ***a = Avm***, basically work in this geometry, ie, the wind projection is calculated simply as ***S*sin(a)***, and the corresponding water flow is calculated as ***LWC*CCF*Va*S*sin(a)*X***. In fact, this gives an overvalued flow of water, since the decrease in the wind projection is not taken into account when the angle of attack or area is changed to adapt to wind forces with velocities greater than ***Vm*** or ***Vs***.

We assume that the velocity distribution of the wind velocity obeys the Weibull distribution with the mean value of the parameter ***k*** = 2 (the Rayleigh distribution):

$$f(v) = 2 * v / c^2 * \exp[- (v/c)^2]$$

where the parameter ***c = 1.13*Va*** is determined from the average velocity.

Thus, in order to solve this problem correctly, we must first solve the problem of finding the angle of attack ***a*** for each given velocity ***v*** for a given method of securing the mesh or sail, then find the corresponding efficiency ***X*** and the water flow, and then sum (or integrate) these values by indicated probability density.

To do this, we must first approximate the dependencies ***Cx***, ***Cy***, ***X*** for our possible meshes and sails based on CFD calculations. In the first approximation, we confine ourselves to piecewise linear dependences only on the angle of attack.

(1) **Rmesh1:** ***CFD calculations for a single-layered Raschel mesh***
Cx = 0.00626*a + 0.0991 [< 30º, R^2 = 0.993] ***Cx = 0.00117*a + 0.261*** [> 30º, R^2 = 0.797]
Cy = 0
X = -0.406*a + 39.8 [R^2 = 0.464]

(2) **Rmesh2:** ***CFD calculations for a double-layered Raschel mesh***
Cx = 0.0143*a + 0.149 [< 30º, R^2 = 0.810] ***Cx = 0.00159*a + 0.556*** [> 30º, R^2 = 0.175]
Cy = 0
X = -0.615*a + 64.7 [R^2 = 0.511]

(3) **Kmesh:** ***CFD calculations of permeable kite fabric (sail)***
Cx = 0.0201*a + 0.0 [< 30º, R^2 = 0.988]
Cy = 0.0350*a + 0.0207 [< 30º, R^2 = 0.993]
X = -0.695*a + 47.4 [R^2 = 0.903]

The first version of the calculation assumes that the mesh is used in the free hanging mode (which is set by zero velocity Vm). Then the angle of deflection of the mesh at a given wind speed is determined by the tangent of the attack angle according to ratio of the mesh weight (taking into account the weighting coefficient CWF) to the drag force:

$$TAN(a) = S*CSW*CWF*g\,/\,(Cx*S*\rho*v^2/2) = CSW*CWF*g\,/\,(Cx*\rho*v^2/2)$$

The second version of the calculation assumes that the initial angle of attack is constant and is equal to the predetermined up to speed Vm, and then the attack angle a is calculated from the condition that the resultant of the aerodynamic forces is maintained constant in absolute value at further increasing the wind speed v:

$$c*S*\rho*v^2/2 = C*S*\rho*Vm^2/2 \rightarrow c*v^2 = C*Vm^2, \text{ где } C = \sqrt{(Cx^2+Cy^2)}$$

The third variant of the calculation (which can also be combined with the first or second variant of the calculation) assumes that the given area S is constant only up to the velocity Vs, and then the aerodynamic area s of the active surfaces decreases so that the resultant of the aerodynamic forces is maintained constant in modulus at further increasing the wind speed v:

$$C*s*\rho*v^2/2 = C*S*\rho*Vs^2/2 \rightarrow s*v^2 = S*Vs^2$$

In any variant, the effectiveness of X and the flow of water are calculated from the angles of attack found for a given wind speed, and then is integrated by the Rayleigh distribution.

In parallel, the maximum aerodynamic loads are calculated at the maximum design wind speed Vf, which will then be used to calculate the balance of forces. In the general case, Cx is not equal to zero, even at zero angle of attack, that is, there may be a wind speed that will destroy the design of AirHES, despite the proposed automatic control measures. In particular, when calculating wind turbines such an extreme speed is usually taken equal to 5 times the average speed Va, which roughly corresponds to the probability once for 50 years of observations.

Calculations show that at such hurricane wind speeds (~ 50 m/s) only the third option is possible - controlled reduction of the active area of the aerodynamic surface of the mesh or the sail (up to zero). In fact, this means that the meshes or sails should either be folded (similar to the automatic sail systems of modern yachts), or individual sails must be landed down in succession closer to the ground, or the entire AirHES must be descended to the ground in case of critical wind loads exceeding a given level.

Formally, we will assume that the third version of the calculation will be used if $Vs < 0$, otherwise we will assume that $Vs > 0$ simply sets the maximum wind speed at which AirHES is descended entirely to prevent its destruction without regulation.

Based on the results of the calculation of water productivity for a given value of hydraulic losses, one can calculate from the Darcy-Weisbach formula the required internal diameter of the hose and the speed of water in it:

$$HL = (DFF/D)*Vw^2/2/g = (DFF/D)*[Q/(\pi*D^2/4)]^2/2/g$$

And then one can calculate the thickness of the hose dh, required for a given water pressure at the bottom part of hose.

2 Calculation of the balance of forces

Calculation of the balance of power is built for the most stressful point - the place of fixing the hose and ropes to the flight part of the AirHES. At this point, aerostatic lifting forces from the balloon ***T0y***, aerodynamic forces on the balloon ***Tax/Tay***, aerodynamic forces on the supporting kite or glider ***Tkx/Tky***, aerodynamic forces on the water intake meshes or sails ***Tcx/Tcy***, and weights of all elements, including the weight of the balloon shell ***Ws***, weight of kite/glider ***Wk***, weight of mesh or sail ***Wc***, weight of hose/ropes ***Wh*** and weight of water in hose ***Ww***. In the absence of wind, the aerostatic lift with allowance for the redundancy factor ***BVF*** can be written as:

$$T0y = (Ws + Wk + Wc + Ww + Wh) * BVF * g$$

Then the total force on the side of the flight part ***Tm*** will be geometrically composed of:

$$Tm^2 = (T0y + Tay + Tky + Tcy - g*Wk - g*Wc - g*Ws)^2 + (Tax + Tkx + Tcx)^2$$

Preliminary calculations show that normally the aerodynamic forces of ***Tax/Tay*** acting on the balloon are three orders of magnitude smaller than the other forces, and they can be neglected in the engineering approximation. Similarly, the weight of the balloon shell ***Ws*** can be neglected, since for sufficiently large AirHES this gives an error only ~ 1%.

Considering that the thickness of the hose wall ***da*** of diameter ***D*** (or, in general, the total section of the wall of the hose and ropes) with density ***ρ*** and the specific strength of ***YS*** is directly determined by the tangential force ***Tm*** at the most stressed point, we find that the weight of the hose/ropes ***Wh*** can be expressed directly through this force at a given aerodynamic margin of strength ***AMS***:

$$da = AMS*Tm/(\pi*D*YS) \rightarrow Wh = \pi*D*da*L*\rho = AMS*\rho*L*Tm/YS$$

Combining these three equations, we obtain the standard quadratic equation for ***T0y***, solving it and using the maximum value of the root (since our task is to raise the AirHES as high as possible), we obtain the maximum load value ***Tm*** at the given maximum of the design wind speed ***Vf*** obtained in the calculation of the water productivity.

Here, in fact, there is the main contradiction: maximizing the productivity of AirHES involves working in the region of average wind speed ***Va***, and calculation of its strength elements, which determines its cost, has to be done for wind speed ***Vf***, which is 5 times greater (ie, creates loads of 25 times the operational ones) and at which the AirHES actually operates only once for 50 years.

Based on the results of this initial calculation, the final calculation of aerostatic balance is carried out, all weight loads are summed up, the volume of the balloon and the conventional weight of its shell are calculated, as well as its aerodynamic loads, after which the final value of the maximum force ***T*** is calculated and the error level of the initial calculation ***Err*** is determined.

Finally, by the slope of the maximum force vector ***T*** we can calculate the conditional head and power of the AirHES. In fact, both the head and the power vary with different wind speeds and must also integrate over the Weibull distribution. In addition, as shown in [2], the hose in the region of low velocities deviates quite strongly from the line of the force vector. However, for calculation in the range of values of the maximum force ***T*** these deviations do not exceed the level of engineering accuracy of 10% and are not taken into account in this model.

3 Calculation of economic indicators

When calculating economic indicators, the values of the main elements of the AirHES are calculated and added up:

1. mesh or sail of the cloud collector, $S*CSP$
2. sail of a supporting kite or glider, $Sk*KSP$
3. hose and ropes from Dyneema, $Wh*DSP$
4. shell of the balloon according to the conventional radius of the ball of the same volume, $4*\pi*BR^2*SSP$

The total cost of materials is multiplied by the MWF appreciation factor, which is related to the costs for the process of production of AirHES. Usually, **for mass production** (on average, for the cost of goods of industry), this coefficient is approximately equal to two (this can be estimated approximately by cost analysis, for example, for computers or cars). The production of AirHES in terms of the specifics of the work is closest to the garment industry. According to expert estimates of economists and technologists working in the field of pricing in the garment industry, in the cost of products 2/3 or more is the cost of the material, i.e. this coefficient of MWF in the garment industry is ~ 1.5. Thus, if we are considering the mass production of devices based on the AirHES technology (for example, for obtaining water in hard-to-reach areas), then the $MWF=2$ estimate is fully justified and even very conservative, given that the most expensive element of the AirHES (hose from Dyneema) is practically does not need additional man-hours.

In the case of using AirHES for the production of electricity, the cost of the turbogenerator is added to these costs, the price of which is conditionally estimated at twice the price of the electric motor of the corresponding power in kW - this is given by the following approximation on the basis of the analysis of the price range of electric motors: $\sim 225.16731*P^{0.6924}$

Finally, hydrogen for filling the balloon is also included in the primary costs $BV*\rho*HSP$, where $\rho=0.1\ kg/m3$ is the hydrogen density.

The full cost of AirHES, the unit cost per kW (if there is electricity generation), and the conditional cost of water (i.e., the ratio of total cost to total water production for the entire lifetime of the installation, $/m3) and the conditional cost of electricity (i.e. the ratio of total cost to total electricity output for the entire lifetime of the installation, $/kWh). The conditional nature of these indicators arises from the fact that AirHES produces two kind of goods (or even three, if hydrogen is included) and there is no possibility to distribute costs separately for water and electricity. Nevertheless, it is possible to take into account the world average cost of fresh water and electricity in order to calculate the total revenue for water, electricity, and total revenue for the estimated lifetime of the installation.

This allows us to derive the final economic criteria for investing and optimizing AirHES. The most important such criterion is ROI - return on investment, ie, what percentage of the return for each dollar invested is expected to be received from the AirHES during the lifetime of the installation. Even more informative is provided by the payback period, i.e., the time for which the investor will fully return his money and be able to receive a net profit. This parameter does not depend on the expected lifetime and other additive parameters, so this is the best candidate for the target optimization criterion - that is, the design of the AirHES that will ensure the minimum payback period (the maximum speed of capital turnover) can be considered as the most profitable (in given technical constraints, of course). It is also allow easy to compare this with other alternatives for investment in energy and water supply.

Optimization of the complex model of AirHES

The engineering mathematical model of the AirHES, implemented in the form of a Java/C class, includes a large number of preset parameters that can be adjusted, for example, to the corresponding weather data, either to the required performance, or to appropriate material properties estimates. Most of these parameters have predefined values corresponding to average estimates, but they can be adjusted at your discretion.

Since it was not possible to predict in advance the constructive preferences and their influence on the objective function, the following nine parameters were singled out for complex optimization:

```
int    CCT = 3;            // * Cloud collector type: Rmesh [1/2] or Kmesh[3], CCT [1,2,3]
double Vm = 10;            // * Max possible wind speed with fixed attack angle, Vm, m/s [0...50]
double Vs = 20;            // * Max possible wind speed with fixed collection area, Vs, m/s [-50...50]
double Avm = 15;           // * Initial fixed attack Angle, Avm, degrees [0...90]
double CWF = 2;            // * Cloud collector weight factor, CWF [1...10]
double L = 2000;           // * Length of hose (max altitude and head), L, m [1500...3000]
double HL = 100;           // * Head loss in hose, HL, % [0...100]
double BVF = 1;            // * Balloon Volume factor, BVF [1...10]
double Sk = 0;             // * Area of supporting kite, Sk, m2 [0...S]
```

The simplest method of optimization (the Monte Carlo method) with a gradual narrowing of the parameter range allows you to quickly check all possible constructive solutions and determine the most promising sets of parameters, for example, using the following code in Java:

```
double Kmin = 100;
for(int i=0; i<1000000000; i++)
{
        airhes.CCT = getRndInt(1,3);
        airhes.Vm = getRndInt(-50,50); if(airhes.Vm < 0) airhes.Vm = 0;
                if(airhes.Vm == 0 && airhes.CCT == 3) continue;
        airhes.Vs = getRndInt(-50,50); if(airhes.Vs == 0) airhes.Vs = airhes.Vm;
        airhes.Avm = airhes.CCT==3?getRndInt(0,30):getRndInt(0,90);
                if(airhes.Vm == 0) airhes.Avm = 90;
        airhes.CWF = getRndInt(20,100)/10.;
        airhes.L = getRndInt(1500,3500);
        airhes.HL = getRndInt(0,110); if(airhes.HL > 100) airhes.HL = 100;
        airhes.BVF = getRndInt(10,100)/10.;
        airhes.Sk = getRndInt(0,airhes.S);

        airhes.AirHES_calc();
        if(airhes.H < airhes.Hmin) continue;
        if(airhes.PB < Kmin) Kmin = airhes.PB;
}
```

In this code, a random set of parameters from the specified ranges is first checked for model constraints, then a calculation is made for the class instance, it is additionally verified that the elevation height of the AirHES exceeds the specified threshold ***Hmin***, and when the next minimum of the objective function (payback period) is reached, these parameters are stored. Several iterations with the compression of the desired parameter range make it possible to quickly find the necessary design solutions and the values of the optimal parameters.

The table shows examples of such optimization calculations for ***S=1 km2***, where:

1. full optimization, which gives a minimum payback period and uses both adjustment mechanisms (both for the angle of attack and for the area of the mesh)
2. uses freely hanging meshes and adjusts the mesh area
3. uses freely hanging meshes and the descent of the AirHES entirely
4. uses the adjustment for the angle of attack and the descent of the AirHES entirely
5. uses the angle adjustment, without descent to 50 m/s
6. uses freely hanging meshes, without descent to 50 m/s
7. uses a fixed angle of attack without adjustment, and descent at 12 m/s

8. uses a fixed angle of attack without adjustment, and descent at 15 m/s
9. uses a fixed angle of attack without adjustment, and descent at 20 m/s

	1	2	3	4	5	6	7	8	9
Cloud collector (Rmesh[1/2] or Kmesh[3]) type, CCT	1.00	1.00	1.00	1.00	3.00	1.00	1.00	1.00	1.00
Possible Lifetime, LT, yrs	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Average wind speed (base mode for calculation), Va, m/s	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Max possible wind speed with fixed attack angle, Vm, m/s	25.00	0.00	0.00	9.00	9.00	0.00	12.00	15.00	20.00
Max possible wind speed with fixed collection area, Vs, m/s	-6.00	-8.00	11.00	14.00	50.00	50.00	12.00	15.00	20.00
LWC, g/m3	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Cloud capacity factor, % [CCF]	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00
Collection area, m2 [S]	1000000.00	1000000.00	1000000.00	1000000.00	1000000.00	1000000.00	1000000.00	1000000.00	1000000.00
Attack angle, deg [a]	40.00	90.00	90.00	38.00	26.00	90.00	28.00	42.00	38.00
-> Cx = f(a,v) for this Cloud collector by CFD	0.31	0.37	0.37	0.31	0.52	0.37	0.27	0.31	0.31
-> Cy = f(a,v) for this Cloud collector by CFD	0.00	0.00	0.00	0.00	0.93	0.00	0.00	0.00	0.00
-> Efficiency X = f(a,v) for this Cloud collector by CFD, %	23.56	3.26	3.26	24.37	29.33	3.26	28.43	22.75	24.37
-> Cloud collector specific weight, CSW, kg/m2	0.05	0.05	0.05	0.05	0.04	0.05	0.05	0.05	0.05
-> Cloud collector specific price, CSP, $/m2	0.25	0.25	0.25	0.25	1.00	0.25	0.25	0.25	0.25
Cloud collector weight factor [CWF]	2.00	9.50	6.10	4.80	9.10	9.90	8.60	2.90	4.60
Length of hose (max altitude and head), L, m	2312.00	2272.00	2350.00	2009.00	1655.00	2329.00	2291.00	2249.00	2273.00
Head loss in hose, HL, %	1.00	3.00	2.00	7.00	7.00	2.00	1.00	2.00	1.00
Hydrostatic margin of safety [HMS]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Aerodynamic margin of safety [AMS]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Balloon Volume factor [BVF]	1.90	1.30	2.80	4.90	1.20	8.60	3.20	8.00	7.80
Balloon Cax	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Rope/hose specific price, DSP, $/kg	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Area of supporting kite, m2 [Sk]	1281.00	8425.00	21737.00	140.00	12992.00	87203.00	36579.00	44920.00	98091.00
Attack angle of supporting kite, deg [ak]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
-> Ckx = f(a,v) for supporting kite by CFD	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
-> Cky = f(a,v) for supporting kite by CFD	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Kite fabric specific weight, KSW, kg/m2	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Kite fabric specific price, KSP, $/m2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Flow by real wind speed, m3/h	293.21	438.56	363.87	517.95	650.05	722.16	498.35	785.40	993.54
Diameter with this % head loss, mm	211.03	199.00	200.28	179.54	196.62	263.46	260.91	272.46	343.83
Flow velocity, m/s	2.33	3.92	3.21	5.69	5.95	3.68	2.59	3.74	2.97
Water weight in hose, kg	80865.81	70666.66	74036.34	50863.53	50251.27	126968.39	122485.59	131123.86	211047.74
The calculated wall thickness at HMS, mm	4.98	4.62	4.80	3.68	3.32	6.26	6.10	6.26	7.98
Weight of Cloud collector with drops at CWF, Wc, kg	100000.00	475000.00	305000.00	240000.00	364000.00	495000.00	430000.00	145000.00	230000.00
Weight of supporting kite, Wk, kg	51.24	337.00	869.48	5.60	519.68	3488.12	1463.16	1796.80	3923.64
Tmax, N	5039254.91	10168175.31	14599162.75	18261672.71	82506910.38	187278913.57	25267568.82	45367575.55	79837306.94
The calculated wall thickness at AMS, mm	6.34	13.56	19.35	26.99	111.37	188.65	25.70	44.19	61.62
Hose weight (Dyneema), kg	9422.49	18674.19	27732.33	29655.89	110433.30	352752.50	46816.64	82517.63	146763.16
Load weight, kg	190339.54	564677.85	407638.14	320525.02	525204.25	978209.01	600765.40	360438.29	591734.54
Balloon Volume at BVF, m3	401827.93	815645.78	1268207.56	1745080.67	700272.33	9347330.52	2136054.74	3203895.93	5128366.01
The calculated radius of balloon (by aerostatic balance), m	45.78	57.96	67.15	74.69	55.09	130.68	79.89	91.45	106.98
Balloon shell weight (155 g/m2), kg	4081.72	6543.61	8782.33	10864.92	5911.00	33261.45	12432.48	16290.53	22291.31
T, N	5422489.52	10895973.20	15331791.43	19467699.39	83196940.70	194145848.68	26557750.13	47367236.45	83089064.18
% of error for aerostatic balance	7.07	6.68	4.78	6.20	0.83	3.54	4.86	4.22	3.91
Head, m	1501.29	1509.91	1508.34	1511.67	1571.11	1509.83	1516.20	1505.36	1508.51
Power with efficiency 90% +% of head loss in hose , kW	**1067.69**	**1573.68**	**1317.76**	**1784.01**	**2327.02**	**2617.89**	**1832.70**	**2838.72**	**3635.25**
Total Cost, $	2774121.84	4949629.59	7096563.80	7764734.14	24739863.13	77238482.62	11526685.10	19381307.30	33541623.90
Specific Cost, $/kW	2598.24	3145.25	5385.33	4352.41	10631.55	29504.04	6289.47	6827.49	9226.78
Prime cost (only for water), $/m3	**0.11**	**0.13**	**0.22**	**0.17**	**0.43**	**1.22**	**0.26**	**0.28**	**0.39**
Prime cost (only for electricity), $/kWh	0.03	0.04	0.06	0.05	0.12	0.34	0.07	0.08	0.11
Water (income for LT, tariff $1/m3), $K	25685.30	38417.72	31874.95	45372.78	56944.07	63260.97	43655.41	68800.81	87034.17
Electricity (income for LT, tariff $0.1/kWh), $K	9353.00	13785.45	11543.56	15627.91	20384.73	22932.76	16054.42	24867.16	31844.77
Total income for LT, $K	35038.30	52203.17	43418.51	61000.69	77328.79	86193.73	59709.83	93667.96	118878.94
ROI for LT, %	**1263.04**	**1054.69**	**611.82**	**785.61**	**312.57**	**111.59**	**518.01**	**483.29**	**354.42**
Payback period, yrs	**0.79**	**0.95**	**1.63**	**1.27**	**3.20**	**8.96**	**1.93**	**2.07**	**2.82**

It is easy to see that optimization tries to minimize the weight and cost of a hose or ropes from the Dyneema by maintaining the minimum possible height limited to 1500 m, and the maximum decrease in wind loads at the expense of the performance of the AirHES. Therefore, the reduction in the price of Dyneema is a decisive factor for the progress of AirHES (it suffices to say that at a price of $50/kg, the payback period decreases almost to half a year, and at $10/kg - to three months).

The last three examples are considered as a possible compromise, when we are obviously going to deteriorate the economic indicators to increase the AirHES's performance and its technological simplicity. Such an approach is justified for creating pilot plants, for example, for obtaining fresh water in the **Water Xprize project** [25], where it is proposed to create a device that gives 2 m3 of water per day with a water cost below $0.02/liter = $20/m3. From the table, it can be seen that AirHES covers these indicators by two orders of magnitude, that is, in this case, it makes sense to optimize AirHES not only in terms of payback period, but also in terms of productivity. To find the solution, we add the area of the cloud collector [100-300 m2] to the number of optimized parameters and establish a minimum of productivity with a two-fold margin, at a level of 4 m3 per day. Also, for an almost portable installation, we will exclude active sail area adjustment methods that are difficult to implement at the first stage of the project, and will minimize the cost of the installation.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cloud collector (Rmesh[1/2] or Kmesh[3]) type, CCT	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	3.00
Possible Lifetime, LT, yrs	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Average wind speed (base mode for calculation), V, m/s	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Max possible wind speed with fixed attack angle, Vm, m/s	17.00	15.00	20.00	25.00	0.00	0.00	0.00	0.00	12.00	9.00
Max possible wind speed with fixed collection area, Vs, m/s	-8.00	15.00	20.00	25.00	15.00	20.00	25.00	50.00	25.00	50.00
LWC, g/m3	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Cloud capacity factor, % [CCF]	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00
Collection area, m2 [S]	206.00	219.00	166.00	156.00	300.00	258.00	241.00	236.00	117.00	257.00
Attack angle, deg [a]	52.00	36.00	44.00	39.00	90.00	90.00	90.00	90.00	50.00	28.00
-> Cx = f(a,v) for this Cloud collector by CFD	0.64	0.30	0.31	0.31	0.37	0.37	0.37	0.37	0.64	0.56
-> Cy = f(a,v) for this Cloud collector by CFD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
-> Efficiency X = f(a,v) for this Cloud collector by CFD, %	32.72	25.18	21.94	23.97	3.26	3.26	3.26	3.26	33.95	27.94
-> Cloud collector specific weight, CCSW, kg/m2	0.10	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.04
-> Cloud collector specific price, CCSP, $/m2	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.50	1.00
Cloud collector weight factor [CCWF]	2.30	2.70	2.80	3.00	8.10	8.50	9.10	9.50	3.10	4.90
Length of hose (max altitude and head), L, m	2464.00	2549.00	2412.00	2400.00	2254.00	2184.00	2179.00	2479.00	2321.00	1681.00
Head loss in hose, HL, %	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Hydrostatic margin of safety [HMS]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Aerodynamic margin of safety [AMS]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Balloon Volume factor [BVF]	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.00	1.00	1.10
Balloon Cax	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Rope/hose specific price, DSP, $/kg	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Area of supporting kite, m2 [Sk]	9.00	131.00	117.00	109.00	132.00	105.00	92.00	59.00	62.00	0.00
Attack angle of supporting kite, deg [ak]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
-> Ckx = f(a,v) for supporting kite by CFD	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
-> Cky = f(a,v) for supporting kite by CFD	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Kite fabric specific weight, KSW, kg/m2	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Kite fabric specific price, KSP, $/m2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Flow by real wind speed, m3/h	0.17	0.17	0.17	0.17	0.16	0.17	0.16	0.16	0.17	0.17
Fm	15.65	34.10	62.50	95.82	19.33	29.80	42.65	138.90	46.56	46.95
Fmx	15.65	34.10	62.50	95.82	19.33	29.80	42.65	138.90	46.56	11.82
Fmy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.44
Vf	50.00	15.00	20.00	25.00	15.00	20.00	25.00	50.00	25.00	49.00
Af	0.00	35.99	44.00	38.99	11.61	7.97	5.97	1.92	0.00	0.49
Wind projection of Collection area, m2 [S*sin(a)]	162.33	128.72	115.31	98.17	300.00	258.00	241.00	236.00	89.63	120.65
Flow by average V, m3/h [LWC*V*S_wind*X*CCF]	0.38	0.23	0.18	0.17	0.07	0.06	0.06	0.06	0.22	0.24
Calculated Water collection rate (in S_wind), L/m2/day	56.82	43.74	38.09	41.62	5.66	5.66	5.66	5.66	58.96	48.52
Diameter with this % head loss, mm	4.24	4.23	4.24	4.24	4.20	4.22	4.21	4.21	4.22	4.27
Flow velocity, m/s	3.30	3.30	3.30	3.30	3.29	3.30	3.29	3.29	3.29	3.31
Water weight in hose, kg	34.80	35.90	34.01	33.86	31.28	30.57	30.27	34.46	32.41	24.03
The calculated wall thickness at HMS, mm	0.11	0.11	0.10	0.10	0.10	0.09	0.09	0.11	0.10	0.07
Weight of Cloud collector with drops at CWF, Wc, kg	47.38	29.57	23.24	23.40	121.50	109.65	109.66	112.10	36.27	50.37
Weight of supporting kite, Wk, kg	0.36	5.24	4.68	4.36	5.28	4.20	3.68	2.36	2.48	0.00
Tkx, N	506.25	663.19	1053.00	1532.81	668.25	945.00	1293.75	3318.75	871.88	0.00
Tky, N	4241.25	5556.04	8821.80	12841.56	5598.45	7917.00	10838.75	27803.75	7304.38	0.00
Tcx, N	3223.42	7467.83	10374.34	14947.64	5797.53	7688.00	10278.06	32780.16	5447.81	3038.70
Tcy, N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11677.80
Tmax, N	5999.56	10172.81	14821.11	21419.49	8863.97	12062.94	16255.21	46336.97	10044.04	12543.53
The calculated wall thickness at AMS, mm	0.38	0.64	0.93	1.34	0.56	0.76	1.03	2.92	0.63	0.78
Hose weight (Dyneema), kg	11.96	20.97	28.91	41.57	16.16	21.31	28.65	92.90	18.85	17.05
Load weight, kg	94.50	91.68	90.84	103.19	174.22	165.73	172.25	241.82	90.02	91.45
Balloon Volume at BVF, m3	105.00	101.87	100.93	126.13	193.58	184.14	191.39	268.69	100.02	111.77
The calculated radius of balloon (by aerostatic balance), m	2.93	2.90	2.89	3.11	3.59	3.53	3.58	4.00	2.88	2.99
Balloon shell weight (155 g/m2), kg	16.68	16.35	16.25	18.85	25.08	24.26	24.89	31.21	16.15	17.39
Tax, N	834.60	73.61	130.07	235.78	112.94	194.20	311.35	1561.45	202.00	835.68
T0y, N	1028.96	998.29	989.16	1236.03	1897.09	1804.60	1875.64	2633.13	980.18	1095.38
T, N	6507.81	10195.83	14883.63	21562.90	8908.81	12163.25	16439.39	47537.80	10126.25	12713.80
% of error for aerostatic balance	7.81	0.23	0.42	0.67	0.50	0.82	1.12	2.53	0.81	1.34
Head, m	1756.38	1513.28	1519.79	1516.03	1519.89	1502.55	1505.71	1512.78	1775.55	1601.05
Cost of supporting kite, $	9.00	131.00	117.00	109.00	132.00	105.00	92.00	59.00	62.00	0.00
Cost of Cloud collector, $	103.00	54.75	41.50	39.00	75.00	64.50	60.25	59.00	58.50	257.00
Cost of hose, $	1195.56	2097.12	2891.14	4157.50	1615.82	2130.68	2864.58	9290.00	1885.37	1705.29
Cost of shell ($3/m2), $	322.89	316.44	314.51	364.87	485.49	469.58	481.82	604.09	312.60	336.64
Sum Cost of material, $	1630.45	2599.31	3364.15	4670.37	2308.31	2769.76	3498.66	10012.10	2318.47	2298.93
Cost + Work (by doubling), $	3260.90	5198.61	6728.30	9340.74	4616.63	5539.51	6997.32	20024.19	4636.93	4597.87
Cost of Hydrogen ($5/kg ~ $0.5/m3), $	52.50	50.93	50.47	63.06	96.79	92.07	95.70	134.34	50.01	55.89
Total Cost, $	**3313.40**	**5249.55**	**6778.77**	**9403.80**	**4713.42**	**5631.58**	**7093.01**	**20158.54**	**4686.94**	**4653.75**
Prime cost (only for water), $/m3	**0.23**	**0.36**	**0.46**	**0.64**	**0.33**	**0.39**	**0.49**	**1.40**	**0.32**	**0.31**
Water (income for LT, tariff $1/m3), $K	14.70	14.65	14.67	14.68	14.39	14.54	14.40	14.41	14.50	14.92
ROI for LT, %	443.73	279.13	216.44	156.13	305.20	258.18	203.05	71.49	309.29	320.66
Payback period, yrs	**2.25**	**3.58**	**4.62**	**6.41**	**3.28**	**3.87**	**4.92**	**13.99**	**3.23**	**3.12**

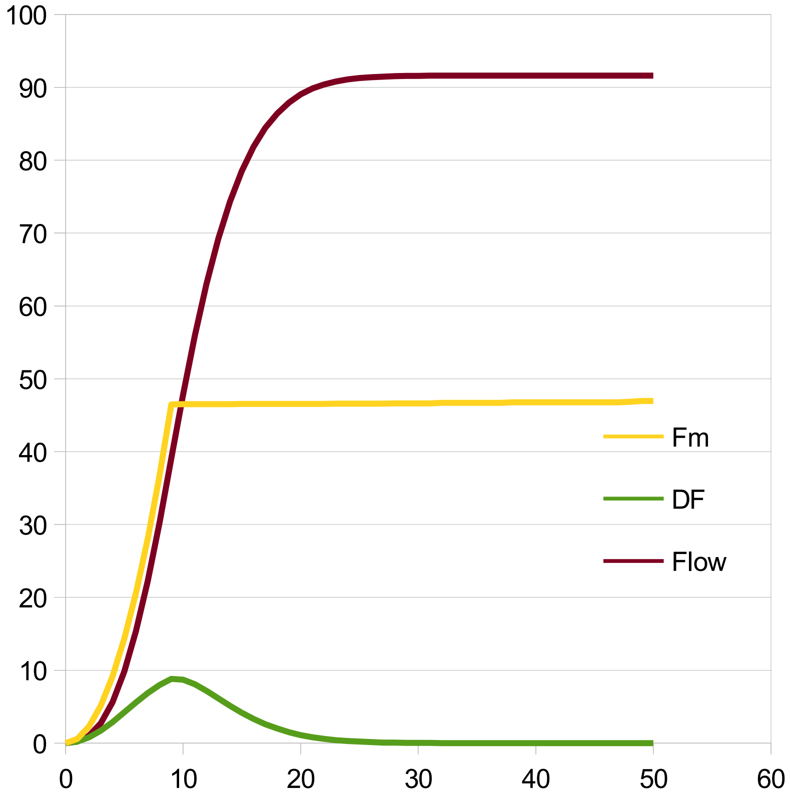
In the table:

1. full optimization, which gives a minimum payback period and uses both adjustment mechanisms (both for the angle of attack and for the area of the mesh)

2. uses a fixed angle of attack without adjustment, and descent at 15 m/s
3. uses a fixed angle of attack without adjustment, and descent at 20 m/s
4. uses a fixed angle of attack without adjustment, and descent at 25 m/s
5. uses freely hanging meshes and descent of AirHES entirely at 15 m/s
6. uses freely hanging meshes and descent of AirHES entirely at 20 m/s
7. uses freely hanging meshes and descent of AirHES entirely at 25 m/s
8. uses freely hanging meshes, without descent to 50 m/s
9. uses the angle adjustment and descent of AirHES entirely at 25 m/s
10. uses the angle of attack adjustment, without descent to 50 m/s

Option 1 is given for an example, but it can hardly be implemented in the pilot version. Variants 2, 3, 4, 5, 6, 7, 9 presuppose additional servicing of such an AirHES. Option 8 is extremely expensive. The most promising option is 10, which requires the development of a system of automatic control of the angle of attack. Ideally, if this system will work automatically on purely physical feedbacks (for example, by introducing elastic elements into the rigging of the trailing edge of the sail).

v	a	Fm	DF	Flow
0	28.00	0.00	0.00	0.00
1	28.00	0.57	0.20	0.20
2	28.00	2.30	0.80	1.00
3	28.00	5.16	1.72	2.72
4	28.00	9.18	2.90	5.62
5	28.00	14.35	4.22	9.85
6	28.00	20.66	5.58	15.43
7	28.00	28.12	6.86	22.28
8	28.00	36.73	7.97	30.25
9	28.00	46.48	8.82	39.07
10	22.60	46.51	8.72	47.79
11	18.60	46.51	8.08	55.87
12	15.56	46.52	7.17	63.04
13	13.19	46.52	6.15	69.18
14	11.31	46.52	5.13	74.31
15	9.80	46.53	4.18	78.49
16	8.56	46.54	3.33	81.83
17	7.53	46.54	2.60	84.43
18	6.67	46.55	1.99	86.42
19	5.94	46.55	1.50	87.92
20	5.31	46.55	1.11	89.02
21	4.78	46.55	0.80	89.83
22	4.31	46.55	0.57	90.40
23	3.91	46.57	0.40	90.80
24	3.55	46.57	0.28	91.07
25	3.24	46.59	0.19	91.26
26	2.96	46.59	0.12	91.39
27	2.71	46.59	0.08	91.47
28	2.49	46.61	0.05	91.52
29	2.29	46.62	0.03	91.55
30	2.11	46.63	0.02	91.57
31	1.94	46.63	0.01	91.59
32	1.80	46.69	0.01	91.59
33	1.66	46.69	0.00	91.60
34	1.54	46.69	0.00	91.60
35	1.42	46.69	0.00	91.60
36	1.32	46.69	0.00	91.60
37	1.22	46.69	0.00	91.60
38	1.14	46.78	0.00	91.60
39	1.05	46.78	0.00	91.60
40	0.98	46.78	0.00	91.60
41	0.91	46.78	0.00	91.60
42	0.84	46.78	0.00	91.60
43	0.78	46.78	0.00	91.60
44	0.72	46.78	0.00	91.60
45	0.67	46.78	0.00	91.60
46	0.62	46.78	0.00	91.60
47	0.57	46.78	0.00	91.60
48	0.53	46.85	0.00	91.60
49	0.49	46.95	0.00	91.60
50	0.45	46.95	0.00	91.60



The table and the graph show how the specific wind loads ***Fm*** (N/m2) behave, as well as the differential and integral moisture flux, depending on the wind speed.

It should be remembered that all calculations of the cost of water are based on the expected service life of the main elements of the AirHES for 10 years. However, to satisfy the requirements of the **Water Xprize project** it is sufficient that this installation should work for at least 3 months.

AirHES kite for global water supply

The Water Xprize project implies the creation of a local source of affordable, but rather expensive fresh and drinking water, mainly for the poor countries of Africa, Asia and Latin America, that is, for about 1 billion people. It is obvious that even if it would be possible to create such a high-tech device, then to give this expensive device into every African village in a relatively short time and with insufficient material resources of these poor countries is an impossible task. It seems that the goal is unattainable, but there is a way out! It is the technology of AirHES that allows to simplify this device so much that it can be made even in a small workshop of any African village.

The most technologically complicated element of AirHES is an aerostat, which constantly keeps AirHES in the air, but it is really difficult to do in a village workshop, and moreover constantly to fill this balloon with hydrogen or helium. Therefore, it will have to remove away! It is obvious that ideal fresh water, which is everywhere over our head in the clouds, can be obtained from there only if there is a wind that drives these clouds through the sails of the AirHES. But the same wind can also hold the AirHES itself, if it is made in kite form.

And what about the wind absent? It just means that AirHES will not work in the wind absent, and we will lower it to the ground. Such AirHES is just a big paraglider, it can safely be lowered in case of insufficient wind and then restarted with a suitable wind. Will this greatly affect the production of water? It turns out that it affects not very strong if the AirHES is correctly optimized, since with a small wind we would receive an insignificant additional part of the total output according to our past calculations for the Weibull distribution. And besides, water is an accumulated resource, it does not have to be produced continuously as electricity…

Let's add to the model the parameter ***Vr***, the minimum wind speed that will run and hold the AirHES at the proper altitude ***Hr*** (say, only 100-200 m below the basic operating altitude ***Hmin***, but still inside the cloud). It is obvious that the launch will additionally be facilitated by two factors: first, the heaviest elements (rope and hose) will add their weight gradually, as they rise, but at the same time the wind with altitude usually increases, and secondly, when lifting, the hose will be empty, and the weight of the water will be added gradually, and moreover water will arrive from the sails only when lifting will be already completed. And besides, since such AirHES will not produce electricity, we can increase the diameter of the hose to allow the flow not to be continuity through the hose cross-section and thereby significantly reduce the hydrostatic pressure, in order to use a cheap hose made of PE or PVC instead of Dyneema. Then the aerodynamic loads will carry not an expensive and technologically complicated hose from Dyneema, but cheaper and more widely available ropes from Dyneema of the same total cross-section.

Then the whole process of production of such AirHES will be reduced, in fact, to elementary sewing and assembly operations that can really be carried out in any workshop in any African village, and it will allow quickly and universally to introduce this technology to produce clean drinking and fresh water.

Consider the examples in the table:

1. variant 10 of the previous table, from the design of which the balloon was removed
2. the same option (adjustment on the angle of attack without descent to 50 m/s) with optimization
3. fixed angle of attack without adjustment and descent at 16 m/s (optimized)
4. fixed angle of attack without adjustment and descent at 20 m/s

	1	2	3	4	5	6	7	8
Cloud collector (Rmesh[1/2] or Kmesh[3]) type, CCT	3.0000	3.0000	3.0000	3.0000	3.0000	1.0000	1.0000	2.0000
Possible Lifetime, LT, yrs	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
Average wind speed (base mode for calculation), Va, m/s	10.0000	10.0000	10.0000	10.0000	5.0000	5.0000	5.0000	5.0000
Min possible wind speed for run, Vr, m/s	5.0000	4.0000	4.0000	4.0000	2.0000	0.0000	0.0000	0.0000
Max possible wind speed with fixed attack angle, Vm, m/s	9.0000	8.0000	16.0000	20.0000	20.0000	20.0000	0.0000	20.0000
Max possible wind speed with fixed collection area, Vs, m/s	50.0000	50.0000	16.0000	20.0000	20.0000	20.0000	20.0000	20.0000
LWC, g/m3	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000
Cloud capacity factor, % [CCF]	67.0000	67.0000	67.0000	67.0000	67.0000	67.0000	67.0000	67.0000
Collection area, m2 [S]	257.0000	299.0000	297.0000	292.0000	100.0000	48.0000	48.0000	48.0000
Attack angle, deg [a]	28.0000	27.0000	17.0000	14.0000	29.0000	44.0000	90.0000	90.0000
-> Cx = f(a,v) for this Cloud collector by CFD	0.5628	0.5427	0.3417	0.2814	0.5829	0.3125	0.3663	0.6991
-> Cy = f(a,v) for this Cloud collector by CFD	1.0007	0.9657	0.6157	0.5107	1.0357	0.0000	0.0000	0.0000
-> Efficiency X = f(a,v) for this Cloud collector by CFD, %	27.9400	28.6350	35.5850	37.6700	27.2450	21.9360	3.2600	9.3500
-> Cloud collector specific weight, CSW, kg/m2	0.0400	0.0400	0.0400	0.0400	0.0400	0.0500	0.0500	0.1000
-> Cloud collector specific price, CSP, $/m2	1.0000	1.0000	1.0000	1.0000	1.0000	0.2500	0.2500	0.5000
Cloud collector weight factor [CWF]	4.9000	2.8000	2.4000	2.4000	5.0000	5.3000	10.8000	2.0000
Length of hose (max altitude and head), L, m	1681.0000	1683.0000	1734.0000	1729.0000	0.0000	0.0000	0.0000	0.0000
Head loss in hose, HL, %	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
Hydrostatic margin of safety [HMS]	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000
Aerodynamic margin of safety [AMS]	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
Balloon Volume factor [BVF]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Balloon Cax	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300
Rope/hose specific price, DSP, $/kg	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
Area of supporting kite, m2 [Sk]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Flow by real wind speed, m3/h	0.1599	0.1679	0.1669	0.1722	0.0479	0.0265	0.0224	0.0163
Fm	46.9521	35.8657	90.1329	116.6191	237.6121	62.4960	31.7015	139.8168
Fmx	11.8237	6.0325	43.7376	56.2800	116.5398	62.4960	31.7015	139.8168
Fmy	45.4389	35.3547	78.8096	102.1400	207.0700	0.0000	0.0000	0.0000
Vf	49.0000	49.0000	16.0000	20.0000	20.0000	20.0000	20.0000	20.0000
Af	0.4900	0.2500	17.0000	14.0000	28.9900	44.0000	9.4900	89.9900
Fnx with Vr, N/m2	7.0325	4.3400	2.7336	2.2512	1.1654	0.0000	0.0000	0.0000
Fny with Vr, N/m2	12.5044	7.7228	4.9256	4.0856	2.0707	0.0000	0.0000	0.0000
Wind projection of Collection area, m2 [S*sin(a)]	120.6542	135.7432	86.8344	70.6412	48.4810	33.3436	48.0000	48.0000
Flow by average V, m3/h [LWC*V*S_wind*X*CCF]	0.2439	0.2813	0.2236	0.1926	0.0478	0.0265	0.0057	0.0162
Calculated Water collection rate (in S_wind), L/m2/day	48.5217	49.7287	61.7983	65.4192	23.6574	19.0475	2.8307	8.1188
Diameter with this % head loss, mm	4.1592	4.2408	4.2308	4.2844	2.5671	2.0266	1.8949	1.6670
Flow velocity, m/s	3.2708	3.3028	3.2988	3.3197	2.5697	2.2832	2.2077	2.0707
Water weight in hose, kg	22.8385	23.7727	24.3773	24.9263	0.0000	0.0000	0.0000	0.0000
The calculated wall thickness at HMS, mm	0.0714	0.0729	0.0749	0.0756	0.0000	0.0000	0.0000	0.0000
Weight of Cloud collector with drops at CWF, Wc, kg	50.3720	33.4880	28.5120	28.0320	20.0000	12.7200	25.9200	9.6000
Tcxr with Vr, N	1807.3493	1297.6576	811.8792	657.3504	116.5398	0.0000	0.0000	0.0000
Tcyr with Vr, N	3213.6244	2309.1172	1462.9032	1192.9952	207.0700	0.0000	0.0000	0.0000
Tcx, N	3038.6972	1803.7212	12990.0672	16433.7600	11653.9800	2999.8080	1521.6710	6711.2074
Tcy, N	11677.8037	10571.0628	23406.4512	29824.8800	20707.0000	0.0000	0.0000	0.0000
Tmax, N	11589.6106	10400.4812	26525.4883	33812.4356	23590.5992	3002.3969	1542.7271	6711.8668
The calculated wall thickness at AMS, mm	0.7395	0.6509	1.6639	2.0945	2.4388	0.3932	0.2161	1.0686
Hose weight (Dyneema), kg	15.7561	14.1563	37.1984	47.2806	0.0000	0.0000	0.0000	0.0000
Load weight, kg	88.9666	71.4170	90.0877	100.2390	20.0000	12.7200	25.9200	9.6000
T, N	11589.6106	10400.4812	26525.4883	33812.4356	23590.5992	3002.3969	1542.7271	6711.8668
Tr with Vr, N	3265.6999	2368.1254	1435.1955	1129.3142	117.0644	124.6560	254.0160	94.0800
Head with Vf, H, m	1622.1917	1657.4971	1511.8393	1511.0487	0.0000	0.0000	0.0000	0.0000
Head with Vr, Hr, m	1400.0932	1407.8280	1429.8847	1405.9053	0.0000	0.0000	0.0000	0.0000
Cost of Cloud collector, $	257.0000	299.0000	297.0000	292.0000	100.0000	12.0000	12.0000	24.0000
Cost of hose, $	1575.6084	1415.6284	3719.8396	4728.0622	0.0000	0.0000	0.0000	0.0000
Sum Cost of material, $	1832.6084	1714.6284	4016.8396	5020.0622	100.0000	12.0000	12.0000	24.0000
Cost + Work (by doubling), $	3665.2168	3429.2569	8033.6791	10040.1243	200.0000	24.0000	24.0000	48.0000
Additional costs for for LFC posts, $					0.0000	300.0000	300.0000	300.0000
Total Cost, $	**3665.2168**	**3429.2569**	**8033.6791**	**10040.1243**	**200.0000**	**324.0000**	**324.0000**	**348.0000**
Prime cost (only for water), $/m3	**0.2617**	**0.2332**	**0.5496**	**0.6656**	**0.0483**	**0.1396**	**0.1651**	**0.2443**
Water (income for LT, tariff $1/m3), $K	14.0068	14.7047	14.6179	15.0849	4.1414	2.3215	1.9625	1.4244
ROI for LT, %	382.1543	428.8023	181.9576	150.2461	2070.7226	716.5022	605.7036	409.3232
Payback period, yrs	**2.6167**	**2.3321**	**5.4958**	**6.6557**	**0.4829**	**1.3957**	**1.6510**	**2.4431**

Thus, it can be seen that a wind speed of ~ 4 m/s provides sufficient lifting power to hold such a kite water station at the required altitude. Typically, the thickness of the boundary layer of the atmosphere (in which there are instability of air currents and sudden changes in wind speed) does not exceed 1500 m, therefore at higher altitudes the AirHES should continue to operate quite steadily for a long time. It seems to us that the need to monitor current weather conditions and prevent unplanned descents is a moderate and acceptable payment for the simplification of the design, while performing the main task - to obtain a cheap and generally accessible global source of fresh water for 1 billion people.

Optimization of fog collectors by using the AirHES model

The model of AirHES can also be used to optimize existing systems for collecting fog. In the previous table, the last 4 columns just show examples of this approach:

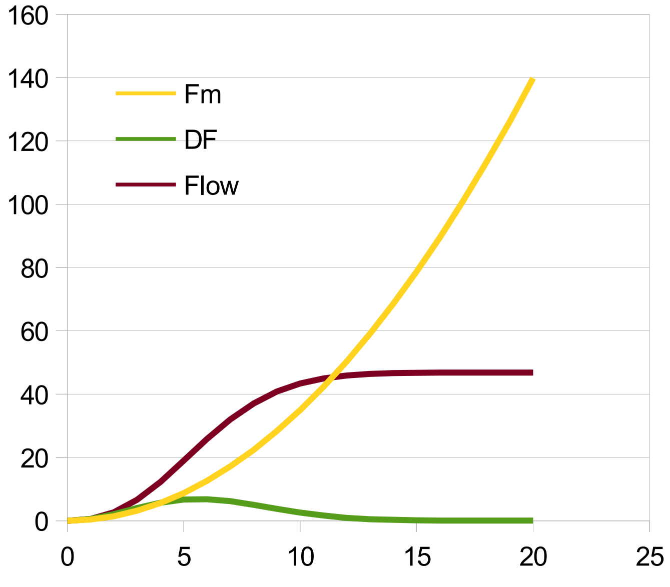
5. kite version of the fog collection system up to wind speed of 20 m/s
6. fixed angle of attack of a single-layer mesh without adjustment up to wind speed of 20 m/s
7. a freely hanging single-layer mesh up to wind speed of 20 m/s
8. a standard LFC collector 48 m2 with two-layer mesh up to wind speed 20 m/s

As can be seen from the table in all variants, the length of the hose is zero, because these devices (like traditional fog collectors) are located directly on the ground and are optimized for on-land use. Variant 5 was chosen so that its wind projection approximately corresponded to the area of the standard LFC - 48 m2. For variants 6 and 7, the mesh area of 48 m2 was also fixed. In addition, all calculations are performed for an average wind speed ***Va*** of 5 m/s, taking into account the influence of the land surface.

In addition, since the calculation based on the AirHES model automatically assumes the omni-directional effect (automatic turn of the mesh or kite against the wind), the performance for stationary variants 6, 7 and 8 was obviously overestimated in our calculations (purely geometrically, twice) in comparison with variant 5.

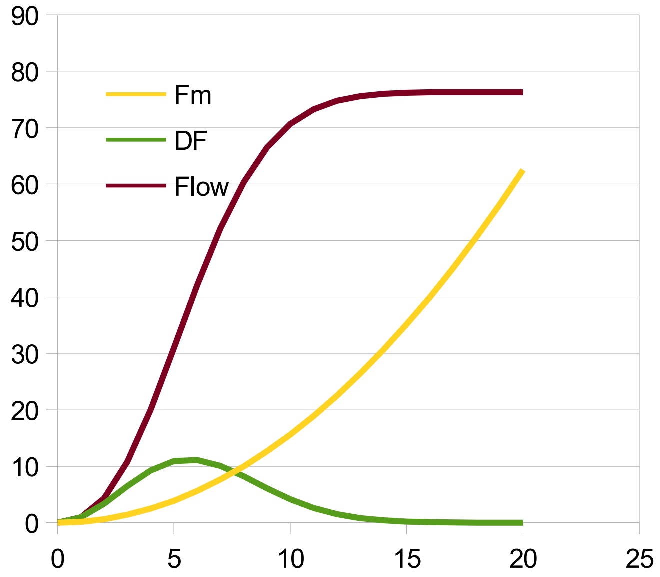
Finally, stationary execution assumes a significant rise in the cost of the construction of collectors due to additional elements (posts, struts). In [26], the construction of LFC 48 m2 with an estimated cost of $378 ($225 in materials, $63 in labor, and $39 in incidentals) is described in detail. In FogQuest Manual 2011 (page 62) for LFC 40 m2 an estimate of $500 is recommended. Based on these estimates, we assume that the rise in the cost of a stationary collector will be ~ $300.

First, let us estimate how accurate our correlations are for the known LFC data from [26]. The data on the collection of fog 5.3 - 13.4 L/m2/day is quite consistent with the estimate for the AirHES model - 8.1188 L/m2/day for option 8. The cost of water for our model is $0.2443/m3, but this only includes capital costs in LFC. However, these costs account for only 22.7% of total capital expenditure according to [26]. If this is taken into account, as well as normalize the indicated prime cost $1.9/m3 for the productivity indicated for it ~ 5 L/m2/day, then we get for the variant 8 a fairly close estimate of ~ $1.74/m3.



As expected, the existing LFC 48 m2 (variant 8, perpendicular double mesh) has the biggest specific water cost from collector - $0.2443/m3, the highest cost of the collector - $348, and the lowest integral productivity by the Weibull distribution of 16.3 L/h, and besides is subject to very high wind loads (up to 139.8 N/m2 at a wind speed of 20 m/s).

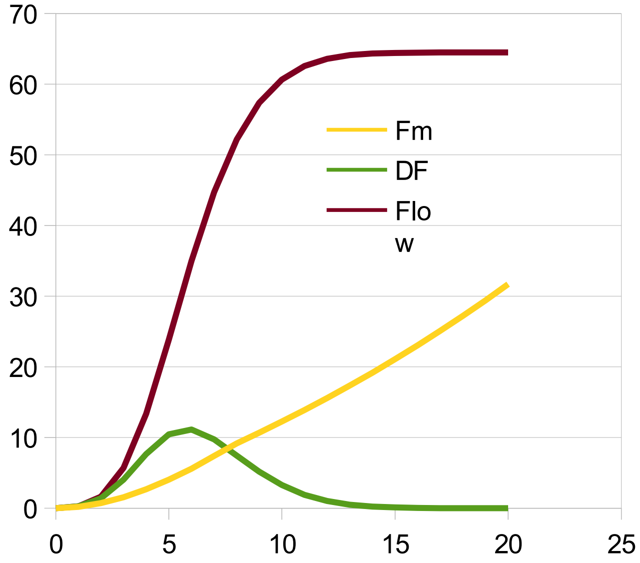
Now let's see what our model gives, which automatically finds more optimal solutions.



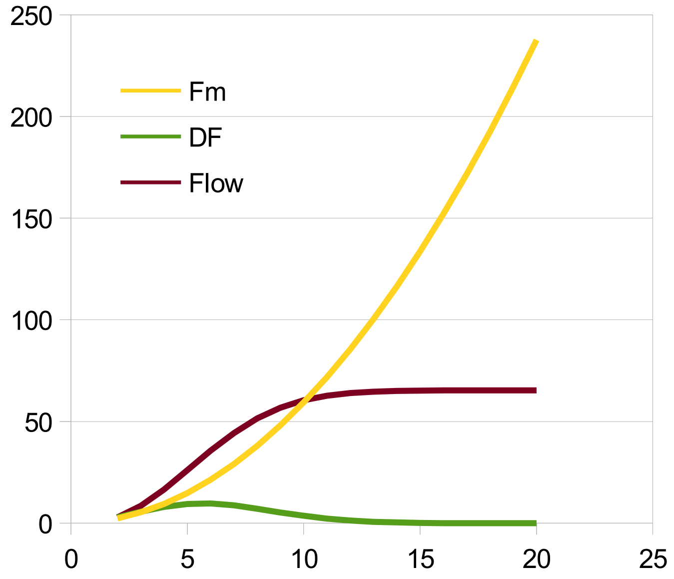
Even when using a stationary collector, the model finds it more optimal to use a single-layer mesh with a predetermined fixed angle of attack of 44-45 degrees (option 6). This significantly increases the overall efficiency of the mesh (up to 26.5 L/h), even despite the reduction of the wind projection of the mesh of the same original size (48 m2) to 33 m2. The loss of droplets from drop because of the deflection of the mesh will also decrease with such an inclined mesh geometry. As a result, the specific cost of water is reduced to $0.1396/m3, and wind loads down to 62.5 N/m2 (at 20 m/s).

Almost the same optimum result (22.4 L/h of total productivity) our model shows with free hanging of the mesh (variant 7). In this case, the model offers a significant "weighting" of the mesh to a value of ***CWF=10.8*** (for example, by using additional drainage elements) to provide approximately the same optimal angles of attack ~ 40-50 degrees with average wind speeds ~ 5-6 m/s. The change in the angles of attack of such freely hanging mesh, specific horizontal loads (Fm, N/m2), as well as differential (DF) and integral (Flow) moisture flux is shown in the table.

v	a	Fm	DF	Flow
0	90,00	0,00	0,00	0,00
1	88,04	0,1820034	0,2461197861	0,2461197861
2	82,31	0,7146054	1,3983546026	1,6444743887
3	73,56	1,5617934	4,0528193305	5,6972937192
4	63,15	2,679084	7,672446979	13,3697406982
5	52,69	4,03309125	10,4791962026	23,8489369009
6	43,33	5,6105298	11,1282827493	34,9772196501
7	35,53	7,41296745	9,7538653985	44,7310850487
8	29,98	9,1767936	7,4554507588	52,1865358074
9	26,34	10,6915302	5,1821453187	57,3686811262
10	23,35	12,26355	3,2830008397	60,6516819658
11	20,86	13,8958578	1,9102143428	62,5618963086
12	18,76	15,5907072	1,0260783949	63,5879747035
13	16,97	17,3505709	0,5106868811	64,0986615846
14	15,43	19,1777964	0,2361359627	64,3347975473
15	14,1	21,078675	0,1016749405	64,4364724878
16	12,94	23,0533632	0,0408223367	64,4772948245
17	11,91	25,0933787	0,0152887292	64,4925835536
18	11,01	27,2196612	0,0053542968	64,4979378504
19	10,2	29,412836	0,0017518983	64,4996897487
20	9,49	31,70148	0,0005369722	64,5002267209



In addition, there are also experimental data to believe that droplet losses will decrease with such a freely hanging single-layer mesh, since the wind will not tear-off the droplets, but will drive them along the mesh. As a result, the specific cost of water is reduced to $0.1651/m3, and especially wind loads down to 31.7 N/m2 (at 20 m/s).



Well, the best figures for the specific cost of water show the kite collector (variant 5) - $0.0483/m3 with the lowest cost of $200 and the greatest overall productivity of 47.3 L/h, which is three times higher than the standard LFC with the same wind projection. And it is clear that our model has chosen the maximum angle of attack from a given range. Obviously, if this restriction were lifted, even better indicators would be achieved at still greater angles of attack. I wrote about this possibility earlier in [3] on the basis of the analysis of aerodynamics and kite efficiency (page 8):

«Existing fog collectors are quite expensive, because they use the two pillars (posts) between which stretched mesh. These supports should be fixed by cables, and the process is quite time-consuming installation and should always be carried out in the field conditions in the mountains. In addition, the fixed position of mesh is not always optimal because the wind can change the direction.

In this sense, fog collector, built on the basis of a multi-tier kite would give a lot of benefits. Such kite collectors could be mass produced in advance in workshops by industrial way and transported to the installation site in the folded compact and light form. When mounting in the mountains it would be necessary to only one ground-support anchor. They automatically have always supported its optimal location against the wind, and in addition, they themselves could climb much higher and capture a greater flow of fog or clouds. For automatic opening in the wind they would simply have slight special wings (valves) on the top tier of the kite. In addition, these almost ground kites could have a low aerodynamic quality (ie the rope angle only ~ 20°), but a very high efficiency of water capture ~ 60 %.»

Nevertheless, the kite variant also has its drawbacks. In spite of simplicity of its fastening at one point, this fastening must withstand the greatest loads - up to 2359 kgf (at 20 m/s), which is 3.5 times more than the load on the posts of the standard LFC (671 kgf), and 15 times more, than the load for the option of free hanging of the mesh (154 kgf).

Another drawback is that the full opening of the kite to achieve design productivity requires some initial wind speed ***Vr*** (2 m/s for this variant 5), which is an important and critical condition for on-land systems. We can suggest some constructive trade-offs (for example, using a flagpole for constant lifting the edge of the kite), but this will complicate and increase the cost of the system.

Thus, the model does not give unambiguous recommendations, but it gives scientific grounds for practical testing of these findings within the framework of the programs FogQuest, WasserStiftung and other similar groups.

[1] Kazantsev A.N. Feasibility studies for various examples of AirHES
[2] Kazantsev A.N. AirHES blow-by
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