KiteGen Research High Altitude Wind Generation Tropospheric Wind Exploitation Under Structural and Technological Constraints

Method · January 2019

DOI: 10.13140/RG.2.2.12701.97766

1 author:

Massimo Ippolito
KiteGen

KiteGen Research

High Altitude Wind Generation

Tropospheric Wind Exploitation Under Structural and Technological Constraints.

C001-2019-98

Version	2.1
Created	2013/11 Cherubini, Ippolito
Revised	2016/01 - Ippolito
Authors	Massimo Ippolito Eugenio Saraceno
Doc Name	C001-2019-98- Tropospheric wind exploitation under structural and technological constraints.docx

Comments to: m.ippolito@kitegen.com

Status

Last Revision	30 January 2019
Access	P

Abstract

Among renewable energy sources, high altitude wind power has gained incredible attention triggered by KiteGen's first and successful empirical experiments in 2006. KiteGen planned and committed to design and validate an industrial scale generator, investing 200 man/years on the project, completing the research and adopting for development a special machine design methodology. KiteGen offers superior strength, steadiness, and coverage compared to traditional wind turbines and the LCOE could be the lowest since oil's golden age, an unprecedented accomplishment.
Baseload behaviour is the most desired feature for truly renewable energy, and up until now, only hydroelectric power has been suitable to fulfill this requirement. The KiteGen Carousel's architecture will now absolutely provide this feature in most of the world's geographical locations.
However, despite its incredible potential based on a strong theoretical framework and technological validations, the technology for high altitude wind is still generally unknown. One of the reasons for this lack of awareness is the widespread lack of understanding of energy and economic issues, allowing lobbies and diverse political and personal agendas to block promising solutions and tecnofixes[1].
The aim of this work is to help researchers and/or stakeholders better understand the specific KiteGen design basis and feasible architectures, including system dynamics, in order to easier re-create realistic models for independent assessments, thus avoiding incorrect and misleading evaluations of this tremendous opportunity to exploit tropospheric winds.

Techno Fixes classification score for KiteGen	
Effectiveness at reducing greenhouse gas emissions:	**10/10** - embodied energy of KiteGen is 1/100 of wind turbines. Baseload feature no need of backup power. This means a strong carbon negative.
Living up to the hype (science-to-spin ratio):	**10:1**- up until now, there has been no broad advertising or dissemination of the achievements of the successful research. Only a few scientists and respected professionals around the world are aware and fully understand the technology.
Democratic ownership and control:	**10/10** – very decentralised and distributed at community levels, local employment potential, not selfish individual and expensive implementation as with solar PV
Social justice:	**10/10** – no negative side-effects and allows wide deployment of electricity availability into off-grid areas. It reduces or eliminates energy poverty. Electrical energy access while easy the life, enhance education, birth control and reproduction responsibility.
Sustainability:	**10/10** auto-breeding technology, inexhaustible natural source of power. No land consumption
Scalability:	**10/10** – could provide for virtually total global consumption including primary energy, storage is completely solved, no relevant negative side effects to the atmosphere.

[1] The word "Tecnofixes" itself has assumed a negative connotation in discussions about the future, and KiteGen as geoengineering has often been blamed for this as hype, but metrics are still important.
https://corporatewatch.org/wp-content/uploads/2017/09/Technofixes.pdf
The first deployment steps typically require public investment as a consequence of the positive research outcome. Private investment follows on the basis of the track record of the machines, but primarily due to the policy/institutional acceptance of this innovation, which is currently lacking, leaving the innovators struggling to establish the obvious: http://kitegen.com/pdf/Reaction_Ecorys.pdf

Technical Obsolescence of Loyd's Model: Wind Speed Management and Power Curve

Most of the scientific papers addressing the potential interaction between high-altitude wind power and various wind-harnessing machines are based on M.L.Loyd's original formulation introduced in 1980 [1]. A specific section of the Loyd paper is focused on analysis of the process to harness energy by means of reeling out the wing tether.
Since 2003, KiteGen has introduced a series of patents focused on the Carousel architecture and the pumping kite, called a "yoyo", based on a C-shaped wing.
The KG Carousel is a novel concept that tremendously improves wind-wing interaction and approximates maximum theoretical efficiency well beyond the Loyd evaluation, avoiding the need of a leeward drift that would leave unexploited the natural wind for aerodynamic activation, thus offering a worthwhile baseload behavior in most of the world's geographical locations.
Figure 3 shows the power density probability, correctly implying that the simplified set of equations, here proposed, are valid at a given percentage of the year. Wind availability as a function of altitudes of 50%, 68% and 95% is depicted in different geographical areas as well the capacity factor of the machines.

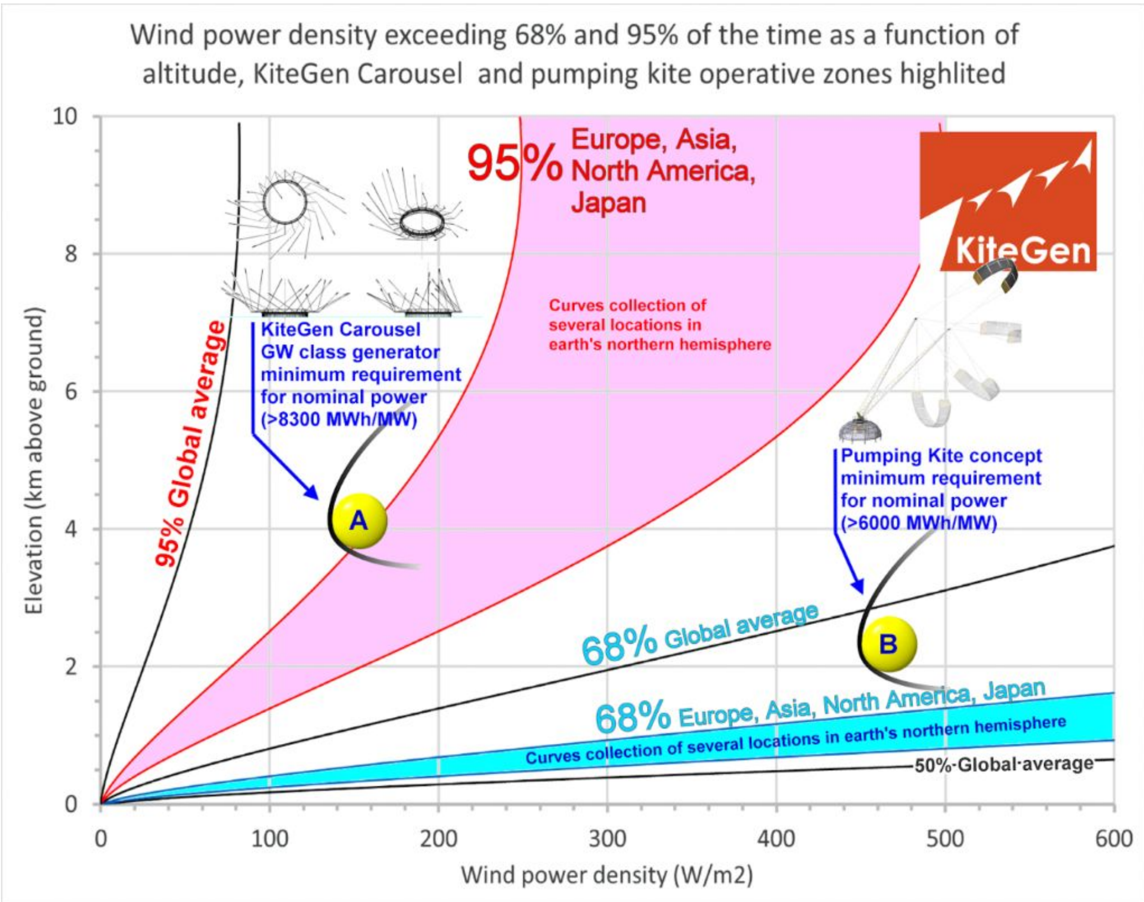


Fig.1 Capacity factor of the Carousel and the pumping kite architecture vs. wind power density and operative altitude. Source: Author's reworking of a collection of publicly available reanalyses. The temperate belt of the planet's southern hemisphere could provide even higher power densities.

KiteGen architectures expose a cut-in V_{Fmax} of 4 m/s, enough to develop the required nominal force. The power density of the cut-in wind is about 30 W/m2 so that the simplified formula set, shown in Table 1, is valid 95% of the time, as it is the rate the global average collected wind power density exceeds 30 W/m^2 above an altitude of 2000 m. In other words, KiteGen power kites will fly everywhere at full nominal force at least 95% of the time. The pumping kite architecture will produce power when the wind speed exceeds the cut-in value and will reach full power at V_{Pmax} at least 68% of the time (6000 h/y) working at altitudes ranging from 1000 and 2000 m (depending on the site, most of the favorable areas are found in the temperate belts of the northern and southern hemispheres).
The Carousel architecture is fully operational 8,300 hours per year because it has a cut-in speed that matches nominal power. This greatly reduces the minimum wind speed requirement, creating a remarkable capacity factor of more than 95%, resolving any intermittency issues and providing humankind access to a tremendous energy accumulator represented by the atmospheric geostrophic pseudo-flywheel.
The pumping kite was originally conceived as a KSU (kite steering unit) intended as a modular element of the KG Carousel, suitable to control each wing from the top of the wide ring, the rotor.
The planned research to set-up and validate such a single-wing module led to a reciprocating process called a “yoyo” or a pumping kite with the project name of KiteGen Stem, where the cycle is closed, recalling the wing in sideslip when the line reel-out is at its maximum extension. This allowed KiteGen to investigate this novel and smaller architecture without losing the achievements collected in the KG Carousel ideation, including predictive control, creating the potential for an entirely new class of potentially viable generator architectures and application fields. However, the Carousel by far maintains absolute performance superiority.

During the first test campaign of the KSU, the need to precisely and actively control the tension in the lines emerged, because the tremendous variability of wind speeds implied great variations of line stress and with it, the tremendous risk of damaging or even blasting the wing due to pressure overload.

This observation leads to a dramatic redefinition and simplification of the mathematical tools describing KiteGen’s architectural approach, thus nullifying the Loyd Model and associated unjustified refinements made by numerous other authors. The primary reason is that line tension must be directly tied to the max structural value allowed by the system’s kinematic chain.

An extended observation of the wing’s flying behavior was enough to deduce with certainty that such a simplified approach is valid at least 95% of the operational time of the KiteGen architecture, excluding conditions of sustained absence or very low wind speeds, where the fluid dynamics and geometrical complexities again manifest, as well as a cutoff of energy production.

Unfortunately, most of the scientific works [2] [3] [4] [5] appearing after both the Loyd and KiteGen formulations are exclusively focused on this 5% of the operational time, hiding the simplicity, elegance and incontrovertible positive essence of the concept. In fact, they are trying to refine an excessive and useless optimization strategy which leads, in the presence of wind, to unrealistically high powers, and on the other side, investigating supposed absolute upper-bound limits of the technology by inaccurate introduction of Betz's limits and/or geometrical deratings, de facto focused only on the take-off and cut-in operative zones.

In this paper, we will attempt to create a reasonable rationale, to provide readership evaluation tools useful to realistically and correctly determine, and theoretically validate, expected performances, without the excesses of unnecessarily enthusiastic attitudes and the potential misunderstanding of our system caused by people who incorrectly attempt to redefine Loyd's formulation in their literature. Our intent is that this explanation, not new but generally ignored or undermined, will be an incredibly pleasant surprise for most of the curious and enthusiasts of troposphere wind exploitation, as well as those who are advocates of optimal wind-powered, fully renewable energy sources.

First Observation:

The axial wing and tether force F depends on the squared wing flying speed V_K and on the wing surface A

$$F = \frac{1}{2}\rho V_k^2 A C_L$$

V_k depends on the squared wind speed V_w and on the squared aerodynamic efficiency E= $\frac{C_L}{C_D}$ also known as Glide Factor. Thus, the formula may be rewritten:

$$F = \frac{1}{2}\rho(V_w cos\theta)^2 AE^2 C_L$$

Please note that, referring to both the pumping kite and carousel architectures, if the wind speed is reduced below VFmax, the force may be maintained by reeling in the lines in order to create an apparent wind that compensates for the loss of the natural (and some energy is spent to some extent). On the other hand, if the wind is stronger than VFmax, the lines are reeled out to maintain the limitation. The latter is the manner in which the pumping kite produces power, following the relationship $P=F_{max}(V_w-V_{Fmax})$. The Carousel also may reel-out the lines to produce contingency power to be spent directly when it comes to the side and needs to be reeled-in. The balance of all the lines lengths is held in equilibrium while power applied to the grid is created by rotation of the KSU's base (the rotor), pulled by the wings over the large circular stator, sliding by means of passive levitation.

In any case, the complexity of Carousel operation fades by spending some time following a detailed simulator in action that includes the piloting AI.[2]
Also, the pumping kite architecture implements a similar behaviour. If the wind speed is reduced, the force can be restored by braking or reeling in the lines in order to create additional force that compensates for naturally occurring wind. On the other hand, if the wind is stronger, creating a force exceeding a given limit, the lines may be reeled out quickly enough to reduce the naturally occurring wind speed and restore the traction force limitation. Such features are used by KiteGen, among others, to maintain constant line tension as will be better detailed later.

Second Observation:

When the wing's nominal **flying conditions are met and achieved** (95% of the time), tether forces and flight speed become, and must be, constant under the structural limits, including safety factors. The system could be simplified with a new device that has the properties of a **sky/wind-mass hook** with a slight drift leeward (about 3 m/s with the KiteGen power wing) and creates the ability to quickly choose the tangential position in air space inside the operative cone, with a translation speed of about 80 m/s. This observation allows focusing on the best path in air space without the burden of complex models based on aerodynamic and Euclidian formalisms.

Third Observation:

Line drag cannot be added to the wing drag because it acts axially, like gravity to a glider, without limiting the flying speed, hence the system AE.
The delay that the line imposes to the path in airspace affects only the angle with respect to the wind and is never a degradation, because it only modifies the power spot shape.

Design Strategy

In automation experienced design, machine safety, security and reliability are the main design guidelines, so that the determination of the optimal reel out speed may become a best practice to achieve the maximum allowable lift force, fast tracked and clipped.
After that, the device has the main objective of maintaining the desired force constant, by means of PID controls and predictive control strategies, working at a constant power output rate. If the wind exceeds the maximum rated speed, the kite will be flown at a sub-optimal angle with respect to the crosswind direction, exiting from the "power spot" and ensuring that the maximum force is not exceeded.
This functional specification allows setting the desired device parameters by design and keeping the machinery light and swift, unlike the wind turbines that must be over-engineered enough to deal with whatever wind conditions may occur.
Force, Power and speed expressions are very simple within our force limitation control strategy and the power curve is divided into four zones, depending on absolute wind speed.

---

[2] This simulator, and its AI piloting unit, was conceived and implemented at the very beginning of KiteGen activities, de facto its early success enabled the commitment to develop the technology, beyond the previous successes of empirical field tests. https://www.youtube.com/watch?v=Fxo8HofKofY

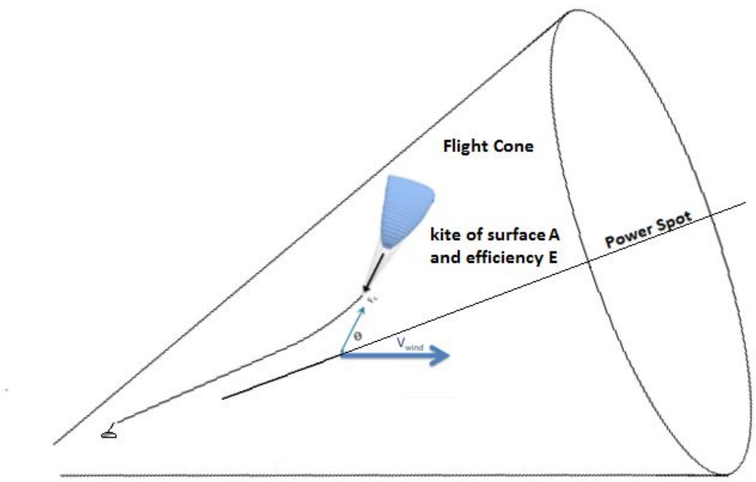
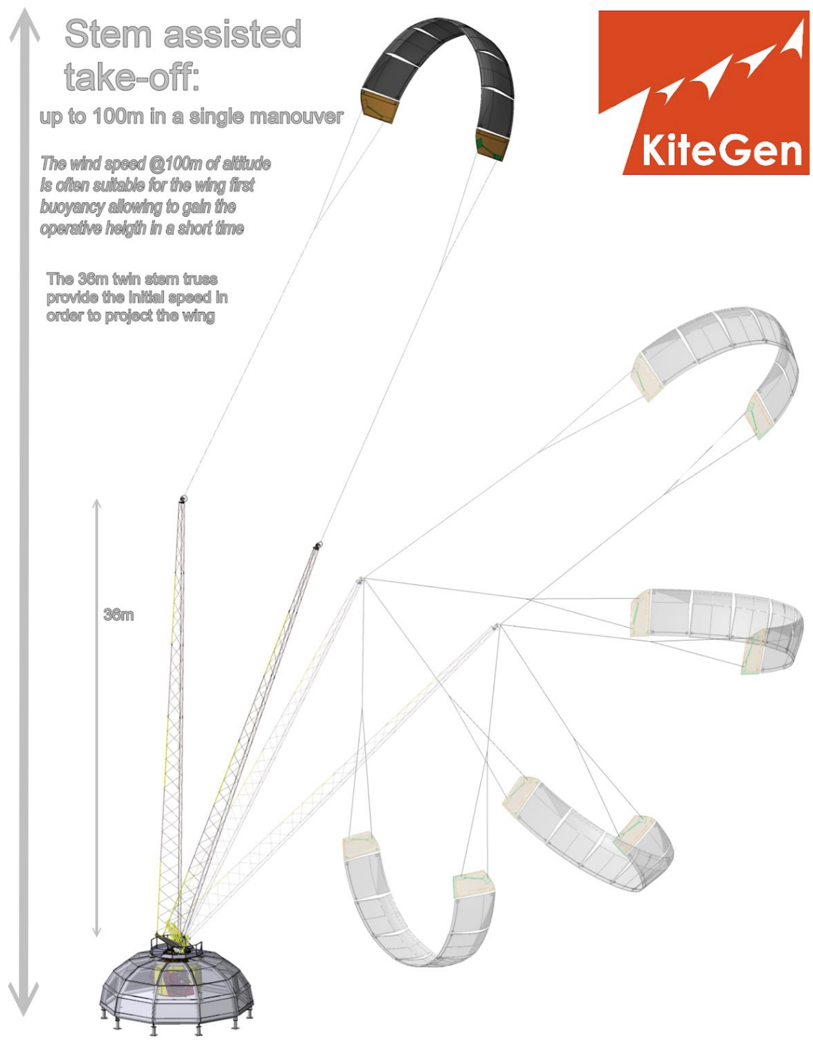


Fig.2 Representation of the flight cone and the Power Spot. The KiteGen Ground Robot automatically aligns the direction of the lines to the direction of the wind by use of a free rotating engine room. The kite flies around the power spot axis following a lemniscate path, unwinding the lines up to the speed V_{Pmax}. Whenever the wind speed exceeds design parameters $V_{Fmax}+V_{Pmax}$, the kite is moved by the robot to a more optimal location within the flight cone, removing it from the location in the power spot cone where the design parameters would have been exceeded.



KiteGen Stem			
A	B	C	D
Machine OFF	Machine not reeling out. Note that zone B has negligible occurring frequency	Full Force Zone: machine operating at maximum force	Full Power Zone: machine operating at maximum force and maximum power
$P = 0$ $F = 0$ $V_r = 0$	$P = 0$ $F = \frac{1}{2}\rho(V_w cos\theta)^2 AE^2 C_L$ $V_r = 0$	$P = F_{MAX} V_r$ $F = F_{MAX}$ $V_r = V_w - V_{Fmax}$	$P = P_{MAX}$ $F = F_{MAX}$ $V_r = V_{Pmax}$

Tab.1 Simplified formula set for the four areas of the KiteGen Power Curve where P is power, F is force, V_r the line unwinding speed and V_w equals the wind velocity.

- Zone A: The machine is switched off because the absolute wind velocity is below the cut-in velocity. The latter depends upon which curve of the family of lift force curves applies to the specific lifting operation of the kite, where the upper boundary is the curve given by the Loyd equation and the other members are continuously derated by the cosine factor. The only effect of the derating of the lift force curve is to shift the cut-in speed a little rightward.
Zone A and Zone B are divided by the minimum wind speed required to allow the wing to achieve buoyancy, develop some force and take off. This speed is dependent on the aerodynamic efficiency of the wing.

- Zone B: The machine does not reel-out the cables, the force in the cable is below the nominal force.
Zone B and Zone C are divided by the full-force velocity V_{Fmax}

- Zone C (Full Force Zone) The absolute wind speed is above the allowable full-force wind velocity. The machine operates with nominal tension in each line. The power generated varies and is below maximum. The machine is regulated in order to maintain a constant nominal tension on the tethers. Operation in Zone C is the only opportunity to exploit Loyd optimization to quickly achieve full power..
Zone C and Zone D are divided by the full-power velocity V_{Pmax}

- Zone D (Full Power Zone): The absolute wind speed is above the allowable full-power wind velocity V_{Pmax}. The force in the lines is maintained equal to the nominal force FMAX and the generated power is equal to the maximum power P_{MAX}. The machine is regulated by positioning the kite outside the power zone (Figure 2) where the power harvested by the kite is reduced by the cosine of the angle θ.

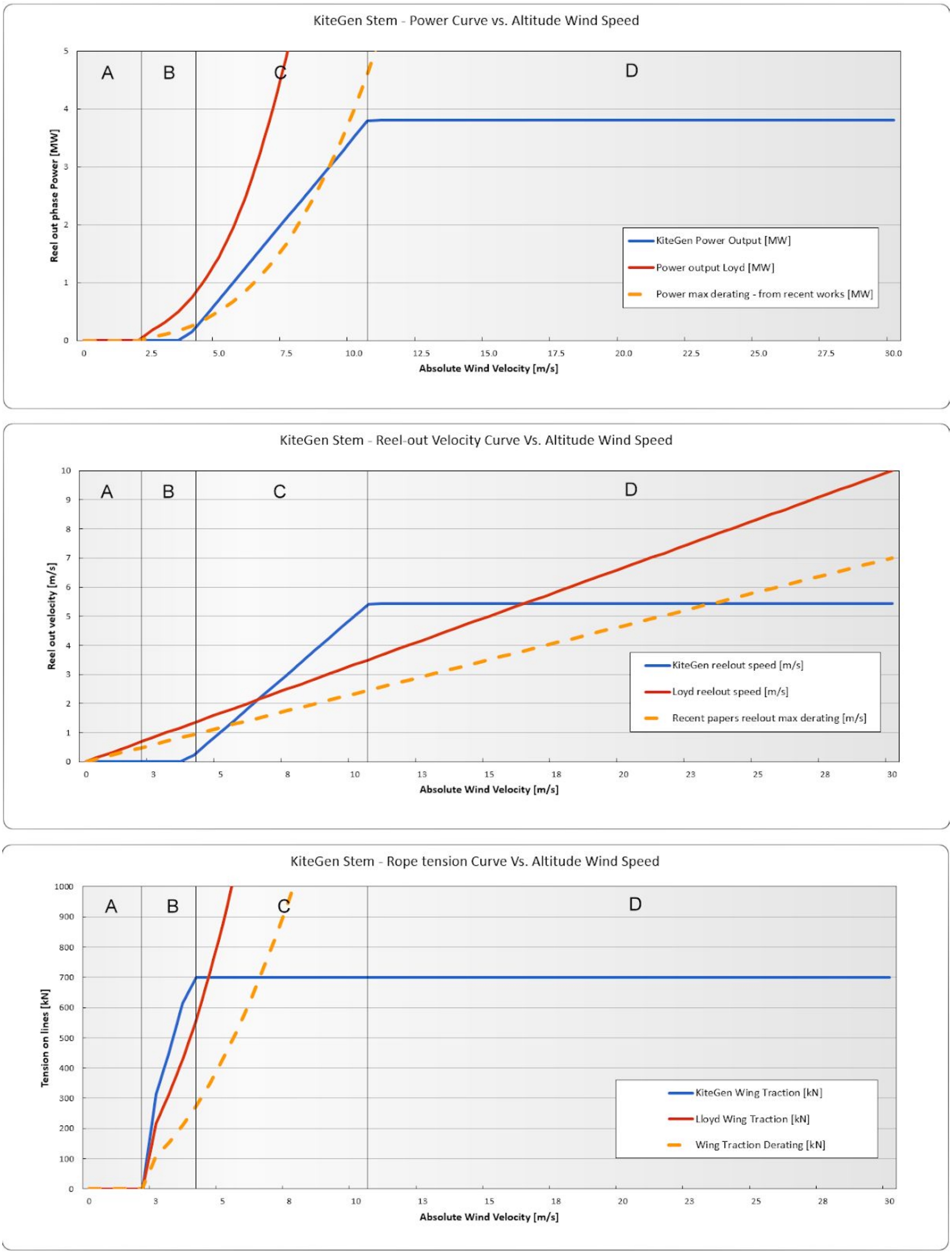


Fig.3 KiteGen reciprocating cycle active phases: power, reel out speed and force, in comparison with the Loyd et al. reel-out strategy.

Thanks to this approach, the cables always operate at their nominal tension and the generators operate at nominal torque and/or power. Note that the KiteGen line tension exceeds the Loyd curve in Zone B, because no reel-out is occurring, so all the available wind is fully utilised for buoyancy and takeoff. It is easy to understand that further up-scalability could be achieved increasing the force the system withstands thus the generated power as well, without apparent limits; however, this feature involves the entire kinematic chain, including wing tensile strength, that could lead to deep redesign activity.

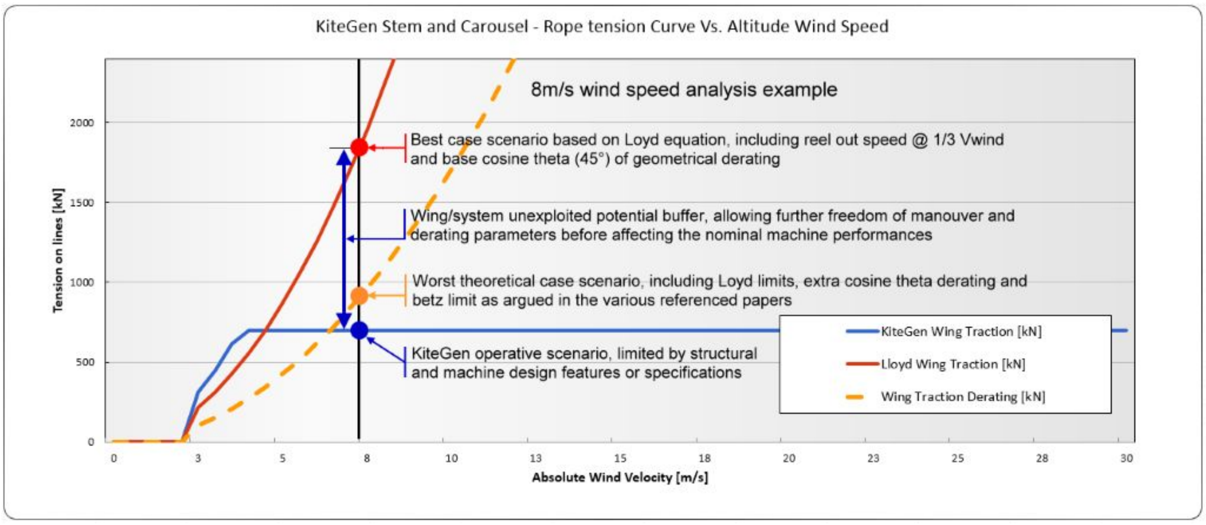


Fig.4 KiteGen operative scenario vs. optimization approach

The graph in Fig.4 shows the exceeding potential vs. actual wing traction, providing a stable line tension. With less wind, the automation design must deal with supply discontinuity. At the opposite end, a suboptimal path in airspace would be chosen to limit the wing traction.

The additional derating parameters that can capitalize the potential buffer in order to guarantee the performance are:

1) Loss of stiffness in the wing ribs
2) Wind power spot 3d shape and bounds variation
3) Wind shear discontinuity and gusts
4) Weather conditions such as rain and icing
5) Wing leading edge wear

All the listed factors show that our force limit approach and its de-rating of theoretical performance actually removes the unmanageable complexity that arises from them.
In doing so, all the complex phenomena happen in the buffer zone and we don't have to deal with them, as the only true and unavoidable derating factor is the possible lack of wind that, in the most common scenarios shown in fig.1, occurs less than 5% of the year.
All the graphs shown here are based on KiteGen's giant C-shaped wing of 130 sqm and 28 of AE. Further upward scalability can be achieved with a bigger and/or improved wing with higher aerodynamic efficiency.

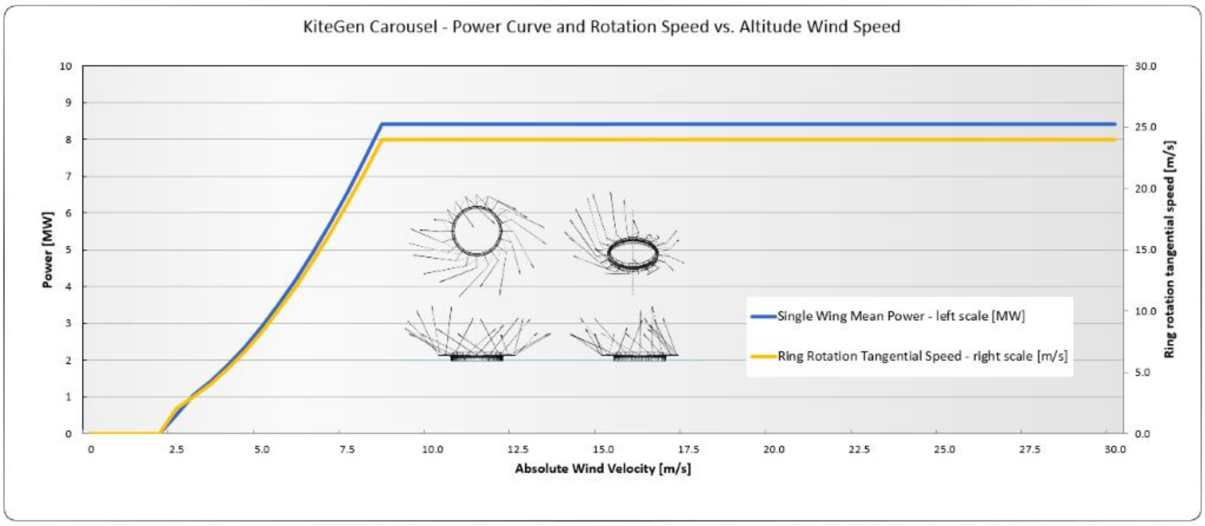


Fig.5 KiteGen Carousel single-wing active Power curve and rotor speed
Kitegen Carousel operation is continuous and does not require full stroke cycles or line reel-in/out, requiring a substantially lower nominal wind speed compared to wind turbines and pumping designs. A short passive phase occurs during the jibe, when the wing needs to change wind-side interaction.

The Negligible Influence of Betz's Limit on the KiteGen Stem

As well stated in [3]

Notions of efficiency are extremely important in energy generation; Carnot efficiency is fundamental to the study of heat engines, while wind turbines cannot exceed Betz's limit. An understanding of efficiency is based on an upper bound. The efficiency of a wind turbine is defined as the ratio of the derived mechanical power to the maximum power that can be removed from the wind passing through the disc occupied by the turbine. This is a very useful measure, because the diameter of the turbine and its cost are strongly related. Hence, the Betz efficiency of a turbine is one of the quantities that can be used to predict the return on investment.

The Betz limit can meaningfully be applied to kites, since the area a kite moves in is generally very large, and the kite will only remove a small fraction of the wind energy passing through that area. Well before becoming aware of high altitude or tropospheric winds stronger and more constant than biosphere winds; KiteGen addressed undisturbed wind flow exploitation at low Betz efficiency, that has since been revealed as a viable resource worth at least three times the power that can be harnessed by a wind turbine under the same conditions. This enabling feature is currently neither understood nor addressed in any current literature.

Several articles [3] [4] investigate the Betz limit issue applied to high-altitude wind energy. The Betz limit applies to aerodynamic profiles harvesting kinetic energy from the flow from a given section. Wind turbines sweep a circular area, slowing the incoming air flow so that the wind speed, after passing through, is slower. The kinetic energy associated with the speed difference is harvested by the turbine. The theoretical maximum energy can be harvested is

59% as demonstrated by Betz. KiteGen sweeps a far larger area than a wind turbine generating the same power. Thus, the air flow is less disturbed and the aerodynamic profile works with a locally faster wind. Looking at the Betz limit of High Altitude Wind energy systems is another example of poorly-conducted research trying to find a limit to something that **does not need to reach that limit** to work well. The harvest efficiency of the KiteGen is always lower than the Betz limit by design, but the power harvested is threefold that of a wind turbine of equivalent size because of the lesser brake effect on the air masses, resulting in a higher speed of the airflow elaborated by the larger aerodynamic surface wiped.

Following Betz's search for the effective speed of the airflow when it touches the actuator, roughly in the middle between the speed of the undisturbed wind and the air speed after being elaborated by the actuator, if the actuator is less efficient, the speed of the airflow on its surface will be higher than that available to the blade of a wind turbine. Thus, it actually gives KiteGen a distinct advantage in terms of harvestable power.

Conclusion

Great news! The math needed to understand the two KiteGen architectures is straightforward, making it incredibly simple to plan a fully-specified design for independent evaluation and finally begin to recognize, with absolute clarity, the distinct advantages over all other means of producing electrical energy.

In particular, no square-cube law is involved, such as those that heavily affect wind turbines, as mandatory limits to free scalability.

When the nominal flying conditions of the wing are met and beyond, there is absolutely no need to run models computing aerodynamic equations because most of the variables normally associated with these models are not variables at all; they are *constants*.

Coming back to the findings, the performances of the generators depend on the size and the AE of the wing which then affect the cut-in wind speed and the tensile strength of lines and wings affecting nominal mechanical power, taking into account common mechanical safety factors.

It is clearly understood that up-scaling the generators is a function mainly of sustained force in the kinematic chain, while the wing AE and size improvements compensate for a lower cut-in.

The reel out speed V_r of the lines is: V_{wind}-V_{Fmax} and is limited at V_{Pmax}, a constant.

The maximum operative force is simply F_{MAX} and is a constant imposed by the structural resistance of the kinematic chain of the specific machine.

The power is $P=F_{MAX}V_r$ and is limited at P_{MAX} which is another arbitrarily chosen design constant. KiteGen for security doesn't need multi-decennal site wind assessments as HAWT requires, because the design and dimensioning choices match the maximum possible stress imposed on the machines, completely solving fatigue issues and over-dimensioning constraints, paving the way toward the dreamed-of dematerialisation of the energy infrastructure.

Our simplified formulation is genuinely good news, especially for those who are interested in the matter but have been confused by misleading papers and their unnecessarily tortuous math tools arising from incorrect model setups[3], like the differential equation approach, found in most of them, that hides the refinement and power of our design concept.

REFERENCES:

[1] M. L. Loyd, Crosswind kite power, Journal of Energy, vol. 4, no. 3, pp. 106–111,1980
[2] S.Costello et al. Analysis of the Maximum Efficiency of Kite-Power Systems Apr 2015 https://infoscience.epfl.ch/record/207053/files/Costello_2015_JRSE_submission1.pdf;
[3] M.De Lellis et al. The Betz Limit applied to Airborne Wind Energy – 2018
[4] M.Kheiri et al. On the aerodynamic performance of crosswind kite power systems – 2018
[5] G.Sanchez-Arriaga, R.Schmehl et al. A lagrangian flight simulator for airborne wind energy systems – 2019
[6] Cristina L. Archer, Ken Caldeira, Atlas of high altitude wind power, Department of Global Ecology, Carnegie Institute for Science, 260 Panama Street, Stanford, CA 94305, 16 June 2008.
[7] Cristina L. Archer, Ken Caldeira, Global Assessment of High-Altitude Wind Power https://www.researchgate.net/publication/26624790_Global_Assessment_of_High-Altitude_Wind_Power
[8] G.Abbate, Commentary to the paper A Betz-Inspired Principle for Kite-Power Generation (S. Costello et al., preprint 2014) http://kitegen.com/pdf/Commentary_paper_Costello.pdf

A complete list of a hundred papers citing Loyd can be found at:
https://arc.aiaa.org/doi/10.2514/3.48021

http://www.kitegen.com/pdf/KiteGen_Presentation_ENG_economics.pdf

[3] It is curious that the reiterated poor mathematical modelisations of sciences, including economic and climate, are negatively affecting humankind's wealth and well-being, incurring tremendous, self inflicted, collateral damage. Economic models cannot forecast recessions. Climate models cannot forecast and do not even track historical trends. Energy is by far the most challenging field for model effectiveness due to its multidimensional and multivariate complexity, typically undermining net energy concepts and the dynamic of related phenomena, such as peak-oil supply which is currently occurring and is in indirect but strong correlation to the rapid growth of global debts and its impractical deleveraging. Finally, the continuing and hot debate over mathematical modeling occurred around the Austrian School of Economics need to gain new momentum, and KiteGen will be the unanticipated entity that will invalidate most of their orthodox beliefs. Zealots of extended mathematical modeling miss the indisputable fact that trying to set up accurate model isn't enough, since diverging small or important unforeseen events and often nonlinear feedback or variable saturation effects inevitably occur, making any model unusable or, at least, very difficult to align. However, this topic isn't within the scope of this paper despite the fact it is a practical demonstration of mathematical models' flaws due to poorly understood matters that can affect all of us. KiteGen gained great confidence in energy-economic assumptions alongside 10 years of hard science and technological development thanks thousands of deep confrontations with energy stakeholders fascinated and curious about KiteGen.

Appendix

Zoom out of the figure of power densities, in order to include the wind turbine operative zone.

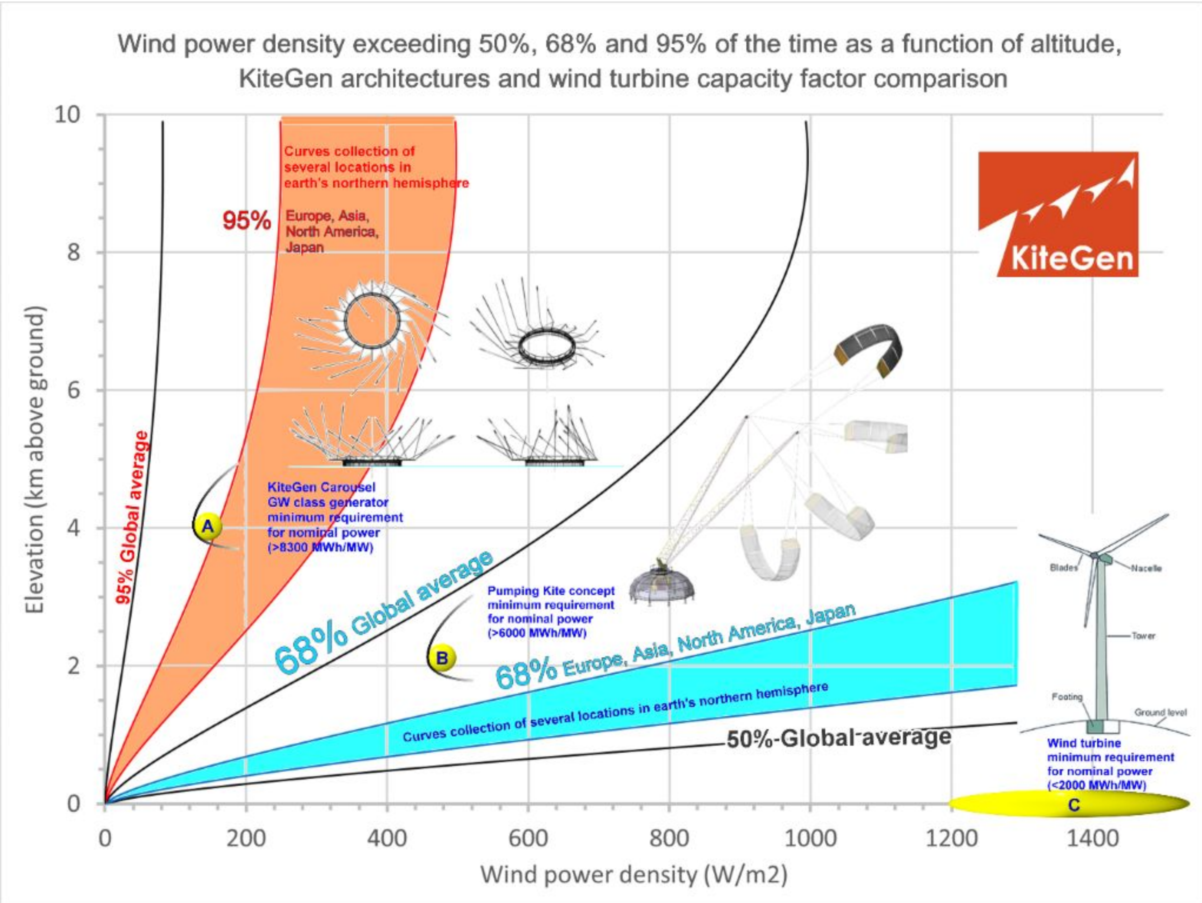


Fig.6 The graph in Fig.1 was rescaled to include wind turbines

The KiteGen Carousel architecture is superior to all other methods to harness high-altitude winds and it is also superior to the best baseload power plants, including coal, gas and nuclear. Unfortunately, this baseload feature is rarely understood by inexperienced but vocal researchers approaching renewables sources and KiteGen, as they miss the meaning of energy quality and the prohibitive cost of energy accumulation, topics that are absolutely clear to energy professionals.

The wind frequency data are coming from several available reanalyses. The pink area depicts wind speeds available in the temperate zones of the planet, actually better with respect to the global average. This means that the KiteGen Carousel that requires only a very low wind speed (about 7 m/s on average) will work at high capacity for more than 8300 hours per year, even at altitudes less than 3000 m, especially in energy intensive areas of the world (yellow balloon “A”). The pumping kites need more power density to work at a capacity factor greater than 6000 hours per year at lower altitudes (about 10 m/s on average - yellow balloon “B”). Wind turbines often claim an availability of about 2000 equivalent hours per year in optimal sites, while the global mean is 1500h. They require a minimum wind speed of 13-14 m/s or 1300 W/m2 to provide nominal power (yellow balloon “C”).