Chapter 2
Comparative Analysis of Floating Aerogenerators

Amit Kumar Mondal, Ravi Kumar Patel, Abhishek Sharma, Vindhya Devalla and Surajit Mondal

Abstract This paper presents and compares several concepts of higher altitude wind energy exploitation. This new generation of systems employs tethered wings, aircrafts, multi-copters, balloons in order to harness the higher atmospheric winds. The comparison in this paper covers generators placed in ground as well as in air. From available concepts from literature, the most promising concepts were reproduced on the basis of moving mass (wings and tether), design, operational issues, techno- economic comparison. Key design and operational issues in developing and operating these systems are highlighted. A comparative analysis of floating type aerogenerators has been shown in this paper.

Keywords High altitude wind energy · Airborne wind energy · Floating aero-generator · Magenn air rotor system

2.1 Introduction

To date, major part of energy used by our society has originated from fossil and nuclear fuels, which are presently confronting extreme issues, for example, security of supply, economic affordability, ecological sustainability and disaster risks [1]. To address these issues, world is enacting towards energy policies which are concerned towards expansion of sustainable energy sources. In this context, in the last few decades there has been growth and considerable spread in renewable energy sector [2]. Among the available renewable energy sources wind energy is one of the promising widespread sustainable power sources. Due to non-availability of land resources for further harnessing of wind energy through wind turbines, now the current research is focused towards enhancing the power capacity per unit of land

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area. This has globally acted on the single wind turbines by increasing the nominal power (up to 5 MW) which results in increased blade length (for swept area), height of the turbine axis (to capture strong winds), gears, weight, design, material used etc. [3], but this has a limitation as the overall cost of the fixed type wind turbine is proportional to the fifth power of its height [4].

In this scenario, a new way of tapping the high altitude wind energy (HAWE) using floating aerogenerators shows promising future, this principle was first introduced by Loyd [5]. Wind power density is variable in nature due to Earth's boundary-layer-like effect i.e. wind speed generally increases with the increase in altitude, same has been studied by Archer and Caldierain [6] in 2009 for altitudes between 500 m and 12,000 m, shown in Fig. 2.1. Due to wind shear, lower layers of wind retards the layers above them [7]. Wind become steadier, more persistent and of high speed at higher altitudes [8]. Researcher's round the world are working on this sector, and during the last decade we have seen few promising prototypes.

The major motivation behind harnessing HAWE is from the climate models, which predicts heavy drag forces against wind flows, the same has also been shown by Marvel et al. [9] and Miller et al. [10]. In this paper an attempt to provide detailed study of floating type wind generators has been done in terms of different concepts, systems used.

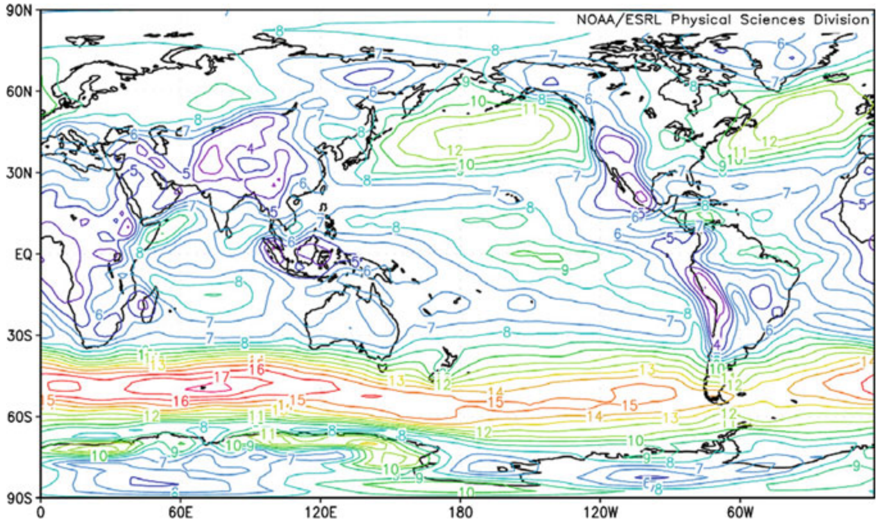

Fig. 2.1 Wind magnitude on pressure level of 850 mbar [11]

2.2 On Going Research

For harnessing HAWE, several techniques are adopted but they can be broadly classified on the basis of the mechanism used for floating, which can be further classified as power generation at ground or sky.

2.2.1 Kite or Airfoil Type

There are different types of floating aerogenerators available on the basis of the type of mechanism used for floating like kite, airfoil, balloon type, rotorcraft type etc. Kite or airfoil type [12–14] floating aerogenerators produces electricity by using the aerodynamic forces into tensile forces via the ropes to the ground station (moving or fixed). The ropes/tethering also provide the desired controlled lift to sustain in sky with the help of the continuous motion of the kite or airfoil. Few of the working prototypes of kite or airfoil based floating aerogenerators are shown in Fig. 2.2, apart the other prototypes using the same concept are as follows:

i. KiteGEN program [15–18]
ii. Peter Lynn Guerilla Kite [19]
iii. Multiple- kite [20]
iv. Laddermill [21, 22]
v. Pumping mill [23]
vi. Axial-Mode Linear Wind Turbine by Gary Dean Ragner [24]
vii. Method of utilization a flow energy and power installation for it by Alexander Bolonkin [25]
viii. Wind Driven Power Generator by Yasunobu Toneaki [26]
ix. Multi-tether cross-wind kite power by Benjamin Tigner [27]
x. Guided wind kite by Franklin F K Chen [28]
xi. Controlling power extraction for wind power generation by Saul Griffith et al. [29]

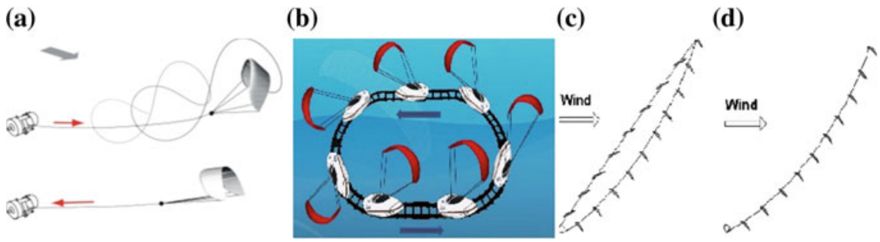

Fig. 2.2 **a** Pumping cycle of parafoil based floating aero generators [14]; **b** Schematic representation of NTS Energie prototype [32]; **c** Working of Laddermill [21, 22]; **d** Working of Pumping mill [23]

xii. Wind drive apparatus for an aerial wind power generation system by Gaylord G. Olson [30, 31]
xiii. NTS Energie prototype [32]
xiv. Wind Energy Device by Norbert L. Osborn [33].
xv. Apparatus for extracting energy from winds at high altitudes by David H. Shepard, Rye [34]
xvi. Apparatus for extracting energy from winds at significant height above the surface by Lambros Lois [35]
xvii. Kite Ground Station and System Using Same by Damon Vander Lind [36]
xviii. Wind energy recovery device and wind power generation device by Toshiyuki Takasaki [37]
xix. Tethered autonomous air vehicle with wind turbines by Eric Blumer et al. [38]
xx. SkySails Power [39]

Kite or airfoil based floating aerogenerators works properly when there is a good amount wind movement, but fails under low or no wind movement cases. Also dynamic modelling corresponding to controlling of these is not linear as it dependent on wind speed, hence it's difficult to model as well as control.

2.2.2 Balloon Type

Balloon type floating aerogenerators [40] are comparatively stable and works during low or no wind movement cases. In these balloon acts as a support body for the hanging or embedded wind turbines and the energy produced is transmitted to the ground station via ropes or tethers. Balloons are lighter than air hollow gas filled support structures, because of this they remain in air and are also easy to control during take-off, landing, maintaining altitude etc.

Apart from the above shown prototypes in Fig. 2.3, other prototypes using the same concept are as follows:

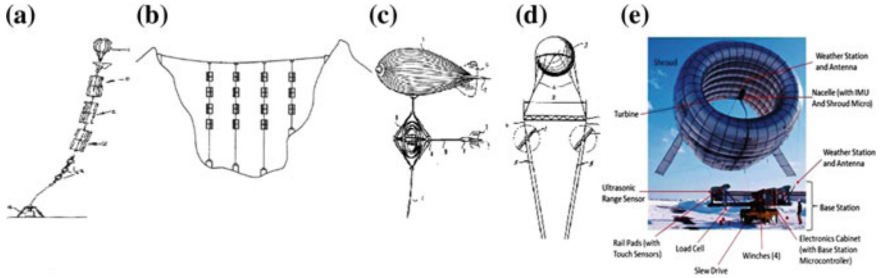

Fig. 2.3 **a** Schematic representation of C M Fry et al. design [41]; **b** Schematic representation of C.M. Fry et al. design [41, 42] using Beldimano's design [43]; **c** Schematic representation of Alberto's Kling's design [44]; **d** Schematic representation of Airship- Windmill [45]; **e** System diagram of Altaeros Energies horizontal axis airborne wind generator [46]

i. William K. Watson's "Airship-floated wind turbine" [47],
ii. Nykolai Bilaniuk's "Airborne wind powered generator" [48].

Although balloon type floating aerogenerators are considered the most stable type floating aerogenerators, but the gas (lighter than air) used for filling these balloons are hydrogen which is sensitive to ignition and helium which is limited and costly [49].

2.2.3 *Multi-copter or Rortorcraft Type*

Multi-copter or rotorcraft type exploits the aerodynamic forces into tensile forces by wind turbines to produce electricity. Flying along controlled path, wings produces aerodynamic and aerostatic lift, which sustains the structure. Due to the rotors, its easy for take-off and landing and during ow or no wind motion these rotors from the ground station power, sustains the structure in air. Few of the available prototypes apart from the one shown in Fig. 2.4, are as follows:

i. Flying Electric Generator [50, 51]
ii. Peter R. Payne et. al's "Self-Erecting Windmill" [52].
iii. Airborne Cyclically controlled power generation using autorotation [53]
iv. Power generation from High Altitude Winds [54]
v. Aleandro Soares Macedo "Hovering wind turbine" [55].

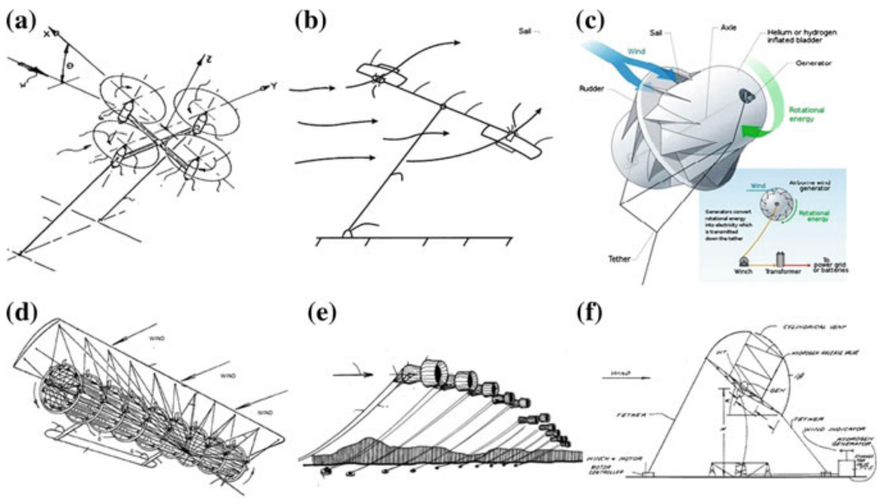

Fig. 2.4 **a** Schematic representation of Flying Electric Generator [50, 51]; **b** Schematic representation of Airborne cyclically controlled power generation using autorotation [53]; **c** Schematic representation of MARS [57]; **d** Schematic representation of David H. Shepard design [54]; **e** Schematic representation of Air Ship Power Turbine [59]; **f** Schematic representation of Tethered Airfoil Wind Energy Conversion System [60]

vi. Magenn Air Rotor System (MARS) [56–58]
vii. Air Ship Power Turbine [59]
viii. Tethered Airfoil Wind Energy Conversion System [60]

2.3 Discussion

Above mentioned HAWE techniques are still under prototype stage and it will take considerable amount of time to make it commercially viable. Although there are several industrial players who are working in this sector like Mahenn Power Inc., Sky WindPower, Joby Energy [61], Makani Power [62], Windlift, Swiss Kite Power, Skysails GmbH, which indeed is a promising fact and will boost confidence of other investors to invest in this sector. Summary of the HAWE harnessing floating aerogenerator prototype classification has been presented in Table 2.1. As per the available literature, a comparative analysis among the different prototypes of floating aerogenerators has been shown in Table 2.2.

HAWE based floating aerogenerators should possess the following attributes [63]:

i. Light weight of the system, which includes generator, wings, blades, balloon etc. [64, 65]
ii. Tethers used for floating aerogenerators have to be rigid enough to sustain the tensile strength and in the same time should have the best power to weight ratio (P/W) [66].

Table 2.1 Summary of floating aerogenerators [67]

General system description	Company	Flying principle	Type	Energy generation system
Turbines on a tethered aircraft	Makani Power	Wings lift	Crosswind	6/8 turbines
	Joby Energy	Wings lift	Crosswind	Several turbines
Tethered Quadcopter	Sky Windpower	Rotors Thrust	Non-Crosswind	4 turbines
Turbines on a lighter than air balloon	Altaeros Energies	Buoyancy	Non-Crosswind	1 turbine
Magnus Effect Turbine	Omnidea	Buoyancy	Non-Crosswind	Buoyant Wind turbine

Table 2.2 Comparative analysis of floating aerogenerators

Floating aerogenerators	Production cost	Wind operability	Mass (kg)/Area
Magenn Air Rotors	20 cents/kWh[a]	3–28 m/s	
Fagiano L M et al. [13, 68] (HAWE)	20 $/MWh	4–25 m/s	500 m^2
Altaeros Energies BAT		Can sustain 44.7 + m/s [69]	
Peter Lynn Guerilla Kite		14–24 mph	
Laddermill [21]	4.38 cents/kWh[c]	4–25 m/s [23]	
Flying Electric Generator by Bryan W Roberts et al. [70]	20 $/MWh	10–35 m/s [d]	9500 kg
Magenn Air Rotor System (MARS)	124 $/MWh [71]	2.5–30 m/s [72] Sustain up to 40 m/s [56]	159 kg [56]

[a]Compared with diesel
[b]Considering Capacity Factor (CF) approximately 0.6
[c]Based on Netherlands Energy Research Foundation (ECN) Simulation model
[d]At an altitude of 4600 m

2.4 Conclusion and Future Perspective

Floating aerogenerators are promising source of HAWE harnessing and conceptually proved their stability. In the last decade, considerable amount of work has been done in the form of patents, prototypes and investment from private and governmental bodies. Depending upon the investment and risk associated with floating aerogenerators, fixed type, small scale floating aerogenerators should be used. Technologies used in floating aerogenerators are at very nascent stage and it will go through with research in perspective of design, material, power electronics to make it viable in long run. Kenny Phan et al. [73] has forecasted a consisted growth of wind energy harnessing in coming decades.

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