TAMPERE UNIVERSITY OF TECHNOLOGY
International Master's Programme in Business and Technology

IMANOL CORTÁZAR GARCÍA DE LA TORRE

TECHNOLOGICAL EVOLUTION OF THE WIND POWER INDUSTRY

Master of Science Thesis

Senior Researcher Marko Seppänen and Professor Saku Mäkinen have been appointed as the examiners at the Council Meeting of the Faculty of Business and Technology Management on December 12, 2009.

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master’s Degree Programme in Industrial Engineering and Management

CORTAZAR GARCÍA DE LA TORRE, IMANOL: Technological evolution of the wind power industry
Master of Science Thesis, 89 pages
May 2010
Major: Industrial management
Examiner(s): Senior Researcher Marko Seppänen and Professor Saku Mäkinen
Keywords: Wind power industry evolution, industry life cycle,

This Master of Science Thesis studies the wind power industry evolution with the objective of evaluating its current status, the near future development and the alternatives to the wind turbine dominant design. For achieving that objective, the study is based on industry evolution analysis tools as the industry life-cycle theories the technology cycles and the *ARI model* (Accelerated Radical Innovation) which focuses on the development and market penetration of the radical innovations.

The thesis is divided into three parts. The first part presents the industry life-cycle theories, the technology cycles and the industry dynamics. On this part there is a special focus on the *ARI model*. The second part provides a brief summary of the history of the wind power industry and also of the key-factors that have influenced on the industry development. This second part also studies the characteristics of the alternative models of wind turbines and their potential for entering into the market of the electricity generators.

The third and last part of the thesis evaluates the information exposed on the second part according to the explained theories. The results show a clear growing trend of the sector and also an evident technological trend toward bigger and more powerful wind turbines. The maturity stage is not expected to arrive until at least the year 2020. During this process the industry will have to achieve several challenges in order to meet the expectative. Two of the most important challenges are: the necessities of lower the total cost of the wind energy production and, also, develop wind turbines that adapt better to the conditions of the location for, thus, optimize their efficiency.

As for the alternative models, for the moment there is not any design with enough potential to substitute the dominant design as massive electricity generator in a short and medium term. However, for the domestic and small scale electricity generation there are a great variety of models for its big potential for the future implementation in rural and urban areas. This thesis, among all the studied models, emphasizes three particular designs: the multi-rotor wind turbine, the Magnus wind turbine and the helicoidally vertical axis wind turbine (VAWT) as an evolution of the Darrieus turbine.

RESUMEN

TAMPERE UNIVERSITY OF TECHNOLOGY
CORTÁZAR GARCÍA DE LA TORRE, IMANOL: Evolución tecnológica de la industria eólica
Proyecto Fin de Carrera, 89 páginas
Mayo 2010
Especialidad: Organización Industrial
Supervisores: Dr. Marko Seppänen y Profesor Saku Mäkinen
Palabras Clave: Evolución industrial, industria eólica, ciclo de vida industrial, modelos alternativos, multi-rotor, Magnus, Darrieus

Este Proyecto de Fin de Carrera estudia la evolución de la industria eólica con el objetivo de evaluar su estado actual, su desarrollo en un futuro próximo y las alternativas tecnológicas al modelo dominante de turbina eólica. Para ello se basa en instrumentos de desarrollo industrial como son las teorías de ciclo de vida de la industria, los ciclos tecnológicos y el modelo ARI (Accelerated Radical Innovation) que se centra en el desarrollo y penetración en el mercado de las innovaciones radicales.

El proyecto está dividido en tres partes. En la primera se presentan las teorías de ciclo de vida industrial, ciclos de innovación y de dinámica industrial. En este apartado se le da una especial atención al modelo ARI. En la segunda parte se presenta un breve resumen de la historia de la industria eólica así como de los factores que han llevado a la industria a su estado actual. En esta segunda parte también se estudian diferentes modelos de turbina eólica y su potencial para entrar en el mercado de producción eólica de energía eléctrica.

En la tercera y última parte se evalúan los datos expuestos en la segunda parte de acuerdo con las teorías explicadas anteriormente. Los resultados muestran una clara tendencia creciente del sector y una evidente tendencia tecnológica hacia turbinas más grandes y potentes. No se espera la llegada a la etapa de madurez del sector hasta por lo menos el año 2020. En este proceso se observan retos que la industria va a tener que superar para cumplir esas expectativas. Los más destacados son: la necesidad de reducir el coste total de la energía eólica, así como desarrollar turbinas que se adapten mejor al medio en el que se encuentran para, así, conseguir maximizar su rendimiento.

En cuanto a los modelos alternativos, por el momento no hay ninguno con el potencial suficiente para sustituir al modelo dominante como generador masivo de electricidad a corto y medio plazo. En cambio para la generación doméstica de electricidad a pequeña escala hay una gran diversidad de modelos con un gran potencial para su futura implantación urbana y rural. Esta tesis hace un especial énfasis en tres de estos modelos: la turbina multi-rotor, la turbina Magnus y la turbina helicoidal de eje vertical como evolución de la turbina Darrieus.

LABURMENA

TAMPERE UNIVERSITY OF TECHNOLOGY

CORTÁZAR GARCÍA DE LA TORRE, IMANOL: Industria eolikoko bilakaera
Karrera-amaierako proiektua, 89 orrialdeak
2010.eko maiatza
Espezialitatea: Antolakuntza industriala
Begiraleak: Marko Seppänen doktorea eta Saku Mäkinen irakaslea
Hitz gakoak: Eboluzio industriala, industria eolikoa, bizi-ziklo industriala, ordezko modeloak, multi-rotor, Magnus, Darrieus

Karrera-amaierako proiektu honek industria eolikoaren eboluzioa aztertzen du, oraingo egoera, etorkizunean izango duen garapena, eta haize-turbina eredu nagusiaren hautabide teknologikoak ikertzeko asmoz. Helburu hau lortzeko, garapen industrialeko baliabideetan funtsatzen da, hala nola, industriaren bizi-zikloaren teoriak, ziklo teknologikoak eta ARI (Accelerated Radical Innovaiton) eredua. Azken honek berrikuntzen garapena eta merkataritzarako bideak aztertzen ditu.

Proiektua hiru ataletan banatzen da. Lehenengoan, bizi-ziklo industrialaren, berrikuntza-zikloen eta industria dinamikoaren teoriak azaltzen dira. Atal honek ARI eredua du oinarri. Bigarren atalean, industria eolikoaren historiaren laburpen txiki bat azaltzen da, baita industria gaurko egoerara eraman duten faktoreak ere. Atal honetan, halaber, haize-turbina eredu ezberdinak ikertzen dira eta, horrez gain, haizeari esker lortutako energiaren merkatuan sartzeko izango lituzketen aukerak.

Azken atalean, aurrerago agertutako datuak ebaluatzen dira, azaldutako teoriak erabiliz. Datuek erakusten duten sektore honen joera baikorra da, eta teknologiari dagokionez, turbina handiagoak eta indartsuagoak lortzeko bideratuta dago. Hala ere, 2020. urtera arte gutxienez, badirudi ez dela arloaren heldutasuna lortuko. Prozesu honetan, industriak hainbat erronkari aurre egin beharko dio. Nabarienak honako hauek dira: energia eolikaren kostua murriztea eta ingurunean hobeto egokitzen diren turbinak garatzea, etekin onena lortzearren.

Eredu alternatiboei dagokienez, gaur egun, ez dago modelo nagusuari aurre agin diezaiokeen modelo alternatiborik, epe labur edota erdikoan elektrizitatea orokorki sortzeko. Eskala txikiko sorgailuen artean, berriz,aniztasun izugarria badugu eskura herri eta hirietan berehala erabiltzeko. Tesi honetan azken hauetako modeloen artean, hiru aztertzen dira bereziki: multi-rotor turbina, Magnus turbina eta Darrenius turbinaren bilakaera den ardatz bertikalako turbina helikoidala.

PREFACE

The work of this Master of Science thesis was carried out in the Department of Industrial Management of the Tampere University of Technology as an agreement between both Escuela Superior the Ingenieros de Bilbao and Tampere University of Technology with the assistance of the Erasmus Program.

First of all I would like to express my gratitude to Dr. Marko Seppänen for the guidance and supervision during the whole process. I am also grateful to CITER research group, especially Professor Saku Mäkinen who gave me the opportunity to write this Master of Science thesis on the Department of Industrial Management. I would like to extend my thanks to Ozgur Dedehayir who helped me on the most critical moments of the theoretical research process. I am also very grateful to Mikel Iglesias and Estibaliz Palma for the excellent traduction of the *Abstract* into Basque.

In addition, I would like to thank all the people that has supported me during this year in Tampere. It is impossible to mention all of them but I am especially grateful to Despoina, Diego, Marcos, Lucía, Paula, Enrique, Elena, Luis, Pepa, Frederico and Adèle for being there whenever I have needed them.

This thesis is the culmination of a process that started six years ago when I was accepted in the Escuela Superior the Ingenieros de Bilbao so it would be unfair not to thank to all the people who has sheared with me those five fantastic years in Bilbao: Aitor, Julen, Álvaro, Pablo and, especially, Lola.

Finally, thanks to my mother Mila, my sister María and my grandparents Dita and Antonio for their love, support and inspitarion during all these years.

Tampere on the 15th of May 2010

Imanol Cortázar García de la Torre

imanolcortazar@hotmail.com
c/La baranda 5
01010 Vitoria-Gasteiz, Araba
Spain

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1. Introduction

Wind power systems have existed for centuries. Windmills were used for extracting kinetic power from the wind and transform it into mechanical power. The first known use of this power was for moving grinding mills. After, the rotational motion was also applied to water pumps. And on the last part of the 19^{th} century it became the source of mechanical power of some industries in central Europe. The first windmill dedicated to the production of electric power was constructed in1890 but is not until 1970, almost one century later, when the governments and companies started investing seriously on the real alternative of the wind power as a source of electric power. Since the year 2000 the production of wind power energy has grown exponentially. Nowadays wind power industry is considered one of the most promising industries of the world. Governments and companies are making huge efforts to promote this power source. But when this growth is going to stop? The actual industry model is going to prevail or is it going to be substituted by other one more sophisticated? Which are the limits of the actual and most extended design?

For finding the answer to all those questions it is necessary to do a deep analysis of the factors that influence the industry, of the past development, and of the predictions for the future. On this thesis the analysis is done based on structured frameworks of industry evolution. There is a special focus on the role of technological innovations and stages of the industry.

First of all, for understanding the current situation it is essential to study the path that the industry has followed since its origins. Thus we can identify the key factors that have modeled the wind power industry until the actual model. The Accelerated Rapid Innovation (ARI) model (Bers, Dismukes et al. 2009) provides a framework for studying the steps and stages of the wind power industry since the 70's decade. The modern wind turbines are the combination of many technological innovations from different fields as mechanic, control systems, power electronics and so on. The fast combination of these systems on the last 15 years makes the ARI model a perfect reference for the study of the industry development.

The industry life-cycle theory (Abernathy and Utterback et al. 1978) divides the life of an industry into stages. It is one of the oldest models of industry evolution but although its antiquity it still a reference of the industry development models. Despite it is not very detailed provides the basis for the more developed models and theories (e.g. McGahan 2000). In the case of the analysis of the wind power industry it is very important to identify the main stages of the industry life cycle. The wind power industry is becoming a global business but nowadays there are still many differences of industry development among continents and even among countries. In some European countries as Spain or Portugal the industry is growing with very high rates. However in other European countries as Denmark, the industry growth has normalized and is not as powerful as in the past. There are countries as China where this technology and business model has been introduced recently but where the growth is increasing strongly. Finally in the South American and African countries there is a huge potential for the wind industry but the implementation can be qualified as experimental. This generalized and simplified global picture shows that the stage of the industry life-cycle is not a global fact and varies among the regions. This thesis focuses its analysis mainly on the European industry. Europe has been the pioneer of the wind power and nowadays still being the global reference; the oldest and most powerful manufacturers of wind turbines are European and the power installed in the “old continent“ is higher than in any other region of the world. The European wind turbine manufacturers are a global reference in its sector.

Another important point of this thesis is the internal and external factors that have influence over the industry. To obtain electrical energy from the wind is possible since the last years of the 19th century. So, which factors have stopped the evolution of the industry during almost all the 20th century and which other factors have triggered the fast development of the last 20 years? Studying and analyzing these factors it is possible to have a general understanding of how the facts that influence the wind business. Thus analyze which influence will have in a medium and long term in the future.

The structure of the industry in changing constantly, some authors (Gort and Klepper 1982) establish the different stages of the industry looking to the number of participants of the industry. There are not many companies that manufacture wind turbines. Building a wind turbine is a very complex process and requires a great number of human, technological and economic resources. It is for that reason that the amount of participants is quite restricted. However the entry and exit from the industry is a useful tool for the analysis of the industry. This analysis is accompanied by a study of the barriers (Porter et al. 1977) of entry to the industry.

Nowadays the wind power industry has a well defined “dominant design” (Suarez and Utterback 1993). The three-blade in-shore wind turbines are the unquestionable market leader. This thesis summarizes the technological evolution of the actual model of three-blade wind turbine and also the development trends of the major companies. In this critical moment of the industry is essential to take into accounts which are going to be the short term innovations that will support the next wind turbines generations.

However there are several alternatives to the actual dominant design. Off-shore wind farms are not a new innovation. The first models were installed on Denmark

(Baltic sea) on the year 1991, but it is not until now when the interest about this kind of wind farms is increasing. The general trend is to make bigger and bigger wind turbines but that also create new challenges on the manufacturing, transport and installation aspects.

But there are also other ways of generating electric power with the wind. Some companies offer models completely different from the dominant design. For the moment those experimental designs do not represent a real alternative for the dominant design. However future improvements of these models can have a place in the market for certain applications and hypothetically become the future dominant design. One of the objectives of this thesis is to study the actual alternatives and evaluate the real opportunities of the models according to the industry evolution theories and characteristics of each design.

In order to conclude the introduction, the main idea of this thesis is to show a historical overview of the evolution of the wind power industry since its beginnings and to provide the clues of the future development of the industry.

2. Theories of industry evolution

The study of the evolution of an industry requires a theoretical background. Researchers and scholars have studied the industry evolution in order to obtain models that explain the behavior of the industries. These models provide organized frameworks that allow the researchers to compare between industries and via analyzing the past, determine the future trends. From the managerial point of view, the industry evolution theories are used to assess the strategic decisions of a company.

2.1. Basic concepts

The basic ideas about the industry evolution and development are not new. The existing models of industry life-cycle are based on the hypothesis that the industry follows a predictable pattern of change. Most of the theories divide their models into different stages. The first models were conceived by the pioneers of the industry life cycle theory; Abernathy, Utterback and Clark. They proposed that the industry had a cyclic behavior and they differentiated those stages of the cycle by analyzing the innovative perform of the firms. McGahan (2000 and 2004) develops a new theory. Instead of defining stages she defines industry trajectories. Each of those trajectories have its own and particular characteristics and defined patterns.

The concept of technology cycles (Anderson, Tushman et al. 1996) is very linked to the industry evolution theories. The objective is to maintain the competitive advantage over the time by adapting the company's strategy to the situation of the industry inside the model. Thus, the innovative streams also play an important role from the managerial point of view. With a proper interpretation of the industry situation throw this models it is possible to anticipate and choose the best strategy in order to achieve competitive advantage over the competitors.

The definition and types of innovation is also a topic that has captured the attention of many experts. The first classification came at the same time as the first industry life cycle theory but with every new model there is a new classification. In this text the basic types of innovations from Abrnathy and Clark (1985) are explained.

The following three sections explain the most important concepts within the industry life cycle theories

2.1.1. Stages of industry life-cycle

In a summary of his studies, Utterback (1996) explained a model of dynamics of innovation in the industry. This model is focus on the product and process innovation and shows the rate of major innovation for both.

As the Figure 2.1 shows, on the first years the rate of product innovation is very high. During this period, called "fluid phase", it is very usual among the competitors to experiment with many prototypes. In the early years of a new technology there is a huge amount of possibilities for its application. Each company aims to get the attention of the buyers on their innovative products. The organizations are more focused on the product innovation than in the process innovation so the development of these last ones is done less rapidly. All the efforts are made towards the consolidation of the new product as a "dominant design" and gradually all the experiments start to converge around this model. The priority is growing in market-share by improving the company's product. Optimizing the different industrial processes to make the already-design invention is not so important at this early stage. Depending on the specific characteristics of the industry this phase can have very wide range of lengths, from one year to several decades.

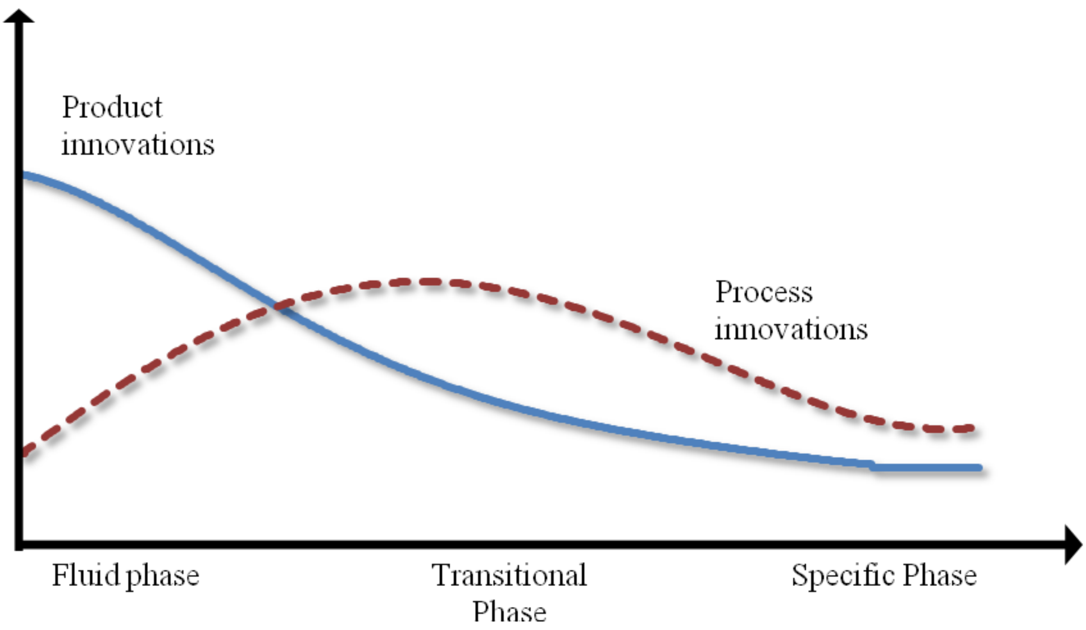

Figure 2.1. *Industry Dynamics by Abernathy and Utterback (1978)*

After this initial stage and always according to the model, there is one design that prevails over all the other prototypes. This is called the "dominant design" and emerges over the variety of different models to become a reference of the industry. When this happens, the amount major product innovations decreases and the rate of major process innovations speed up. The variety of articles decreases and, at the same time, those products are standardized in order to contribute the economy of scale. The processes must be optimized, so the innovative activity is focused on obtaining the same product but with lower cost.

The third stage takes places in some industries. Abernathy and Utterback explain in their model that the rate of innovations decrease dramatically for both product and process. Companies are extremely focused on the costs, volumes and capacities; product and process innovation appears in small, incremental steps. (Utterback 1996)

The most useful applications provided by the model apply to production processes in which features of the products can be varied. The most interesting applications are to situations where product innovation is competitively important and difficult to manage; the model helps to identify the full range of other issues with which the firm is simultaneously confronted in a period of growth and change. (Abernathy & Utterback 1978)

A new point of view is exposed by McGahan (2000). In her opinion the industries evolve along four distinct trajectories: radical, progressive, creative, and intermediating. (McGahan 2000). The strategy of a company cannot succeed unless it evolves according to the industry's change trajectory. The trajectories set boundaries on what will generate profits in a business. Many companies who have tried to innovate outside the boundaries of the industry trajectory have incurred losses.

There are two dimensions in the classification of the trajectories: core activities and core assets. Core activities are particular strengths of a company that attract and retain suppliers and buyers. Core assets are the resources, tangible or intangible, that make a company perform more efficiently the core competences.

Radical change happens when both core competences and core assets are threatened with some outside alternative. This normally occurs when a new technology comes massively into the market. The old products and processes become obsolete rapidly. Some radical regulatory changes can also cause a radical change in an industry. Usually the changes are not sudden, in some cases they take decades, but the end result is a completely reconFigured industry. When a radical change occurs the companies must focus on the implications that the change has on their current strategy and decide between exiting the industry or invest on developing new assets and products. When the company decides to move from their established positions to the new emerging line it is exposed to enormous risks in the process.

When the core assets of an industry retain the most of the value (if they are managed correctly), but the core competences are threatened, then intermediating changes happen. The relationships with the long time customers and with the old suppliers become fragile. From the managerial point of view this is a very difficult situation and the common tendency is to underestimate the threats to the industry. Companies must simultaneously preserve their valuable assets and restructure their key relationships. A way of facing the intermediating changes is diversifying their products and entering into new markets. Thus there is a possibility of changing the activities and getting new customers while maintaining the core resources. Organizations that recognize early the intermediating trajectory usually have long periods for managing a strategic transformation.

The creative changing trajectory entail constant changes on the core assets while the core activities prevail. McGahan (2004) explains this mode of change with the animation film industry. The relationship of the studios with the suppliers and customers are generally stable. But the nature of the industry requires using different assets – actors, actresses, locations, visual effects, etc. – for each new film or audiovisual project. The pharmaceutical industry is a clear example inside the manufacturing industry. It develops constantly new drugs and patents for the same market using the same supplier. This kind of industry trajectory has not been studied deeply but it is characterized for continuous innovative activities in a stable network.

Progressive evolution refers to a creative development where most of the players have incentives to preserve the existing network. The innovative activities are almost limited to the incremental innovations. The core resources become more valuable with the time. The continuous innovative activity has cumulative effects which represent an important entry barrier to the potential entrants. These are considered low risk industries because they don't have to put large amounts of capital at risk before learning whether an innovation creates value. Success in these kinds of industries is usually linked to the ability to respond quickly to the feedback of the final customers.

Klepper's (1996) points out that when a product is introduced, there is considerable uncertainty about user preferences (even among the users themselves) and the technological resources of satisfying them. As a result, many firms producing different variants of the product enter the market and competition focuses on product innovation. As users experiment with the alternative versions of the product and producers learn about how to improve the product, opportunities to improve the product are exhausted and finally product standard, also called dominant design, emerges (Klepper 1996).

Indeed all the exposed theories different in their structure .Each one focuses in a particular point of view of the industry. However, these theories are not incompatible among themselves. Actually, for a correct interpretation of the industry evolution it is very advisable to compare the results of the study with more than one theory in order to obtain different points of view and, thus, obtain more realistic conclusions.

2.1.2. Technology cycles and innovation streams

The competitive advantage is build around the combination of diverse types of innovative behaviors. Successful companies must promote not only the incremental innovations, also product substitutes and architectural innovations. The ability to manage the streams of different kinds of innovations drives to the sustained competitive advantage. A profound understanding of the technology cycles is needed for this task.

Technology cycles are caused for first instance by technological discontinuities that threaten the already existing technology. The scientific advances or the combination of the existing technology are unpredictable. These disruptive happenings introduce an era of turbulent innovation also called era of ferment. Such periods involve between the old and the new technology and also between different variants of the new technology. The era of ferment continues until a standard design called dominant design emerges. The factors that influence the appearance of the dominant design have been much discussed but the most agreed causes are the technological trajectories of the competitors and the political, social and economic circumstances. The position of the dominant design is reinforced by incremental innovations until this regimen is broken by the next substitute product. Then the next technology cycle starts again in the new technological level. Anderson, Tushman and O'Reilly(1996) called these four steps of the cycle: technological variation, era of ferment, selection and retention.

Anderson, Tushman and O'Reilly(1996) introduce the concept of innovation streams. These are defined as patterns of innovation that are required for maintaining the competitive advantage of a firm on the market. Their study focused on products which are made of a set of subsystems (eg. Watches and hearing aids). The innovation streams can be seen in both product level and product subsystem level.

Innovation streams depend on the technology cycles. They define the nature of the innovative activities in each period of the technology cycle. According to the model of technology cycles the authors declare that eras of ferment involve the creation of different models with many and discontinuous product variants but also associated with fundamental process innovations. When the dominant design is identified the innovative effort must be done not only in the incremental mode. The eras of incremental change are associated with streams of incremental and architectural innovation. From the managerial point of view this theory helps to shape the technological evolution and maintain a competitive advantage with proactive decisions.

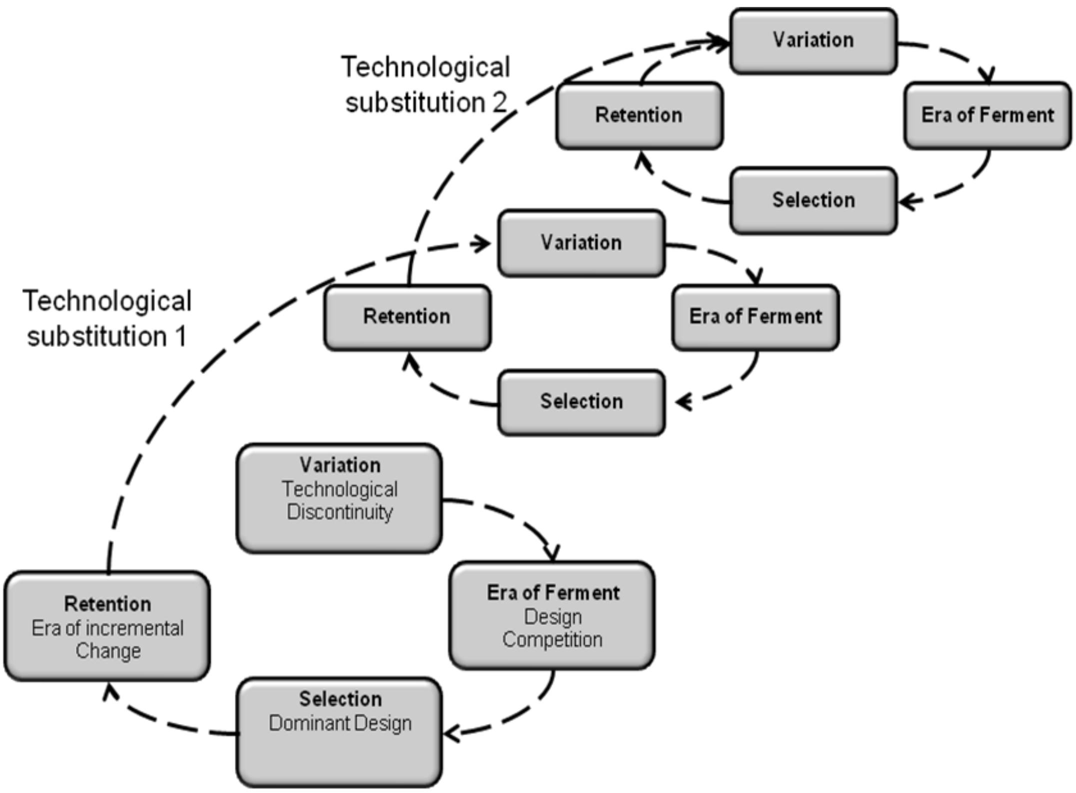

Figure 2.2 *Technology Cycles (Anderson et al. 1996)*

2.1.3. Innovations

According to Gray (1973), an innovation is generally defined as an idea perceived as new by an individual. But in the industrial environment this definition is not enough. An innovation is not just a new idea; an innovation is an idea applied effectively to a real case. (Gray 1973)

The first classification of innovations was made by Abernathy (1978). The two main types are incremental and radical innovations. Incremental innovations are those that improve gradually the products and the production processes. There is any technological discontinuity in the innovative process. Companies use the incremental innovations to improve the efficiency of the processes. The processes are standardized progressing in the economies of scale. The innovations have a cumulative effect in the performance of the firm. They contribute to the increase of the productivity and reduction of the costs. On the other hand, the radical innovations represent a discontinuity on the technological development of a product or process.

These two categories, incremental and radical, are the support of deeper analysis about the nature of innovations. The different innovations are linked to the Industry evolution models of each author. Abernathy and Clark (1985) distinguish four types of innovations included in a two-by-two matrix. The first variable is the nature of the technological innovation. The second one is the market linkages. Both of them can be conservative or disruptive.

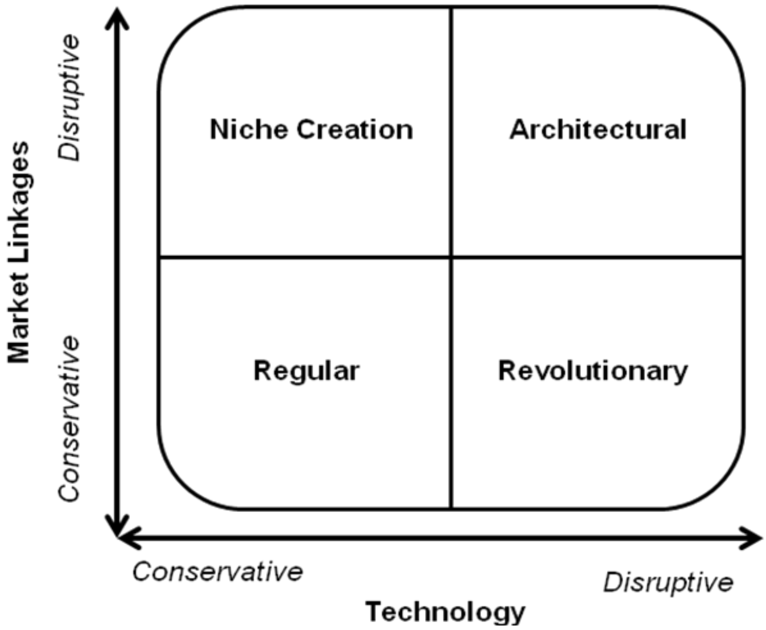

Figure 2.3. *Innovation categories by Abernathy and Clark (1985)*

The regular innovations are built over the existing technology to serve the existing customers of the market. This is the most extreme case of incremental innovation because the both parameters are conservative. It is frequent to find them inside the transitional and specific stages (Utterback 1996). The Niche creations although they also build the innovation over existing technology, are targeting new markets. So the old technology is used with new purposes enlarging the number of potential customers. On the other side of the regulars innovations there are the architectural innovations. The architectural innovations represent a strong discontinuity on the technological evolution and furthermore also reshape the market organization. There are new industries created around these innovations that change the technological core of the business. Old industries are obliged to reinvent themselves in order to survive. The innovation is followed by a fluid stage of the industry and usually after this phase there is a dominant design that emerges and changes the innovative type to regular. The fourth innovative type is the revolutionary innovations where a new technology is introduced into an existing market. There are several studies about the behavior of the companies when they face this kind of innovations. Revolutionary innovations create new businesses and transform or destroy existing one. (e.g. mechanical ice-making destroyed the New England ice-harvesting industry, Utterback 1996, 145-167).

The model developed by Tushman and Anderson (1986) focuses on the effects of the innovations over the competence distinguishing between competence-enhancing and competence-destroying innovations. The first ones are usually developed by industries which are already operating in the sector. These innovations are built over existing and internal knowledge so they represent a technological barrier to the new potential entrants. On the other hand the competence-destroying innovations are more common among the new companies which wish to enter into a certain market area dominated by other companies. Through the competence-destroying innovations the entrants create opportunities.

2.1.4. Dominant design

The dominant design is a concept used by most of the authors when they describe the product and industry life cycle theories. The idea was first introduced by Abernathy and Utterback (1975, 1978 et al.) in several articles. In the early stages of the industry the firms try to satisfy the desires of the customers (which are not fully defined). The organizations try to suit the potential customers offering radical variations of the products. Once the basic requirements are defined the next wave of innovations tries to refine the original designs. These innovations are incremental and cumulative. When the dominant design is fully defined all the efforts are done towards achieving more efficient processes and cost reduction. The production before the appearance of the dominant design is inefficient and unorganized. The dominant design allows the producer to standardize the process and train the workers according to it. As a conclusion, the dominant design transforms the structure of the industry from an unorganized and inefficient production to an effective business providing the customers the goods that satisfy their desires (see Peltoniemi 2009).

According to Suarez and Utterback (1993, pp. 416) “A dominant design is a specific path, along an industry’s design hierarchy, which establishes dominance among competing design paths” (Suarez and Utterback 1993). This introduces the concept of design hierarchy. According to this model, designs which go up on the design hierarchy destroy the existing competence by focusing on new attributes of the products. On the other hand, the designs which go down on the design hierarchy would face the competence via improving the product main attributes with incremental innovations.

As some authors have noticed (Teece 1986, Suerez and Utterback et al. 1995) the dominant design model adapts better to the markets where the customer necessities are reasonably uniform. In some articles where the product key-features vary dramatically between users is more difficult (and in some cases impossible) to find a comparable attribute between products. In the markets of the non-assembled products it is simpler to find a dominant design because the product is more related to the process so the most efficient companies capture rapidly the market-share (eg. Glass industry).

There are several mechanisms of how a design becomes a dominant design. According to Teece (1986) the establishment of the dominant design is related to the entrants of new firms in the industry. This fact fits in the theories of Tushman and Anderson (1986) that mark the end of the “era of ferment” with the apparition of the dominant design. New companies use the research done by their competitors to enter the market. Thus, they design articles with similar features to the existing products. So the competitive activity is done under the same criteria of evaluation and comparison. According to Henderson and Clark (1990) the mechanism to define the dominant design depends mainly on two factors; the economy of scale and the network externalities. Companies that achieve a competitive economy of scale on the manufacturing process of their product are able to sell cheaper articles and have bigger returns than their competitors. The network externalities on the other hand can make a certain product more attractive to the eyes of the customers. Both factors turn eventually into higher returns and a successful performance of the industrial activity. When the number of users raises the amount of resources to improve the industrial and commercial processes also increase (see Peltoniemi 2009).

A powerful factor that determines the dominant design is the strategic alliances between firms. In the industries with a unique and dominant company (eg. Coca-Cola), it is this company who sets the dominant design. Finally there are cases where the dominant design is conditioned by governmental regulations such as safety, economic or environmental laws.

Although the mechanisms of selection of a dominant design have been conscientiously studied, almost all the experts affirm that the phenomenon of emergence of a dominant design is unpredictable due to the countless factors that take part into the process. The appearance of a dominant design is the end result of an auspicious combination of technological, social, financial and managerial factors (Suarez and Utterback 1995).

2.2. Industry dynamics

2.2.1. Entries and exits

A very common parameter for measuring the evolution of a certain industry is the number of companies that enter and exit the market. These rates are an indicator of the general profitability of the business. It is a very complete analysis because involves many variables as the entry and exit barriers and stage of the innovative cycle.

The entries and exits of companies in an industry has been object of several studies from different perspectives. According to Porter (1979) in some industries the early entrants have lower costs compared to subsequent firms that want to follow a similar strategy. Furthermore in some cases the late entrants are unable to follow the path of the previous companies so they are obliged to select different ones. (Porter 1979).

Gort and Klepper (1982) focused their attention on the number of firms in an industry. After a deep research work they devised the following five-stage model.

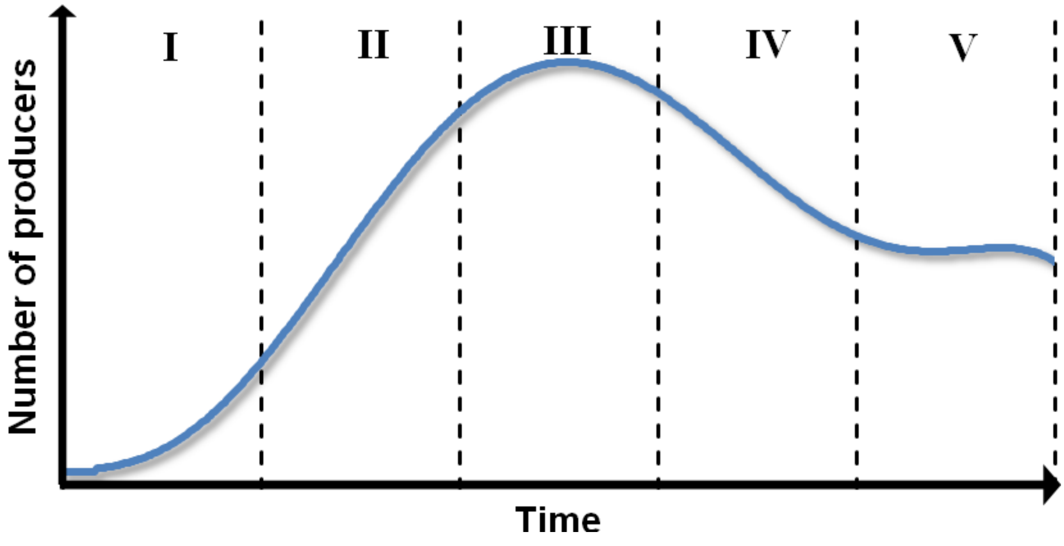

Figure 2.4. *Five stages of new product industries by Gort and Klepper (1982).*

The first stage, Stage I, the new product or technology is introduced, normally by one pioneer producer and in some special cases by more than one. When the product starts to be known by the customers, the number of entries suffers a sharp increase. Most of the new competitors have identify a business opportunity in the sector, but some other theories suggest that these entrants could come also from firms that want to diversify their products or even companies who want to escape from a declining sector.

On the Stage II there is a notably growth on the number of producers. This stage is almost common in all the new product markets. The demand grows rapidly so the existing companies cannot capture the whole market-share. Normally new companies focus their efforts on new products and innovations fading into the background the efficiency and the process innovations. According to the innovation stream theory (Anderson et al. 1996) companies should center on process based innovation for having more possibilities of reinforcing their position on future stages of maturity.

On the third stage, Stage III, there is stabilization on the number of participants. The number of entrants is balanced with the increasing rate of exits. This stage could correspond with the maturity stage of other theories. However, Klepper (1982) does not attribute this stability between entries and exits with the equilibrium of the market. His reasoning points out that this situation is caused by the structural changes of the industry. This maturity of the market on his opinion is the base for the fourth stage (Klepper 1982).

Stage IV is the consequence and end of the structural changes that take place on the Stage III. The period is characterized by a fully negative entry. The end of this stage is characterized by normalization on the rate of entries and exits, which is the starting point of the fifth and last stage.

On the Stage V the rates of exits decreases but the number of entrants is close to cero so the number of participants decreases slightly. Gort and Klepper (1982) associate this decline of the industry with the eventual shrinkage of the market. The products fall into disuse or are substituted by new products from a emerging technology (Gort & Klepper 1982).

In a posterior text, Klepper (1996) identifies six regularities within his previous model of industry entries and exits. These findings are a result of a deep analysis of the development of several industries.

- The first regularity focuses on the number of entrants. In most of the cases it is possible to distinguish two different patterns in the rate of entries; the number of entrants may increase over time or get its maximum at the beginning of the industry. However, in both cases the number of entrants finally becomes small.

- The second regularity refers to the number of producers. Although the number of companies decreases after reaching the industries peak, the industry output maintains a continuous growth despite the decline of participants.

- In third place, Klepper (1996), affirms that at the end of the cycle, the industry stabilizes and the market-share of the dominant firms decreases so the leadership of the industry stabilizes.

- The sharp increase of entrants is associated with the peak of product innovations. When the number of entrants stabilizes the number of innovations decreases and fall over time.

- The efforts in product innovation are substituted progressively with the efforts on process innovation.

- In the period of growth most of the product innovations come from the most recent entrants.

2.2.2. Barriers

The new firms which wish to enter to an industry have to face an uncertain process. There are some factors that discourage the companies to enter into an industry; these are known as entry barriers. In economics the barriers to entry are also known as obstacles in the path for the companies that want to enter a market. On the following paragraphs the main barriers of entry for heavy manufacturing companies, as the wind power industry, are mentioned and explained.

Caves and Porter (1977) define some barriers to the new competition. In first place some existing firms can experiment a situation of excess of capacity. When a firm moves into a new market if the expected sales are overestimated and the initial investment is exaggerated the firm can be incurring into costs of non fixed assets that is going to use inefficiently or in some cases not even use. If there are extra funds is preferable to retain them in other kind of investments as financial products or fixed assets. On second place and also recognized by other authors as Robinson and McDougal (2001) it is the product differentiation. This fact represents an important entry barrier in industries with high degree of product differentiation. However in the industries with very low product differentiation are also unattractive for new players because the firms have to focus heavily on the efficiency of the production for the reason that there is very little value added from the product differentiation. On third place Caves and Porter (1977) mentions the cost structures as a highly dissuasive factor. Investments of the old companies on product differentiation create automatically a cost-barrier for all the new firms. This enables to the small producers to enter the market with competitive products. The initial investment on machinery and facilities also dissuade potential entrants

Robinson and McDougal (2001) also consider the economy of scale a high barrier for new entrants. This factor is usually linked to the firm size that provides several advantages on the manufacturing process. Massive productions are more susceptible of improvements on the production line. Furthermore big firms have more acceptances between the consumers and have privileged access to capital (Robinson and McDougal 2001).

In some sectors the government regulations are a very important obstacle to new companies. In the extreme cases the government can even forbid the entry of a certain company into a sector by establishing a statutory monopoly. In most of the cases the government barriers are just requirements for licenses and permits. Especially on the industries with high impact on the environment or in the public health the regulations are very restrictive. On the worst cases the licenses are linked with corruption cases where only the corrupt companies get the licenses. Luckily these last barriers are not usual but in some countries, especially the under-developed or with not democratic regimens, it is not that rare to find these situations.

The intellectual capital and the technical *know-how* are becoming more and more important on the last decades. The experience of the workers is essential to create an efficient production line. This barrier becomes bigger when the product is technologically complicated. For instance a company that would be interested in entering the wind turbine manufacturing business would need to contract engineers from other companies that manufacture wind turbines in order to build a competitive product. This process is very expensive and in some occasions it is not possible to find the adequate professionals.

But entry barriers are not always the same. Porter (1979) finds entry differences among strategic groups. In his opinion it will be more difficult entering the strategic group of the big national brands than entering the strategic group of the regional manufacturers even if both of the groups are centered in producing the same product. Thus, the entry in one group can be easy or in other cases blocked (Porter 1979).

The analysis of the barriers it is very useful if it is combined with the entries and exits analysis. This way it is possible to measure the business opportunity and the expected return of investment of the new firms. The stage of the industry life-cycle is also linked to the results of these two analyses. If in a certain industry the number of companies is growing fast despite big entry barriers it can be directly linked with the growth stage of the industry life-cycle where the business opportunity is so important that many companies assume the risk of making big investments with the expectations of getting high profit rates.

2.3. Accelerated Radical Innovation (ARI) model

In the last century some of the most important innovations have been defined as radical innovations. These innovations are not limited to any special area. It is possible to observe examples in many industries from information technology to transportation. They take between one decade or two to be completely developed and to generate profit. Historically the radical innovations are characterized for being unplanned and having a meandering development. Until now the internal mechanism and behavior of the model was considered both chaotic and unpredictable.

The ARI methodology was developed during five years since 2003 (Bers, Dismukes et al. 2009). The main objective is to turn the long-term, chaotic and unpredictable process of the promising radical innovations into a rational and organized framework. The model attacks directly to the main issues that slow the innovative cycle. The ARI was born to develop a systematic process to organize and accelerate in a structured way the promising innovations. Thus the potential innovations turn into profitable in a much shorter period avoiding the bankrupt threat and maximizing the opportunities.

The model is based on the detailed study of some of the most important radical innovations of the last 100 years. The most known case is the development of the atomic bomb in the Project Manhattan. It only took six years from the theoretical demonstration of the uncontrolled nuclear fission to the detonation of the two nuclear bombs in Japan during the Second World War. Internet is a more recent example; it turned from a defense closed network to the actual *World Wide Web* in about 10 years. There are much more cases like the *Space Race* or the cellular phone industry. Nowadays there are several radical innovation processes going on as the development of new energies or the implementation of hybrid automobiles.

2.3.1. Patterns in the radical innovations

Form the observation of the past cases through reported literature; the authors (Bers, Dismukes et al. 2009) detect three similar patterns between all the most significant radical innovative processes. Thus, the common patterns are extracted and generalized for the subsequent analysis.

- First, most of the main successful radical innovations emerge from strategic market opportunities or major crisis. Therefore, on the first case, the innovation finds less entry barriers than in the normal industry junctures. The opportunities are generally generated by serious technological discontinuities in the technology cycles (Anderson et al. 1996) (eg. The invention of the microchip triggered the information revolution). These opportunities are caused by technological facts. On the other hand the crisis can be caused by other facts than just the market dynamics. Social changes, wars or energy crisis can activate important changes on the market dynamics. For example the Project Manhattan was radically accelerated because of the threat of the Nazi Germany on the prelude of the Second World War.

- On second place it has been demonstrated that even the most radical innovations need to pass through all the stages of the industry and product life-cycle. The causes that make this kind of processes very fast are not the jump of stages. All the stages make an essential contribution to the development of the product or the process. The key-factor for the increase of velocity of the route is to adapt the strategies to the stage of the cycle where the product is in order to accelerate the whole process.

- The third common pattern concerns the basis of the innovation. The radical innovations are built mainly over existing technologies and knowledge. Even thought they are innovative products the combination of existing knowledge is obvious. So processes with an optimal information management will be more dynamic, efficient and profitable.

2.3.2. Steps of the model

The authors (Bers, Dismukes et al. 2009) have applied the three previous conclusions to the stages of the industry and technology life-cycle model: initiation, implementation and maturity. The result is a generalized model of innovation. From this base they have been searching for opportunities to minimize the length of each period and focus on the key factors of each stage in order to accelerate the whole process and, thus, reduce the overall costs and the development time. Thereby the early commercialization allows returning the investment in a shorter period (Dismukes 2005).

According to the stages of the industry life-cycle model: initiation, implementation and maturity; the authors establish 10 steps ordered in logic and consecutive mode. Thus the stages are concluded as the steps are also completed in the correct order. The first 6 steps correspond to the first stage (inception), the next 4 to the second stage (implementation). When they are completed, the market reaches the maturity. The method is considered a cycle so it can be applied in a iterative way each time that an innovation reaches the maturity after completing the 10 steps. The whole system is very detailed, complex and long; that is why on this text the steps are briefly explained.

The first step is recognizing a clear situation of advantage by the identification of an opportunity or a crisis. This step cannot be accelerated but it is essential. In the case that the radical innovation is introduced in an inadequate environment the probabilities of failure increase dramatically. If the existence of an opportunity or a crisis is not obvious probably it is more profitable to continue exploiting the old products and maintain a low cost investigation on the radical innovation than investing on the new technologies.

The second step is the definition of the innovation and how it will take advantage of the opportunity or the crisis detected in the first step. This requires a detailed analysis of the opportunity and, in addition, a parallel analysis of the possibilities of the new innovation to understand how this new technology or procedure will take advantage of the situation.

The step 3 involves identifying the major challenges that the advance will face. Usually these innovations focus on first place on the technological and scientific aspect and leave for further stages the market, social and organizational challenges. Step 3 is about predicting and minimizing in the early stages the grand challenges that the innovation will confront. Thus it is possible to accelerate the process by minimizing in advance and simultaneously the effects of the threats in the three basic domains which are: scientific and technological, market and societal; and business and organizational.

The fourth and fifth steps are related to each other and they may also be considered as an internal cycle. The fourth step is the identification the key hurdles that the industry will have to overcome from a strategic point of view. Consequently, the fifth step is the assessment of these hurdles. During the development of an industry it is inevitable that new hurdles threaten the future of the industry and that is why these two steps behave in a cyclical way.

Step 6 represents the culmination of the first stage, the inception. After identifying the challenges and hurdles, and building a knowledge organization around the innovation it comes the time where some important alliances and long-term approaches must be done. Suppliers, producers, investors and other stakeholders must have the same vision of the business. There are two main points in which all the stakeholders should agree. In first place the business model has to be completely defined. All the participants must know how much value they are adding to the production chain. With the new versions of old products the business model's core doesn't usually change. On the other hand, the new and disruptive products need also a new, innovative and personalized business model. Every participant must know which are his tasks and his value inside the network. The second key-point is to set a defined roadmap for the commercialization. This roadmap must set clearly which are the objectives, the strategies to follow, etc. The connections between departments and partners for the must be also defined.

The seventh step is the construction of a innovation network in order to build and develop rapidly the new technological product. One organization is not capable to launch on its own a radical innovation. There are many stakeholders involved on a complex network. A requirement for a accelerated cycle is to manage correctly the complex organism (Ståhle and Grönroos 2000) formed by all the stakeholders who play a role on the commercialization of the process. One of the key-points of the ARI model is to seek proactively the stakeholders instead of waiting for them to appear. A fast integration of all the companies involved dynamize the process from the beginning.

The steps 8^{th} and 9^{th} are the ability to make product tests and prototypes respectively in a short period. Testing in the products in many small scale experiments allows the companies to detect in early stages of the project errors on the design before they waste resources in a defective model. On the other hand this fast prototyping system allows to start different lines of design and choosing the most appropriate and giving more design flexibility to the process. These steps are also a cyclic process in which the original design is being modified until the dominant design emerges. Once the dominant design is established, the cycle allows making incremental innovations in order to update the product and therefore creating competitive advantages among the companies.

Finally the 10^{th} step sets the culmination of the growth stage. On this point the dominant design is completely developed and the companies focus on cost reducing and on the process efficiency. The 10^{th} step marks the beginning of the maturity stage and leaves the opportunity to a new innovation to re-start the cycle again.

On the Figure 9, the steps are compared with the stages of the industry life cycle theories. Thus it is possible to observe the relationship among the different ARI steps and the periods of the industry life cycle where they should be applied and, therefore accelerating the whole process.

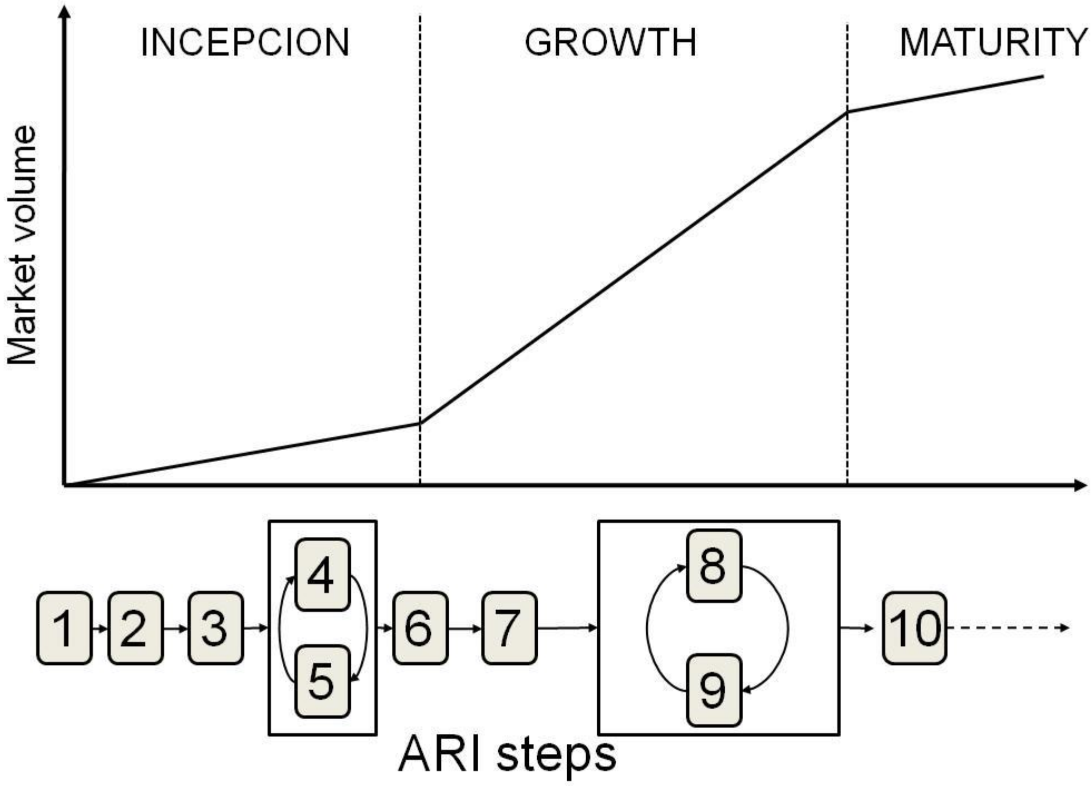

Figure 2.5. *ARI steps related to the industry life-cycle basic stages*

The key factor for the ARI model is defined by the authors as *systematic competitive intelligence*. It is based on the information management tools developed on the last 15 years which can process, select and organize huge amount of information. This tool must be used on the environment of information and knowledge management cycles (Ståhle and Grönroos 2000) during the whole ARI cycle. Therefore the information is available in every moment and, furthermore, it is organized in such way that it is easy to search inside the databases and extract rapidly the necessary information. Managing the information available in an effective way provides a competitive advantage in the marketplace.

3. Methods and data

3.1. Approach

The industry analyses are characterized by their complexity and extension. The final result of a study of such dimensions can vary from one to another even if they are made by highly prepared scholars about the same industry. There are several factors that influence the final results of a certain study. In this section it will be explained under which scope is made the study.

The first challenge that a researcher finds in an industry analysis is determining the boundaries of the industry. It is essential to know what is inside the industry and what is outside it for measuring correctly and under the same scope the different performance of all the stakeholders.

In the case of the wind power industry there are many actors on the scene. The wind turbines are usually sold to private users which sell afterwards the electricity produced to the electric companies of each country. There are also wind-farms owned directly by the electric companies and other wind-farms are owned and managed by joint-ventures of different companies. Usually the most important manufacturing companies offer in their services the assessment, design, construction and maintenance of wind-farms. As well there are small companies dedicated to each one of the previously mentioned divisions. Some electric companies which work frequently with this kind of sources have their own divisions for planning, constructing and maintaining their wind-farms. Thus, these companies only have to buy the wind-turbines to the manufacturers.

The main wind turbines manufacturers usually do not outsource their production. They have their own facilities for building each part of the wind turbine. The wind turbines are assembled on the place where they will work, so the four main components of a wind turbine (nacelle, blades, tower and electric system) are usually manufactured in different plants and assembled directly on the place of service. However, when the big companies face important orders and their facilities cannot cope with the requested production, part of the production is ordered to smaller manufacturers. Those smaller companies are usually focused on the manufacturing and development of specific parts of the wind-turbines but not on the assembly of a complete wind-turbine. Some of them also buy the components that they do not produce and assembly their own turbines.

For the study of the industry, this thesis is going to focus on the main manufacturers excluding from the study the electric companies that manage wind-farms and small scale suppliers. These big wind turbines manufacturers are the reference of the industry and, although they have to satisfy to their clients, the electrical companies and private owners, the innovation and the evolution of the different models depend on their research and innovative work.

The wind power generation is starting to be a common activity in almost all the developed regions of the world. However, this thesis studies in more detail to the most important European manufacturers. Europe is the indisputable leader in power generated and, in addition, is the continent where the industry has its origins. Therefore, the analysis of the pioneer and most extended industry will provide results and models that can be extrapolated to other potential regions currently less developed.

All the factors that influence the industry are not treated equally on this analysis. There is an important effort on the understanding of the technological factors that have shaped the industry; how the technological development have affected the industry and which technologies will have impact on it. The environmental, economic and politic factors are treated with less intensity but always considering their effects on the business of the wind turbines manufacturers.

The alternative models are treated and analyzed as potential alternatives inside the market. The study focuses on the technical advantages that they provide to the industry compared with the existing dominant design (Suarez and Utterback 1993). It is important to identify the main barriers that have made all these designs unviable until now, and which factors can trigger a future development of an alternative model. To understand the real possibilities that the alternative models have for entering the market in a competitive way it is essential to spot the aspects where the research work should be done by the potential new entrants.

The historical review is done under the industry and product life-cycle theories scope. These theories combine many important points of view, from the product innovation to the number of companies on the business. The final result is a big picture of the evolution of the industry with a special focus on the product development, innovative behavior and technological cycles.

Finally, the recent history of the history is analyzed under the scope of the Accelerated Rapid Innovation (ARI) theory model (Bers, Dismukes et al. 2009). The fast incorporation of numerous technologies of different domains to the wind power industry in a reduced period of time makes the ARI model a very useful framework. The model tracks the evolution through dividing the path into small steps and considering each step as a milestone on the road to the maturity of the industry.

3.2. Method

The core of the thesis is determining via established industry evolution models the current situation of the wind power industry and the possible future development of it. It is a fact that the real industry is not as well organized as the theoretical models. That is the reason why the analysis and comparisons have to be done with an extreme care.

The objective is also to apply the concepts of the various industry life-cycle theories to the analysis of the wind power industry. The study is done into different stages. On the first one the industry is analyzed from its origins and the evolutionary path is compared to the frameworks exposed on the first part of this thesis.

Industry stages are identified by track changes on various variables. On the industry life-cycle (Abernathy and Utterback et al. 1978) literature the first part of the analysis consist on tracking the evolution of some general key-variables as: entries, exits, output, revenue, performance and so on. In the case of the wind power industry there are also some other variables that are characteristic of this industry as: total MW installed, price of the electricity, power range of the turbines (kW), electric power generated per square meter used (kW/m^2) etc.

Other dimension of the analysis is the classification of the different innovations that have transformed progressively the industry. Apparently the design has been the same during the last 30 years: the 3-blade wind turbine with horizontal axis. But in the subsystems there have been deep changes. For example, the utilization of new materials have allowed to make lighter and bigger wind turbines and the modern electric systems and gearboxes have made possible to have wind turbines with variable spinning speed which adapt better to the different wind velocity that the old fixed spinning speed models. Those innovations have shaped the actual dominant design. That is why it is important to classify the innovations in order to identify the actual innovative pattern.

But the industry evolution does not depend only on the technological improvements. The factors that affect to the industry have to be extracted from diverse sources in order to make a global analysis. Depending on the nature of the factor the sources will change.

The analysis of the alternative models focuses on the technical advantages over the established models. The main variable taken into account is the kW produced by unit besides the production, installation and maintenance costs. It is important not to forget that the wind turbines are exposed to many different weather conditions. The behavior of all the models under extreme wind conditions and its versatility are also variables of the study.

Most of the models are still under development and are not commercialized so it is also important to estimate the potential of improvement that each model has. With a proper production process the cost can decrease dramatically and, thus, the product becomes more attractive to the potential buyers. But in the case of this section the analysis depends on much more factors than just the usual industry variables.

3.3. Data

3.3.1. Acquisition and selection

The collection of the data has been done according to the standards of the *secondary analysis*. This means that the writer has used exclusively data collected from other researchers and official organizations. Undoubtedly the data used is referenced using the (Author, year) notation and the sources are correctly indicated in the *References* section at the end of the document.

Indeed, the *secondary analysis* offers numerous benefits for the researcher and for the quality of the study. First of all the *secondary analysis* offers the access to good-quality data which increases the quality of the analysis. In addition this method allows comparing data from different sources and therefore having more points of view and interpretations for, thus, enriching the final conclusions. Furthermore the scholars that use the secondary analysis are able to work with data of higher quality than they could collect by themselves. However, the *secondary analysis* also has disadvantages but they are explained on the following section. The main sources considered for the analysis are exposed on the two following paragraphs.

The interest on the wind power industry has attracted the interest of several scholars. The information about the history and evolution of the industry is based on articles published on the on-line scientific libraries. A very important source of information about the performance of the companies in the last 10 years is the annual reports published by the own companies on their corporative WebPages. Companies which participate and share their capital in the stock-market are obliged to publish an annual report of their activities. These reports represent a huge amount of public information.

The companies of the sector have on their brochures and annual reports detailed information about their products and activities but this information need to be contrasted with other sources. The wind power sector have a great number of associations in regional, national and international level as the "European Wind Energy Association (EWEA)", that publish complete reports about the sector. In addition some ecologist associations make their own reports and studies. Furthermore the wind power energy is a usual discussion topic on the media, so on-line newspapers represent a very important source of information.

3.3.2. Limitations

Comparing an industry with models is necessarily a subjective task. There are many facts conditioned by the approach and the methodology used. The selection of an appropriate framework to make the study provides the thesis the necessary credibility, but it is necessary to take into account the limitations of the study.

Certainly some of the limitations are implied in the method of data collection. The *secondary analysis* has some structural and unavoidable limitations:

- *Complexity of the data:* The data available is vast and create problems in the field of the information management. These problems are usually data selection and determination of the level of analysis. In addition the secondary researcher usually is not familiarized with the structure of the data collected by other researches and it is necessary a period of familiarization.
- *Data quality:* usually the scholars are able to work with high quality data but there is no control over the quality of all the sources.
- *Absence of key variables:* The data collected from other researchers is done with their particular purposes. So the variables taken into account by two different researchers even for the same study might not be the same making incomparable their results.

In addition to the limitations of the analysis method this particular study also have its own limitations.

First of all, the conclusions are a product of the interpretation of the acquired data. There is some confidential information that is not published by the stakeholders of the industry. In other words, the results are conditioned by the public availability of the information. Companies do not publish all the internal data to maintain the competitive advantage over their competitors.

The data of some national and regional associations and companies is in some occasions published only on the language of the country of origin. The languages of a specific report or source represent a limitation of the study. This thesis will consider sources in English, Spanish and Basque.

Some of the alternative models prototypes are home-made or designed by small companies which have not measured some technical and economic variables of their prototypes. Some other models are only projected so there are only available theoretical estimations of the performance of the real turbine.

The articles and reports usually include personal interpretations from the writer of the text. Those interpretations are also considered as limitations because introduce a certain degree of subjectivity to the study. Companies want to attract investors, the associations want to generalize the use of the wind power, the ecologic associations want to protect the environment and the local and national governments want to justify their policies. Of course that all those sources are trustable but in some cases introduce a certain point of view that must be considered.

Finally, one of the most important limitations of the thesis is the approach to the wind power industry. The results will be in accordance to the approach defined on previous sections. The similar study made with different industry boundaries could show other results. However, on the conclusions there is a reflection about how does this boundaries affect on the results and some recommendations for further studies.

4. Wind power industry

4.1. Origins and history

This first section studies the development of the wind power industry since its very beginnings. Due to the big extension of the topic, this section is just a brief summary of the most important milestones which, in the author's opinion, have been determinant on the development of this specific industry. The sources are very diverse, from Danish T.V. documentary to specialized literature. The combination of all of these sources provides to the reader a big picture of the past of the wind power industry.

4.1.1. Antiquity

The origin of the wind power use is in the sailing boats. But it was not until the 9th century B.C. that those ideas were not put into practice to the in-shore applications. However the technology sails of the boats were applied to the first windmill blades. The Persians designed the first known fixed wind power system for pumping water. The first documented designs are also Persian, but in this case the purpose of the mechanisms was grain grinding. Similar vertical axis windmills were also developed on China but there is not any documentation about these models, however some studies set China as the birthplace of the wind power systems (D. Dodge, 1996).

The wind power systems were not introduced in Western Europe until the 13th century. Despite the purpose of these machines were the same as the Persian devices, the design was much more evolved and efficient (ibid.). These European windmills had a horizontal axis and they were built using the configuration of the existing water wheels. These machines used wooden cog wheels to transmit the power from the horizontal axis to the vertical one, where the mill was attached. This can be considered as the introduction of the gearboxes to the wind energy systems.

On the following 500 years an accumulation of incremental innovations came up with very efficient and technologically evolved machines. These new windmills could rotate their principal axe to be orientated into the wind. Many aerodynamic innovations were introduced as spoilers and flaps. All these innovations made the wind systems appropriate for more applications than just grain milling and water pumping. They became the main power source in the pre-industrial Europe. But with the invention of the steam machine, these "modern" windmills soon became obsolete.

During the 19th century, on the United States the small wind power systems became very popular. They were not as big as the European models and produced less power (about one horsepower). They were used for water pumping systems. The most common design was the fan-type and the development of steel blades on 1870 made the models lighter and more efficient. (Davenport, 2007) With these new technologies the American wind machines became bigger and very large windmills were built (18 meters in diameter).

At the end of the 19th century a multi-blade windmill was used for the first time to generate electricity. Charles F. Brush built in 1888 a 17 meter rotor which was able to generate 12 kilowatts on D.C. This innovation built over the existing models opened a new approach to the wind power possibilities (ibid.).

By the beginning of the 20th century the two dominant designs of windmills, sail and fan-type, were not competitive for producing appreciable amounts of electrical power. On the decade of the 20's some American companies started the commercialization of small wind generators. These turbines offered a new radical approach on the blade design. The new blades were inspired on the airplane propellers and were similar to the modern wind turbines but in a smaller scale. The power produced by this generation of wind turbines was between 1 and 3 kilowatts of D.C., and they were used in most of the cases on rural areas to charge batteries and for feeding D.C. motor machines. Once again, on the first years of the decade of the 40's the wind turbines became obsolete again. The wind power machines did not generate enough power to supply the increasing needs of the rural communities, and with the arrival of the electrical grid to the American rural areas it was not anymore profitable to buy and install a wind turbine.

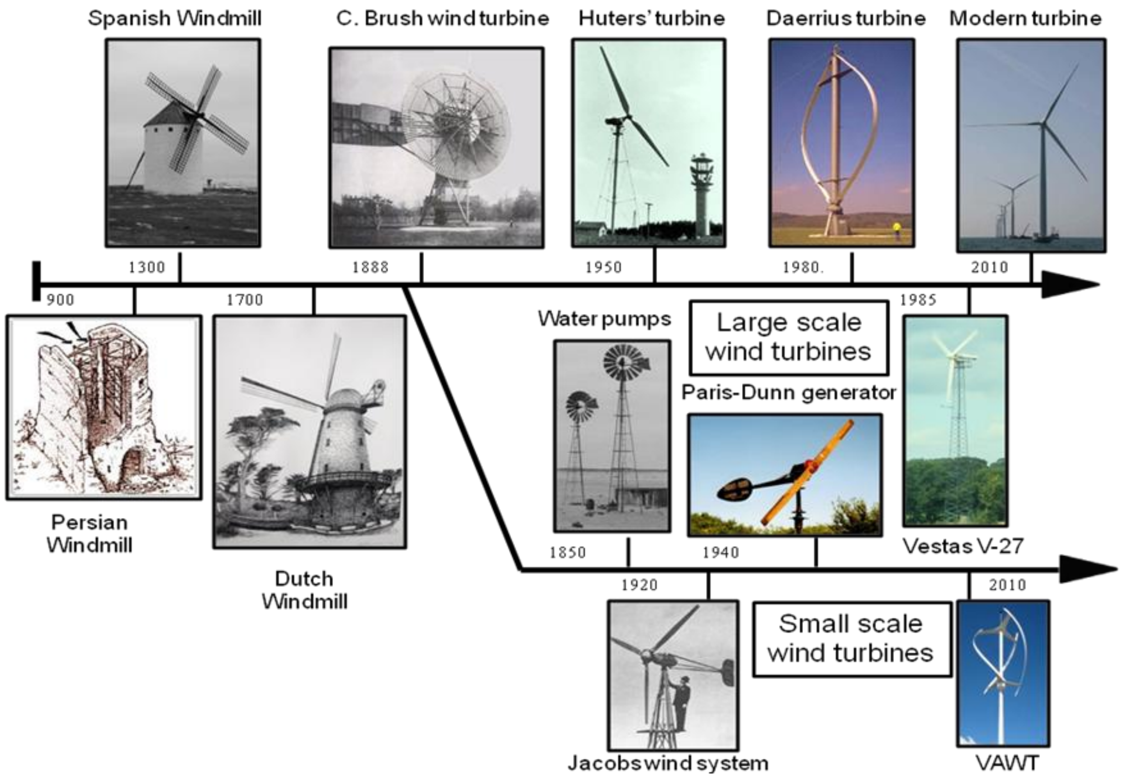

Figure 4.1. *Wind power systems timeline*

While the small wind turbines were losing the interest of the consumers. The attention on large-scale wind turbines was growing. Thus, Russia built a 100kW wind turbine in 1931 to experiment the possibility of generating electricity on a larger scale. This wind turbine was the pioneer of an era of experimentation between 1935 and 1970 where several countries such as United States, Denmark, France, Germany, and Great Britain; built their own prototypes. Each model had its own characteristics but they had some common attributes as the steel blades, the horizontal axis and two or three blades. There were some technical innovations which were introduced on this period that nowadays are still used on the modern turbines; the variable pitch of the blades it is an example.

4.1.2. 1970-1995

On the early years of the 70's decade there was a political event that triggered the development and growth of the wind power industry. The "Arab Oil Crisis" of 1973 showed to the whole world that the oil would not last forever and that some other alternatives for power generation had to be taken into account. The United States of America began a very ambitious but finally inefficient research plan. They would test 13 different small wind turbine designs, five large horizontal-axis turbine (HAWT) designs, and several vertical axis (VAWT) designs (TV/MIDT-VEST, 2010).

The Darrieus program developed the VAWT on the United States. On the early 80's the American government promoted the creation of wind farms using the Darrieus turbine but the market for this technology did not emerge. At that time most of the world wind-farms were being implanted in California which was at the time the global center of wind power generation. The Danish company *Vestas* started a close collaboration with the American company *Zond* for the production and installation of wind turbines on the western American wind farms (Vestas, 2010). The turbine V-27 became very popular and launched the wind power business both in North America and in Europe. All this development was supported by the government of the United States which gave economic support and subventions to the wind farm investors. As the Figure 6 shows, until the early 90's, the world production of wind energy was exclusively North American.

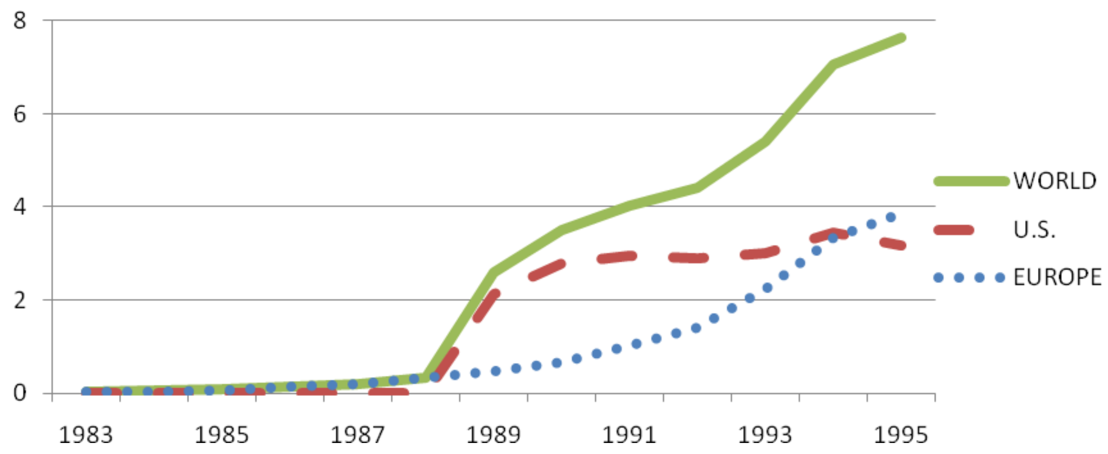

Figure 4.2 *Wind Electricity Net Consumption (Billion KW/h)(DOE, 2010)*

The price of the electricity generated by these farms was still too high compared with the other power sources but with these subventions given by the U.S. government and later on by the European governments; the price of the wind energy was competitive. In addition, the companies of the sector thanks to the R&D activities and the economy of scale were improving the efficiency of their turbines and reducing costs.

4.1.3. 1995-2010

On 1995 the first non experimental off-shore wind farm was built on the coast of Denmark. This installation and maintenance process is much more complicated and expensive than on the in-shore wind farms. In addition on this specific case, all the blades and nacelles were substituted after a few months of service. These unexpected costs almost cause the bankrupt of *Vestas*, the manufacturing company responsible of the farm. However the potential of this new concept of wind farms was obvious. On the sea the wind turbines were bigger, and could achieve higher efficiency levels. In addition the visual impact is quite lower than in the in-shore natural areas.

Vestas luckily started to get important orders from inside Europe. Although the American market was frozen, the European market started its development and many European governments started to subsidize the installation of wind farms just as the Californian authorities had done one decade before. Therefore, in the beginning of the 21^{st} century the wind power production in Europe was already much higher than in the United States (TV/MIDT-VEST, 2010).

The wind power market was growing exponentially and suddenly the number of competing companies increased notably. *General Electrics* (G.E.) came into the wind business by buying the wind section of *Enron*, which had just fallen into bankrupt. On Europe, *Gamesa* which had had a close partnership with *Vestas* during the 90's started to work independently on 2001. *Siemens* bought the Danish company *Bonus* in 2004 and started its operations mainly in the emergent German market.

By the middle of this decade the Asiatic market started its expansion. Although some companies as *Vestas* had installed wind turbines on India the development of these markets was not successful until this second part of the decade. On the last 5 years some Asiatic companies as the Indian *Suzlon* have grown very much, and the other important manufacturers are building manufacturing plants on China and India. China only on the last year has doubled its wind power generation capacity. In addition, the interest of some countries as Australia on wind power Technology is increasing notably.

4.2. Factors that influence the development of the industry

All the industries are exposed to certain factors. The wind power industry particularly has very special influence groups. Its great presence on the mass media and the expectations that the "green energy" will substitute the fossil fuels in a close future makes the wind power energy a public concern. On this section the main "non-technological" factors that influence the industry are presented.

4.2.1. Non-Carbon Energy promotion policies

Nowadays the energy production causes more air pollution than any other industry on the developed countries (AWEA, 2009). The cost of this non-clean energy is not only economic. There are several intangible costs of using fossil fuels as coal and oil: risks to human health, damage to the land produced by the extractions, and all the environmental damages caused by the global warning. The commonly called "green power" (renewable energy) reduce the environmental impact of the process of electricity generation. In addition it is a way to conserve the finite fossil resources of the Earth.

From the economic point of view, the renewable energy provides a protection against electricity price volatility. The oil price varies every day and especially when international crisis occur. For instance when the OPEC (Organization of the Petroleum Exporting Countries) countries reduce the supply of oil, the energy costs of the oil-dependent energy sources increase substantially. This situation has happened on the last decades mainly caused for the political conflicts of the Middle East countries with the Occidental powers (Ruiz, 2004). The renewable energy prices depend mainly on the efficiency of the facilities and on the government subsidies and tax advantages. These two factors are not object of daily volatility. Besides, the stability of the “green power” ensures the future continuity of many jobs.

On the recent history of the wind power from all the factors that influence the industry, the political fact has been determinant on the past and nowadays, it is still being decisive. For instance the first important projects of wind farms were supported by tax advantages given by the American government until 1985. On the beginning of that year the tax advantages disappeared and the American wind projects did not succeed until five years later. The main reason was that the wind farms were not profitable without the subsidies of the American administration and, therefore the wind farm projects stopped dramatically until the American government started subsidizing these projects five years later (TV/MIDT-VEST, 2010).

The actual subsidies and tax advantages are promoted by the national and international organizations. The objective is to transform the current energy model into a sustainable energy model. According to the E.U. Energy White Paper (2009) currently the EU is inside a deep adaptation process to a non-carbon energy production. The objective is to produce the 20% of the EU electricity using renewable energies by 2020. From this percentage a great part will come from the wind generation (E.U. Energy White Paper, 2009). In some regions the wind power objective are ever more ambitious. For instance Dr Peter Hauge Madsen, Head Wind Energy Division, in the RISO National Laboratory of Denmark affirmed on the International Conference on Wind Energy *"WE by 2020"* that “the target of 20% wind power penetration in the Indian Grid by 2020 is a feasible goal” (India PRwire, 2010)

The types of subsidies for green energy are very inhomogeneous. The term of subsidies include direct money transfer to producer and consumers, and also some other methods as tax exemptions, price controls, trade restrictions and limits on the energy market access (EEA, 2004). Historically, the renewable energy subsides in the EU have been relatively low comparing with other forms of energy during periods of fuel transition and technology development.

Thanks to the subsidies the wind power industry has developed a new model of business decreasing notably the costs of the energy. Over the last 20 years, the cost from wind systems has dropped more than 80%. On the Figure 7 it can be seen the radical decrease of the price of the wind energy. Despite that progress, the wind industry is not considered a mature industry and it is expected to continue decreasing the costs of wind energy.

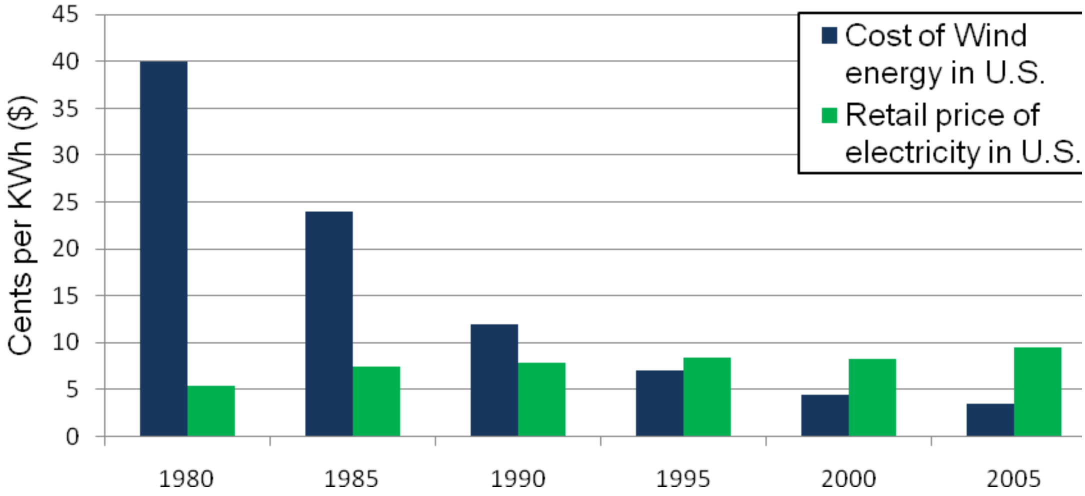

Figure 4.3. Evolution of the cost of the wind energy on the U.S. (US D.O.E., 2010, EIA, 2010)

4.2.2. Other environmental impacts

Wind power is known for being a renewable and environmental sustainable source of power. These characteristics have been a key-factor for its development. The process of extracting mechanical power from the wind is clean and environmentally friendly, but the installation of a wind turbine has an impact on the surrounding natural environment. If the wind power generation is going to be used in a very large-scale during the following century there are several environmental facts that the wind farms constructors have to take into account for a respectful implementation in favor of the location.

The first big impact is the installation of the wind turbines. On urban areas as industrial areas, docks or farms; the setting up process is much easier and does not affect almost in any way to the natural environment. On the other hand, the impact produced on the installation of this equipment on forests and mountains must be considered. Big wind turbines need heavy machinery to be built. For instance, the *Vestas* model V-90 needs 10 trailers to be transported. Also requires a 200m high mobile-crane for building the tower and placing the nacelle and blades on their final position and other different heavy machinery for building the foundations. All this machinery requires the construction of paths and roads inside the forests which can affect deeply to the fragile ecosystems. In addition, the machinery creates noise pollution during all the installation process.

On the off-shore wind farms the installation impact is more reduced. However in some cases there has been observed some cases of water pollution. The process of installation of turbines on the sea is more complicated and expensive but less harmful for the environment.

The marine ecosystems can be affected by another factor of the off-shore wind farms. The towers of the wind turbines can alter the ocean currents, which can modify the characteristics of the bottom of the sea destroying the fragile ecosystems. The wind turbines have to be placed on the right places making sure that will not modify the characteristics of the local environment.

During the life-cycle of the wind power plants the noise pollution and the bird collisions are the two main factors of environmental damage. The noise pollution has two different origins: mechanic and aerodynamic. The new researches are working towards more silent gearboxes and generators which produce a humming noise. Some organizations as the Finnish company WinWinD is offering on their new models low speed generators which cause less noise than the usual generators (WinWinD, 2010).The aerodynamic noise is usually softer than the mechanic noise but is more difficult to attenuate. The main fact that influences the aerodynamic noise is the texture of the surfaces of the blades. With more polished blades the aerodynamic noise decreases and the efficiency of the wind turbine increases but the manufacturing process becomes more expensive.

The detractors of the wind power usually use the deaths of migrating birds produced by the wind turbines as a fact against the wind industry. The death of birds on wind farms is inevitable, but the amount of these deaths can be reduced by studying the characteristics of the local fauna. These studies are already being developed, and focus mainly on the speed and the height of the birds' flight and in their capability to see, listen and dodge the wind turbines. Bigger turbines are easier to see, have more space between each other and their rotation speed is slower. However, according to the study made by Curry & Kerlinger (2004), the annual deaths produced by the wind turbines are insignificant compared, for instance, with the deaths produced by the glass windows or the accidents with cars and trucks.

The environmental impact of the wind turbines goes further than the construction and life-cycle factors. The finite lifespan of wind turbines and the need to replace and recycle them must be taken into account. Most studies have ignored this phase and focused entirely on their operation and installation of wind turbines. The experience on removing wind turbines and recycling their components is very limited due to the short life of the industry and the long life-cycle of the turbines but on the following decade this factor will become essential for the environmental sustainability of the industry. Nowadays the turbines that are being replaced are the old models from the 80's decade which had aluminum blades and are very easily recycled. But, the new models have blades made of fiberglass, carbon fiber and epoxy based composites; which are much more difficult and expensive to recycle.

4.2.3. Social impact

The wind power is generally considered as a green a sustainable source of energy. The perception from the society of the benefits of this energy is essential for its future development. But there are also some characteristics of the wind power generation that make the implantation of this technology very problematic in some communities.

It is important to remember that the wind energy is a local source of power that requires big areas for its implantation. The spatial and urban planning is managed by the local and regional governments which are very influenced by the public opinion. In addition there are some areas owned by several landowners with different economic interests for their lands.

There are two facts that usually affect negatively the possible implantation of a wind farm. First of all is the visual impact. The detractors of the wind farms argue that the natural landscapes are seriously damaged. The shape of the horizon is inevitably modified. On the other hand there are people who find them beautiful and even a symbol of the new "era" of clean energy. The second fact is the noise that the turbines generate. The noise levels are limited by the national legislation of each country but even if the noise emissions are under the limits, the continuous sound of a wind turbine is uncomfortable for the people who live on its surroundings.

The local opposition for the wind power implantation it is defined as NIMBY. NIMBY is an acronym for "not in my back yard". Generally the population agrees with the clean energy generation with the condition that the wind turbines are installed far away from their residence. This opposition is very strong, especially on the small rural communities which are generally opposite to any development that would not improve directly the local quality of life. This phenomenon affects to the installation of many facilities as desalination plants, landfills, incinerators, power plants, prisons, and especially transportation improvements as highways and railways.

On the last decade, especially after the "wind power boom" of the last years, the wind power industry has been involved in some corruption cases. As it has been seen on the Political factor section, the wind farms are objects of important subsidies. The construction of wind farms also represent important investments on some areas that otherwise would be economically unproductive as natural parks or protected areas. For instance the most known cases are related to the irregular awarding of the wind power construction contracts. These wind farms are located according to the economic interest of the corrupted authorities and companies damaging deeply, in some cases, the environment of the region. On the Mediterranean area there have been some cases as in Sicilia, where the European subsidies were diverted to some criminal organizations instead of being invested on the wind energy (Carvajal D., 2009).

These corruption cases added to the visual impact and the noise are damaging heavily the image of the wind power industry generating occasionally rejection among the population. When a new wind farm is being planned there are always suspects about the real interests of the promoters of the facility. Are the turbines really necessary? Or they are just a business for the local companies and city councils?

4.2.4. Energy storage

The wind power production is characterized by an irregular behavior that depends mainly on the weather. The wind production has its own peak hours and valley hours which do not match up with the energy consumption peaks and valleys.

There are two meteorological situations where the wind turbines do not generate power. With very low wind speeds (< 8m/s) the wind turbines are unable to collect enough power from the wind to generate electricity. In some cases they continue rotating for not losing the blades inertia, so the wind turbine becomes a huge fan that consumes power from the electric grid. The other case is with very strong winds. The turbines need to be stopped for not being damaged by the extreme atmospheric conditions.

In some other cases the wind turbines also need to interrupt their service or being unplugged from the electric grid because the power that is generated is bigger than the grid necessities. There have been some cases where the peak hours of wind production have coincided with the valley hours of electric consumption so the whole electric system was supplied by the constant power plants, coal and nuclear, and by the wind power. In those cases in order to match the consumption with the generation, some turbines were unplugged from the electric system, therefore loosing the power generated.

In order to fix this disadvantage of the wind power and maximize its efficiency and improve its versatility there are some projects which allow collecting and saving the energy produced by the wind. Thus, the electricity can be used whenever is needed and the wind turbines are able to work always maximizing their performance.

The Green Power Island in Denmark is a very ambitious project, and currently is on its initial stage. The project involves the construction of an artificial island on the

Baltic Sea with an internal lake. The wind turbines instead of generating electricity would be used as water pumps to extract water from the lake taking it to the sea creating a water level difference between the lake and the sea. When the energy is needed on the hours of maximum demand the sea water would pass through hydraulic turbines and collect the energy created by the wind turbines (Figure 4.4).

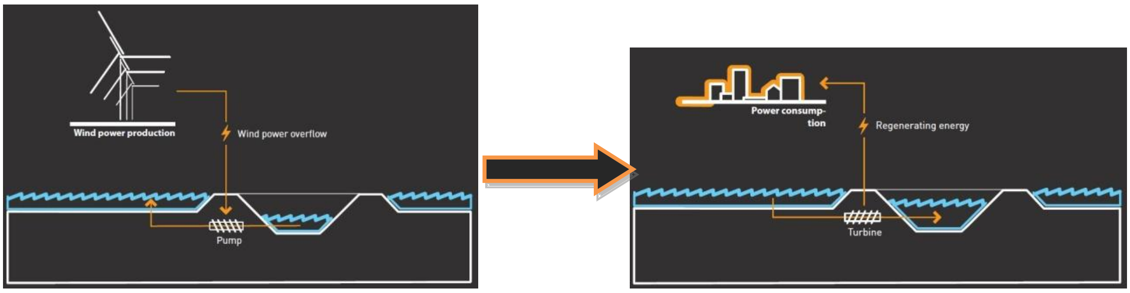

Figure 4.4. *Mechanism of the Green Power Island energy storage system (Gottlieb Paludan Architects, 2009)*

The other known viable project of energy storage is the hydrogen generation and storage on the wind turbines. During the valley consumption hours, the energy from the wind turbines could be used by electrolyzers to generate hydrogen from water. The produced hydrogen would be storage on the turbine tower and used later on via fuel cells. This solution could play a very important role in a hydrogen economy, being the main source of power for the hydrogen powered cars and machines. There are some on-going researches about this technology supported by the national governments but any company has invested yet on this technology. On the Figure 9 it is possible to see internal structure that a hydrogen wind turbine would have.

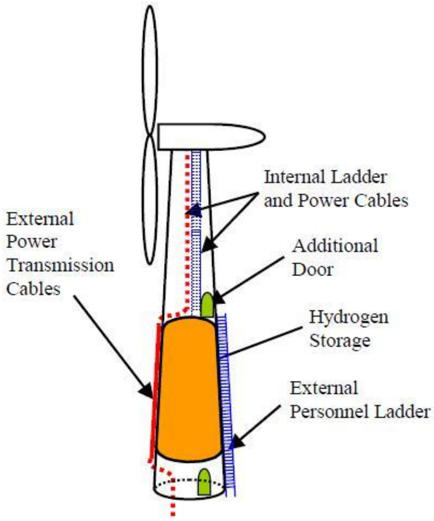

Figure 4.5. Hydrogen producing wind turbine (NREL, 2003)

4.3. Evolution of the dominant design

The wind power industry has grown in very high rates on the last 15 years. But there have been many types and varieties of wind power systems before. As it can be seen on the Figure 10, the intense growth of the industry matches with the generalization of a dominant design. Nowadays the wind power generation is similar to the electricity production of some countries such as India (EIA, 2010). On this section is explained on detail what technological advances have conditioned the evolution of the actual and generalized dominant design: the three-bladed horizontal axis turbine over a tubular tower.

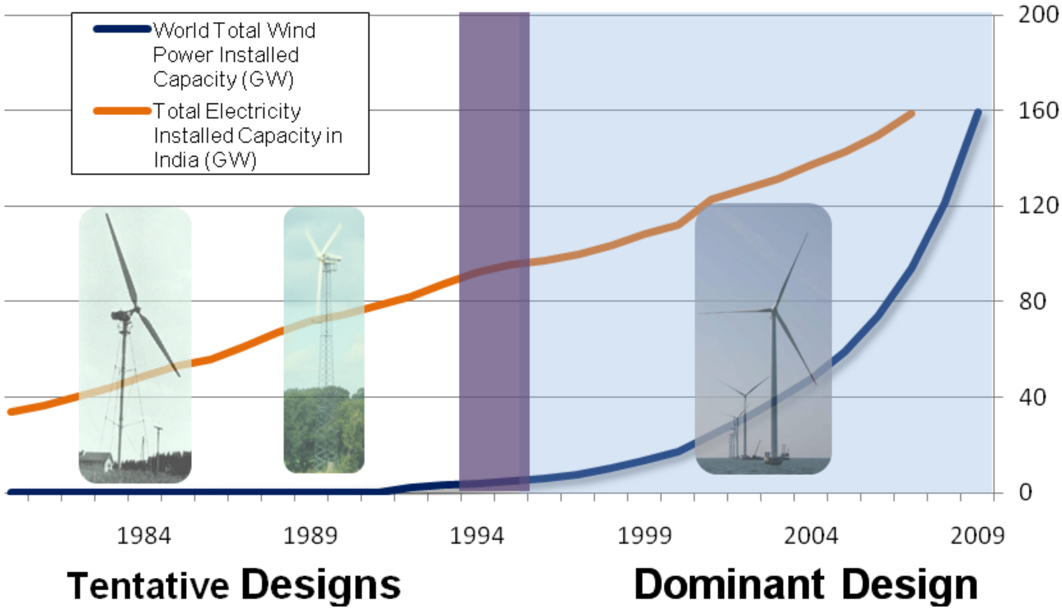

Figure 4.6. Establishment of the dominant design (EIA, 2010, WWEA, 2009)

4.3.1. Generator and gearbox

The electrical system of the wind turbine allows converting the mechanical energy into mechanical power. Originally the wind power generators produced DC (direct current) which was a radical innovation for the 19th century but involved a lot of problems. The first DC wind generators worked at variable speed and their only use was charge batteries; they could not be attached to electric machines which could not cope with the variable voltage and intensity caused by the variation of the wind speed. When the electrical grid arrived to the rural communities the windmills with DC generators became obsolete. The DC designs are more expensive and less reliable compared with the AC (alternate current) generators. However the first variable speed wind turbines were built using DC technology.

When the AC generators started to be used on the wind turbines the synchronous generators were the most used. The fundamental characteristic of synchronous motors and generators is that their rotor speed is always locked in with and exactly proportional to the frequency of the interconnected power grid. Thus, the wind turbines connected directly to the stiff grid must be constant speed machines. However with the implantation of electronic power processing modules, the grid could be supplied with power at constant voltage and frequency. In the case that the turbine works alone its voltage and frequency will be determined by the wind, assuming there is no control system. Wind turbines which use synchronous generators generally use electromagnets in the rotor which are supplied by direct current from the electrical grid. The electrical grid feds with alternate current so it has to be converted to direct current before being sent to the coil windings around the electromagnets in the rotor.

The alternative to the synchronous generators are the induction (asynchronous) generators. This type of generator is specially used on the wind industry although is not widely used for other industries. The asynchronous generator is very reliable and tends to be cheap compared with the synchronous models. The generator has some mechanical properties which are very useful for the wind turbines. The most important is that the generator can “slip” and is not locked to the frequency of the electric grid so it has a certain overload capacity.

The generator it is probably the element that has been less modified to work in a wind turbine. The generators have been studied and developed for many decades. In the actual wind power application both designs, synchronous and asynchronous, are commonly used depending on the particular characteristics of the turbine.

The generator can be connected to the turbine rotor directly or through a gearbox. The gearboxes are used to convert the low rotor speeds (large turbines operate at speeds between 10 and 60 rpm.) to higher speeds to drive the generators (generators are designed to run between 1200 to 1800 rpm)

There is an alternative to the gearbox, the direct mechanical connection between the turbine rotor and the generator. These generators usually consist of many poles and are very large compared to the usual generators attached to gearboxes. However the elimination of the gearbox makes the turbine less expensive and avoids a lot of breaks. The gearbox is usually the element of the wind turbine that breaks more easily and needs more maintenance.

4.3.2. Transformer & Power electronic system

The earliest wind turbine designs were extremely simple. The rotation of the axis was proportional to wind speed so the machines were allowed to run at variable speed. This fact is highly advantageous because the system does not need to control the rotational speed and the energy that could be extracted from the wind increased substantially. However this method was only valid for wind turbines with DC generators. Nowadays the objective is the massive AC generation in order to supply the electric grid, so the electricity must be transformed to the standards of the electric grid. This involves the modification of two main parameters: the voltage and the frequency.

For variable speed large turbines there have been two main systems of conversion: the AC-AC converters and the AC-DC-AC converters.

The AC to AC frequency converters were traditionally electromechanical machines also called cycloconverters. The cycloconverter used thyristor switches programmed to provide a vector control to each generator phase with the grid frequency (50 Hz. in Europe and 60 Hz. in the US). The final result was a very rough waveform. Nowadays with the introduction of IGBTs and sophisticated high power electronic switches allows a better implementation of these systems.

The second system is using a DC current link converter (AC-DC-AC) which converts the varying frequencies and voltages from the AC generator to a DC voltage and then converts the DC voltage back to the AC but with the fixed electric grid voltage and frequency. This system is much easier and less problematic than the previous one, but the efficiency is lower and the equipment more expensive. In each conversion there is a power loss and it is necessary more equipment for the two conversions. The easy control of the output makes this system very appropriate for the wind power generation. However both systems are still in use.

4.3.3. Control System

Wind turbines are designed to produce electrical energy as cheaply as possible. So in order to optimize their production they are designed to work with a certain wind speed. Depending on the model and the location the wind turbines will have an optimum performance for low winds, or for medium and high winds. When the winds are stronger, the turbines work outside their optimization interval so they do not maximize their performance and in addition they need to waste part of the excess of energy of the wind in order to avoid damaging the wind turbine. There are two main mechanisms of doing this safely: pitch control and active stall.

The first mode to control the pitch was purely mechanical. The blades were twisted under the effect of strong winds so the useful surface decreased and the angle of attack was automatically modified. However this technique involved the utilization of very flexible blades which were not properly designed. In those years (beginning of the 20th century) the theories about material fatigue were not developed yet so it was usual to see broken blades. With the introduction of electronic control systems the panorama changed dramatically. With the control systems, the blades were able to rotate around their longitudinal axis in order to vary their exposure to the wind.

Some wind turbines prototypes built on the middle of the 20th century used ailerons (flaps) to control the power of the rotor, just like aircraft use flaps to alter the geometry of the wings to provide extra lift at takeoff. The modern control systems collect information from the weather station attached in the nacelle and from the generator and transformer in order to determine via predetermined algorithms and closed-loop control systems the optimal angle of the blade. On the modern turbines the pitch is controlled by a computer and operated using hydraulic systems.

The passive stall controlled wind turbines have a fixed operation angle so they do not need variable pitch control system. The geometry of the blades is aerodynamically designed to ensure that in the moment the wind becomes too high, it creates turbulences on the side of the rotor blade. Thus the lifting force acting on the blade decreases and the speed of the turbine does not increase lowering the collapse risk.

Modern turbines combine both technologies, stall and pitch control, using “active stall” controlled wind turbines. The control systems actuate over the pitch controlled machines but using the passive stall designs and theories. This turbines control the pitch to optimize the electricity generation with low and normal winds but when the wind speed is too high it modifies the attack angle of the blades creating turbulences. One of the advantages of active stall is that it is possible to control the power output more accurately than with passive stall. The other main advantage is that the turbine can be run almost exactly at rated power at all high wind speeds; the normal passive stall turbine would drop the power output with high winds.

4.3.4. Blades

The blades are a very important part of a wind turbine. They collect the mechanic energy from the wind and transmit it to the rotor. Their composition and design are determinant in the wind turbine design process. The efficiency of the mechanism is directly related to the blade design.

On the commonly used HAWT the shape of the blade has been similar since the early designs of the beginnings of the 20^{th} century. The aerofoil shaped blades based on the plane wings and turbines used the lift principle to extract energy from the wind in the same way that the planes use this principle to fly and to propel themselves. The main technological changes have been done on the size and the material of the wind turbine blades.

The first “modern” wind turbines of the early 20^{th} century had heavy steel blades. Those blades contributed to maintain a constant speed. The blades were able to buffer the changes on the wind speed due to their big inertia. The blades were used at the same time as power collectors and as a flywheel. This effect was very useful for the constant speed machines which were directly attached to the electric grid. However the heavy weight of the blades limited the size of the wind turbine

The next technological step was the introduction of the aluminum composite blades. These blades were much more lighter than its predecessor the steel blades. The low rotating inertia made them very useful on the variable speed turbines. The turbine was able to adapt its rotation to the wind speed and, therefore obtaining a higher power than the fixed speed turbines. The steel blades were the most used blades during the wind power expansion of the 80’s decade.

The performance of the aluminum based blades was acceptable for medium sized turbines, but was not enough for the bigger wind turbines that were being designed on the middle of the 90’s decade. The next technological step involved the polymer composite blades. Those composites were very toxic and hard to manipulate so although their performance on the wind turbines was more than acceptable, they were substituted rapidly by other materials.

Nowadays the blades are made of combination of fiberglass, carbon fiber and epoxy based composites. The blades are based on a central beam which gives the necessary strength to the blade. This beam is covered by a shell with the aerodynamic shape of the blade. This structure allows creating long and light blades. The length of the blades of the most evolved models can reach 50 meters easily.

However the increasing length of the blades involves a very important transport and logistics problem because they cannot be transported by road due to their extremely big size. On 2010 a new technological innovation is being introduced. The blades of the biggest turbines, as the *Gamesa’s* new model G-128, are manufactured in two parts and joined on the place where the turbine is situated (Gamesa, 2010). The company is keeping in secret the new technologies that have made this advance possible in order to protect the innovation from the competence. But if the design is efficient enough, probably the next generation of “more than 50 m“ wind turbine blades will be manufactured in separate parts.

4.3.5. Necelle

The nacelle is the structure where the electricity generation is done. It is placed over the tower and supports the three blades. The components placed on the nacelle are the gearbox, generator, break, hub and the nacelle and blades rotating systems. The nacelle, although being a passive element, it is a very important part of the whole system because it has to transmit the stress from the blades to the generator and the tower

The function of the nacelles on the wind turbines have not changed over the years. The objectives of the incremental innovations have been increasing the strength of the structure reducing its weight at the same time. The modern nacelles include a yaw mechanism, the whole turbine is able to rotate over the tower to face the wind in order to improve the efficiency or, in some cases, avoid the effect of strong winds.

One of the big inconvenient of the horizontal axis wind turbines is the accessibility of the nacelle. The maintenance becomes very expensive on the big wind turbines. In some cases the nacelles are placed at 60 or more meters height. Changing the generator or some other damaged parts contained inside the nacelle requires very expensive machinery as huge cranes. Thus, the vertical axis wind turbines are, from this point of view cheaper machines; the nacelles are placed at the ground level so the access becomes easier and the operations with the cranes are limited to the blade reparation and substitution.

4.3.6. Tower

The first big wind turbines prototypes were bearded over guyed pole towers. This structure consists on a narrow pole tower supported by steel guy wires. The main advantage of these towers is the weight saving but there are many disadvantages that have limited their use to small wind turbines. The guy wires make difficult the access around the tower. In addition the tower is very vulnerable, for instance if any guy wire accidentally breaks the tower could easily collapse. The steel cables are also very dangerous for the wild life because they are difficult to see so the birds and bats can easily collide against them. The cost of manufacturing and building these towers is not lower than the other models and they require much more area for its installation. That is why the guyed pole towers are not used anymore for massive electricity production.

The lattice towers are considerably cheaper than the today's usual tubular towers. The reason why they are cheaper is that they need less than half of the amount of material that a tubular tower of the same size needs. On the first years of the massive implantation of the wind power these kind of tower was the dominant design. Thus, we can still find in the pioneer wind farms turbines with lattice tower. For instance the *Vestas* model V27 which became very popular during the 80's was installed over these lattice towers. However, the basic disadvantage of lattice tower is the visual appearance. Although this fact is clearly debatable, the reality shows that these towers have almost disappeared.

Nowadays the large wind turbines are built over tubular steel towers. These towers are manufactured in sections of 20 to 30 meters so they can be transported by trucks. The assembly is made on the final location of the turbine using cranes. These towers are not completely cylindrical; they are conical instead. Thus, the towers increase their strength and save material at the same time. The adoption of the tubular towers as the current dominant design is usually related to the aesthetic reasons. Simple geometrical patterns with white or light gray paint make the turbines blend well into the landscape. In addition the tubular towers offer a protection for the maintenance workers, especially on the cold weathers (Gipe, 1995).

The most modern turbines, as the G-128 developed by *Gamesa* and commercialized on the first months of 2010, include a tower with similar appearance as the classical tubular towers. The difference is that these new towers are made of prefabricated concrete mixed with steel. The combination of both materials, high-quality concrete and steel, gives strength to the tower that will support the weight of the whole system. For instance, the model G-128 has a tower of 120 meters height holding three blades of 64 meters long generating a nominal power of 4500 kW (Gamesa, 2010).

4.4. Alternative models

Although nowadays there is a very clear dominant design on the large wind turbine industry: three-bladed HAWT with tubular tower. This model has not always been the reference. There are also many technologies which were ruled out on the experimentation era that with the new technological advances have the opportunity to supply or at least co-exist with the actual dominant design. In addition on the last 20 years there have been many other disruptive designs introduced by small companies and government research programs which also offer an alternative to the most commonly extended design.

On this section the most technologically viable alternatives are presented and briefly described. Time will tell if any of the following models has enough potential to displace the current dominant design.

4.4.1. Vertical axis wind turbines

As it name says the vertical axis wind turbines are characterized for having a vertically oriented rotor. There are several different designs and, on this section, the mostly used designs will be exposed and explained briefly.

This type of design has some general advantages in comparison with the horizontal axis wind turbines. First of all the generators and gearboxes can be placed on the ground level eliminating this way the accessibility problems that the HAWT have. In addition the VAWT usually do not need to be oriented, soy they are very suitable for working in conditions of changing wind. However each model has its own advantages and disadvantages.

4.4.1.1 Darrieus Turbine

This wind turbine was invented in 1931 by a French engineer called Georges Jean Marie Darrieus. After 40 years of experimentation and prototyping the US government made a serious investment on the development of these turbines. So the first wind farms installed on the American west were using this type of turbines. The design is very simple apparently. It has a central tower and two twisted blades as it can be observed on the Figure 4.7. The sizes of this turbines evolved very fast so the last designs were very high for the year that were built, (80’s decade) compared with the existing HAWT.

Figure 4.7. *Darrieus turbine*

The Darrieus wind turbines can be packed closely than the HAWT, so in the same area it is possible to place more Darrieus turbines than in the HAWT wind farms. The design is generally less expensive; these turbines do not need to be oriented so the mechanism for orientating the turbine is unnecessary. The modern designs include a pitch control as the HAWT that allows optimizing the power collected from the wind. Unlike other VAWT based on the drag effect, the Darrieus turbines is able to spin faster than the wind which is an advantage for the electricity generation because there is no need of using gearboxes with extreme speed conversions which would trigger the price of the installation.

However there are several inconvenient associated with this type of turbines. The most important is related to the variable torque that the two blades generate. The electricity generated by the turbine has certain frequency that has to be modified with an electronic power system. But the biggest problem comes from the side of the resistance of the materials. There is a certain frequency called resonant frequency, where the whole system begins to accumulate energy on every cycle until the frequency changes or the structure collapses. The Darrieus turbines must have a brake to avoid the sinusoidal torque reaching the resonance frequency. Another problem is the difficulty to protect the turbine from the extreme winds. The turbine is able to work with wind coming from any direction but when the wind speed is over the design limits the turbine is still generating torque.

Other problems are the guy cables needed for supporting the central tower on the big Darrieus turbines. As in the HAWT, the towers that needed guy cables for standing are very dangerous for the wild life, especially migratory birds and bats. In addition these cables makes difficult to operate near the turbine. The last important fact against these turbines is that there is a part of the blade which is situated very close to the ground so the wind speed is not as high as in the top of the turbine. This effect makes the turbine not completely efficient and generates internal tensions inside the blades, therefore incrementing the fatigue damage.

4.4.1.2 Sabonius turbine

The Sabonius turbine is one of the simplest designs for HAWT. It was developed by a Finnish engineer called Sigurd J. Sabonius on 1922. As it can be seen on the Figure 12 the original design of the turbine consists of two half cylinders attached to a vertical shaft. The Sabonius turbine is considered a drag type design so it cannot spin faster than the speed of the wind. The curvature of the scoops generates less drag when they are moving against the wind than when they are moving with the wind, thus the power generated by the turbine is the difference between both forces.

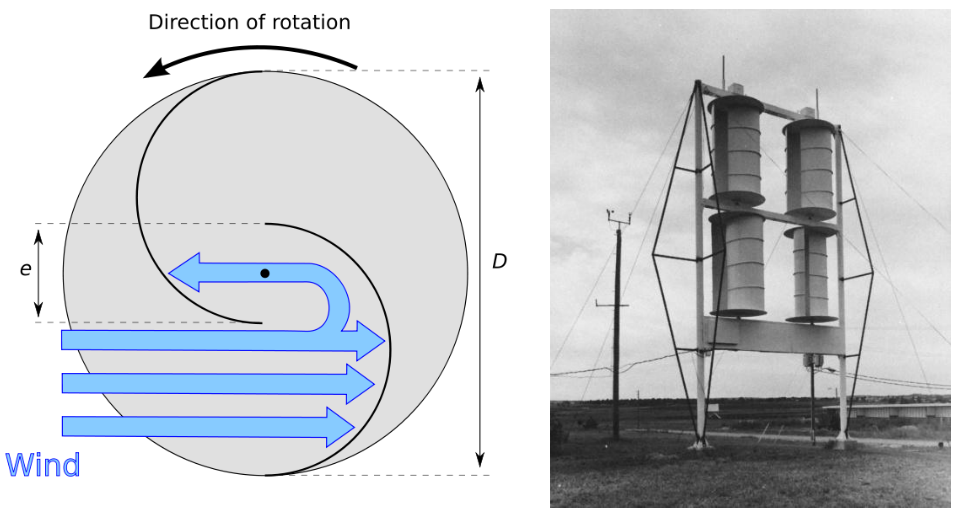

Figure 4.8. Drag principle and a prototype of Sabonius turbine

The main advantages of this turbine are the simplicity of the design and its versatility and reliability. The turbine is commonly used when the reliability is more important than the efficiency, for example most common anemometers are a variation of the original Sabonius design. The turbine does not need almost any maintenance so it is very used as an electricity supplier of small electric devices as meteorological buoys.

The turbine start working with very low wind speeds. Some modern designs combine the Sabonius turbine with modified designs of the Darrieus turbine for small and domestic generators and other urban uses as lampposts (Figure 4.9). The Sabonius turbine would be the power generator of the machine with low wind speed while the Darrieus would produce the power with high wind speeds.

Figure 4.9. *Darrieus-Sabonius urban wind turbine*

However the low efficiency of the design makes them unable to the massive electricity generation. The rotor spins to a very low speed so it usually needs a gearbox between the rotor and the generator. There have been modern prototypes on the last years but the efficiency cannot compete with other models of wind turbines.

4.4.1.3 MagLeb wind turbine

The MagLeb project has captured the whole world attention since 2006. Some sources (Zijun Li, 2006) consider this design as a breakthrough on the wind power industry evolution. The MagLeb turbine is sustained using magnetic levitation instead of commonly used axial bearings. The ambitious MagLeb project involves the construction of a building-size turbine. This turbine would generate, according to the designers, 1-2 GW of power. This means that with only one MagLev turbine it would be possible to generate the same energy than in a wind farm with 223 last generation G-128 wind turbines of 4.5 MW.

The magnetic levitation allows minimizing the friction between the huge rotor and the base. In addition the blade design increases the generating capacities. Almost all the machinery and generators are placed on the ground level and the electricity generation is concentrated in one place, not as the disperse wind farms. All these facts make the maintenance very low compared with the HAWT wind farms.

Figure 4.10. *MagLev wind turbine brochure (MagLev, 2006)*

But MagLev design also has some weaknesses. Only the magnetic bearings would consume great amount of energy that is being generated by the turbine. The alternative to these magnetic bearings is the utilization of permanent magnets but in this case the price of the materials needed for the project would increase even more. The visual impact of the MagLev turbine is very important. The turbine has the height of a 20 floor building and a more than 100 meter radius.

There are not news about any MagLev turbine under construction or planned. The huge money investment needed for a project of these characteristics and the risk that involves building such a big turbine that has only been tested on prototypes scares the potential investors. Besides, it is very difficult to find nowadays a place to build a giant machine without finding local social and political opposition.

4.4.1.4 G model wind turbine (GMWT)

GMWT, also known as the “Gelibolu model wind turbine”, is an advanced VAWT. It is a Darrieus turbine type but equipped with three specially designed “Augmentation and directioning wings”. These wings give an additional lift force to the rotor increasing substantially the total efficiency of the turbine. On the “G modeli” wind turbines, the negative powers of the wings that move against the wind are converter to the sides and back of the turbine. In addition the blades create a vacuum behind the turbine which constitutes a lifting power.

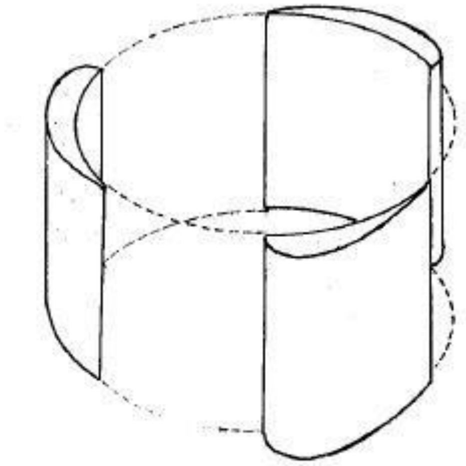

Figure 4.11. *G model blades sketch and hypothetical G model off-shore wind farm*

The designers and developers of this turbine argue that the GMWT gets rid of the functional and structural disadvantages of vertical shafted wind turbines, as the Sabonius turbine, by changing them into additional advantages. Thus these turbines can be manufactured on compact sizes and still producing the same amount of power than other much larger wind turbines. Compared with the Darreius turbine the Gelibolu model wind turbine needs only one fifth of the swept area for producing the same amount of power.

Although the advantages of the GMWT design, there have not been many investments towards the development of this technology. If the measurements made by the developers of these turbines are right, this turbine has a huge potential for entering into the market both as domestic small turbines and large wind turbines.

4.4.1.5 H-rotor turbine

The H rotor wind turbine work under the same principles as the Darrieus Turbine. The blades are pushed by the lifting forces which allows to the turbine to reach higher rotating speeds than the drag-based turbines. The most basic model is based on two symmetric blades spinning around a vertical axe (Figure 4.12.). But using the same principle there are many variations of the basic design. For the moment there is not a dominant design.

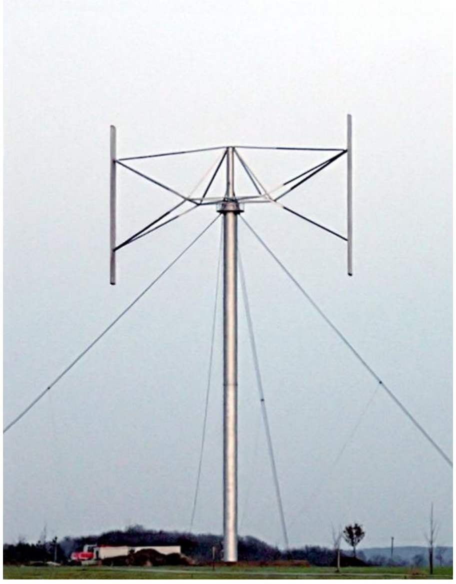

Figure 4.12. *Basic H turbine model*

The simplest two-bladed model has similar disadvantages as the Darrieus turbine as the sinusoidal torque. This problem was partially solved with the addition of a third blade, however the increase of the number of blades decrease the efficiency of these turbines. There are some new models that solve the discontinuous torque problem by installing twisted blades (Figure 4.13.). Thus the torque remains almost constant and the design is much more visual attractive.

Nowadays all the H turbines are small sized turbines. They are used for supplying electricity to isolated farms and small complexes. For instance the Amundsen-Scott South Pole Station is supplied of energy generated for one of these turbines. Some companies as *Quietrevolution*, are offering very attractive designs of VAWT for the urban implantation (Figure 4.13.).

Figure 4.13. *Quietrevoluttion helical VAWT (Quietrevoluttion, 2010)*

4.4.2. HAWT

Although the dominant design is the most known horizontal axis wind turbine there are also some alternatives to the commonly used design. Some of them are just improvements and evolutions, but in some other cases the turbines work using different physical principles. The most viable projects are shown on this section.

4.4.2.1 Ducted rotor

The ducted rotor turbines have a diffuser surrounding the blades with the main objective of concentrating the wind and, therefore increasing the wind speed. More than a revolutionary design the ducted rotor wind turbines are considered an evolution of the most extended three bladed HAWT. The US government experimented with ducted rotor prototypes on the 70’s decade but they were ruled out. On the last part of the 90’s decade a company from New Zealand, *Vortec*, tried to bring them back into the market but they went into bankrupt after building some unproductive prototypes (Figure 4.14).

Figure 4.14. *Vortec wind turbine*

The incorporation of the diffuser around the rotor involves a very serious weight and cost penalties and does not increase extremely the wind turbine efficiency. Experiments in wind tunnels with excellent artificial conditions, and with threefold rind flaps (Ozer Igra, 1976) have shown a concentrating effect of roughly 1.8. In addition the turbine must have a very precise jaw mechanism in order to orientate the nacelle towards the wind. If the orientation control fails the whole turbine would be exposed to terrible drag forces.

Although all this unfavorable facts there are currently some companies, as the French *Cita Wind*, offering on their brochures domestic ducted rotor turbines. These small turbines, Figure 4.15., do not have as much as problems as the big models and slightly improve the efficiency of the not-ducted small wind turbines. However their use on large scale wind turbines is highly improbable.

Figure 4.15. *Cita Wind wind turbine*

4.4.2.2 Multi-rotor

The most developed multi-rotor wind turbine is being nowadays developed by the American company *Selsam.* The turbine as it can be seen on the Figure 4.16., has multiple and coaxial rotors. The axis is not aligned with the wind for preventing the rotors "shadowing" each other in the wind.

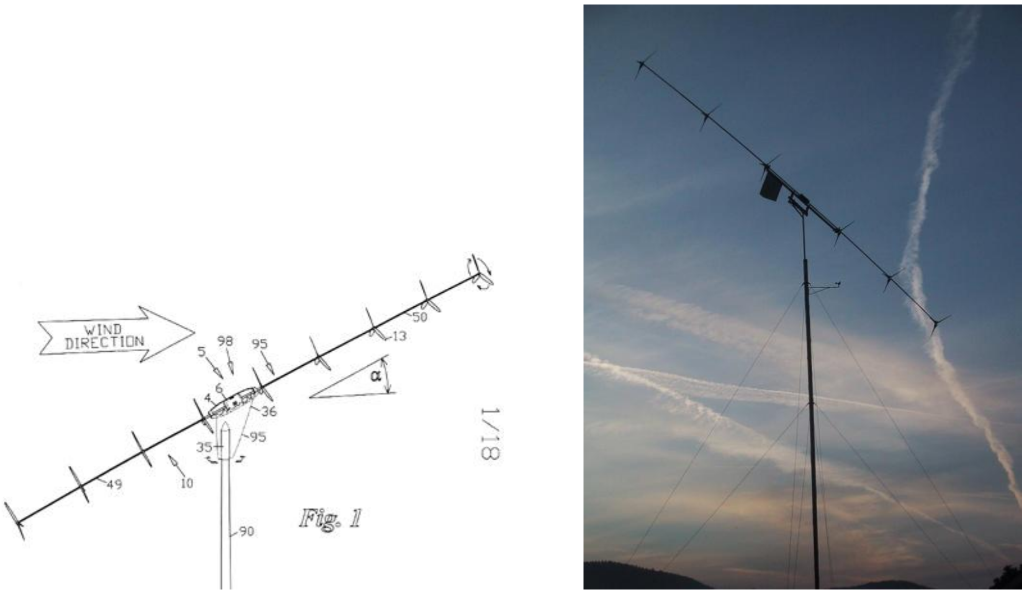

Figure 4.16. *Multi-rotor turbine sketch and prototype (Selsam, 2010)*

Although the prototypes have only been tested in small scale turbines the results have been remarkably positive. For instance a multi-rotor turbine with seven rotors was able to generate the same power as six wind turbines of the same size. But, although this great results, the multi-rotor wind turbine has not being tested in a larger scale.

Nowadays there are two main factors that are hindering the development of these turbines. The first one is their appearance. The *Selsam* design doesn't (at least in its current form) provide much in the way of visual appeal. On second place, the turbine is dangerous for the wild life due to the big amount of blades on its rotor. However, *Selsam* is working hard to improve these aspects and promoting the offshore application of the multi-rotor wind turbines as it can be seen on the Figure 4.18.

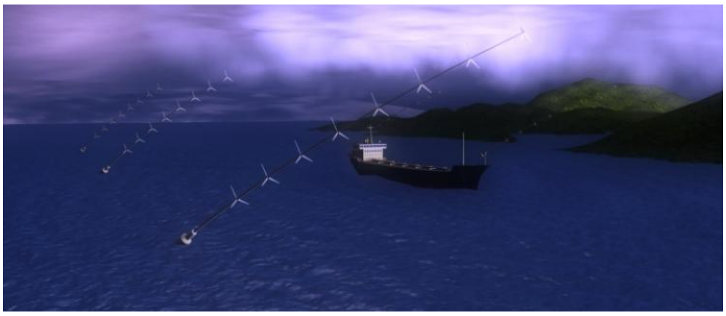

Figure 4.18. *Hypothetical multi-rotor offshore wind farm (Selsam, 2009)*

4.4.2.3 Contra rotating wind turbines

The current single rotors only convert a fraction of the power of the wind. The objective of the contra rotating wind turbines is to increase significantly the power captured from the wind. These wind turbines have two coaxial rotors spinning in opposite direction. The technology is not new, the military torpedoes, helicopters and airplanes have used it before; but it was used as a motor instead of generator.

According to experiments made by the California Energy Commission (2002) the contra rotating rotor could extract 40% or more energy from wind steam in low wind conditions. In addition the torque produced by the two rotors contra balance each other so the sustaining tower is exposed to a much lower bending stress.

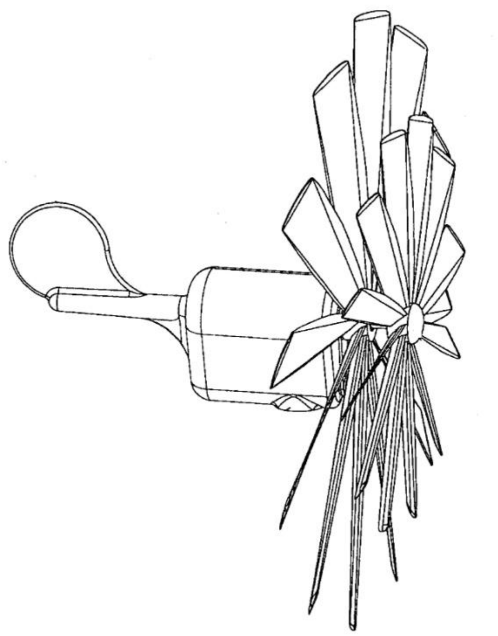

Figure 4.19. *Contra rotating turbine sketch*

The main difficulty is the generator design. There are two solutions to this problem; the first one involves the utilization of a unique generator designed to be used with two rotors. The other one is using one generator for each rotor. Both of the solutions involve a significant increase on the turbine cost and complexity of the installation. In addition the turbines tested were 5 kW turbines, so the efficiency of this design has not being tested in large scale turbines.

4.4.2.4 Magnus wind turbine

The Magnus wind turbine works using a completely different aerodynamic phenomenon that has been shown until now. The force over the cylindrical “blades” is produced due to the Magnus effect. The Magnus effect happens when an object is spinning in a viscous fluid, air in this case. The thin layer of fluid close to the body moves with the body, thus the speed of the wind is different on the top and in the bottom of the cylinder creating a pressure difference due to the Bernoulli principle. As a result, the pressure difference creates a perpendicular component force from the air towards the “backward moving” side (see Figure 24). This effect is very visible on the “mysterious” movements of the spinning balls on some sports as football, tennis, baseball and so on

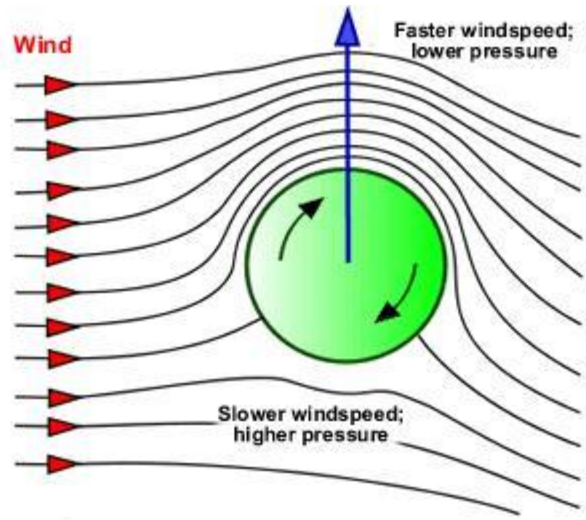

Figure 4.20. *Magnus effect*

The Magnus wind turbine is based on the Magnum principle in the way that the spinning torque is generated by the rotation of its cylindrical blades. The torque depends on the wind speed but also on the rotation speed of the cylinders. Therefore it is possible to have a higher control on the power generated by the turbine via modifying the speed of the rotating cylinders. The first prototypes show that the Magnus wind turbine is especially efficient with low wind speeds (< 8 m/s), where the usual bladed turbines do not reach an acceptable efficiency. The control over the force that is being done by the wind over the cylinders also allows to this turbine to work with very high wind speeds (up to 40 m/s).

Figure 4.21. *Magnus spiral wind turbine* (Mecaro, 2007)

These turbines generate the optimum power between 50 and 500 kW, which makes them very appropriate for the domestic use in small turbines. However, the companies which are developing this model ensure that it is possible to build up to 1-2 MW competitive Magnus wind turbines. It is important to remember that the cylinders must be rotating in every moment, so there is a power loss in order to maintain the rotation that decreases substantially the efficiency of the wind turbines. This power loss increases none linearly with the size of the turbine. That is why big Magnus wind turbines cannot be scaled without an important loss in the efficiency.

4.4.3. Other Designs

The wind power generation is not only possible with fixed rotor technologies. Some companies are developing very innovative designs which also extract mechanical power from the wind and convert it on electricity. This section shows the most evolved technologies: Kite wind generator and the Aerial wind turbine. However there are also some micro wind generators as the windbelts and nano vent-skin that have not being considered due to its low potential for massive electric power generation.

4.4.3.1 Kite Wind Generator

The kite wind generator is considered a disruptive technology. There has not been any similar design until the last decade. The design is inspired on the kite surfers. The mechanism is very simple. The kite, controlled by a computer system, pulls from a cable attached to a cylinder through a pulley system. The cylinder transmits the movement to the generator. When the kite has reached a high altitude the control system lets the kite drop to a lower altitude to start again the cycle.

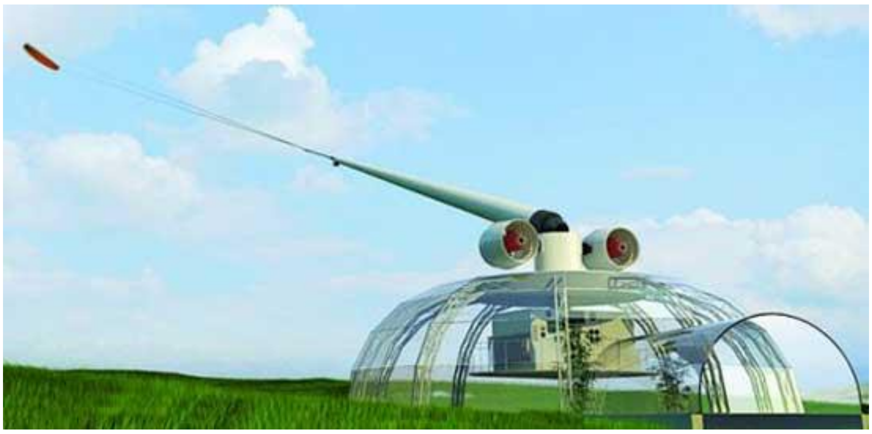

Figure 4.22. *Kite Gen Stem (Kite Gen, 2010)*

The Italian company Kite Gen has already tested successfully the first prototype, the KSU1. This very first model was able to generate 5kW of average power with peaks of 30 kW with a ground wind speed of 4.5 m/s. One of the advantages of this model is that it allows collecting energy from the high altitude winds which are powerful and constant. The design is very suitable for the places where the wind conditions are inadequate for the traditional wind turbines. Kite Gen is also working in more complex designs which involve the utilization of several kites attached to one very big rotor (approximate diameter 1600m). The project is called the Kite Gen Carousel (Figure 4.23).

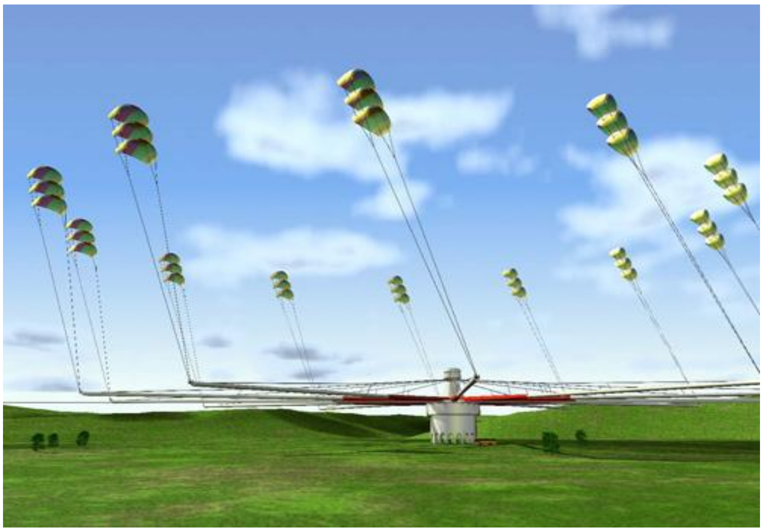

Figure 4.23. *Kite Gen Carousel (Kite Gen, 2010)*

The kite wind generator has demonstrated to be a real alternative for the wind power generation. The kite technology is suitable for any territory and the costs are low compared with other technologies. However, the design still needs to be tested on many conditions so see its behavior under extreme wind conditions and also very low wind situations.

4.4.3.2 Aerial wind generator

The aerial wind generators are already in the market. *Magenn Power* has developed on the last years the first commercial model called Magenn Air Rotor System (M.A.R.S.). This is a high altitude wind turbine. The turbine is lighter than the air so it is literally floating on the atmosphere, in addition its rotation generates the Magnus effect which helps to lift and stabilize the turbine. The turbine rotates under the effect of the wind generating electricity. This energy is transported to the ground via the sustaining cable (Magenn Power, 2010).

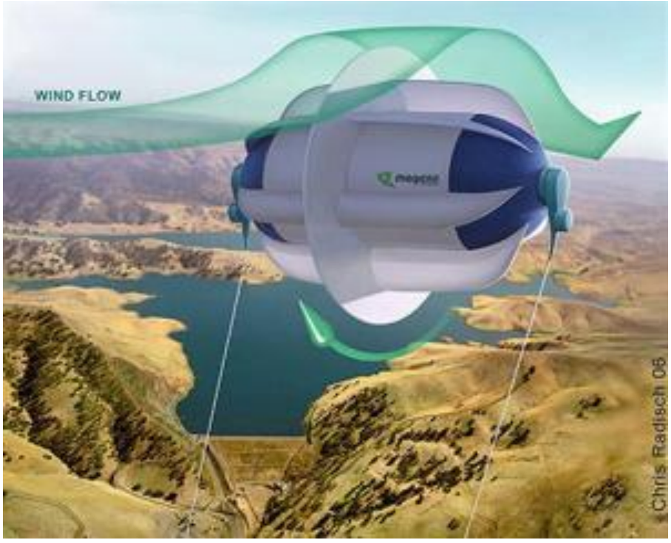

Figure 4.24. *MARS wind turbine (*Magenn Power, 2010)

The main advantage of this turbine is that removes all the placement limitations. MARS is mobile and can be rapidly installed and uninstalled without any heavy machine. The turbine is very silent and operates on high altitudes. It is easily detectable and does not represent any danger for the wild live.

This first model is specially designed for supplying very small and isolated communities, especially on the underdeveloped countries where there are very limited infrastructures. The MARS turbine combined with a diesel generator, for the low wind periods, it is a very economic and fast solution for supplying isolated and structurally damaged areas affected by natural disasters as earthquakes or hurricanes.

5. Wind power industry evolution

The study of the evolution of the wind power industry requires the evaluation of the past evolution, of the current status and the comparison with the established evolution frameworks. Each of the models and frameworks explained on the first section of this thesis contributes with a different approach to the global study of the wind power industry.

On this section, the models are compared to the wind power industry in order to obtain different approaches of which will be the future short and long term development of the wind power industry.

5.1. Classic theories

The industry dynamics model built by Abernathy and Utterback (1978) sets three phases on the development of an industry. These phases analyze the industry from the product and process innovation. On the wind power industry the Fluid phase, where the product innovations are done on the product level can be associated with the experimentation phase that occurred on the wind power industry between the first electricity generation wind turbine on1888 and the establishment of the first commercial wind farms at the end of the 70's decade. On that decade the amount of tentative designs started to decrease and the companies started to focus on optimizing the existing models and the efficiency of the wind farms. This behavior matches quite accurately with the Transitional phase theoretical performance.

The third period defined by Abernathy and Utterback (1978) is the specific stage. On this stage the rate of innovations decreases dramatically, both product and process innovations. This behavior has not been observed on the industry yet. The most important wind turbines manufacturing companies invest every year big amounts of money on their R&D centers. Currently the research centers are focused on the improvement of the efficiency of the turbines and building more advanced versions of the dominant design. But the companies are not interested on the development of other solutions and prefer working and developing the current wind turbine model. Thus the industry is going through the last years of the Transitional phase where the innovation is still important, but the importance of minimizing costs is increasing

According to McGahan's classification of the innovative trajectories (2004), currently the wind power industry is on a progressive trajectory. Now the companies are focused on preserving the existing network. Through each incremental innovation the companies are acquiring more experience and technical know-how. Thus the entry barriers to the new potential entrants are high. However, the high number of potential markets makes possible the incorporation of new companies on the less wind-developed regions as South America, Asia, Oceania or even some European countries. Nowadays on the American and European markets there is a high rivalry for getting important projects and contracts.

5.2. ARI approach

The *ARI model* provides an organized framework of industry evolution divided into steps. Comparing the steps with the history of the wind power evolution we can identify the different steps and facts that the industry has completed and, according to the model, which ones are the stages that the industry will follow and its main factors of change as the challenges and the hurdles of the industry.

The first step of the *ARI model* is the identification of a situation of opportunity and crisis. This happened on the second part of the 70’s decade. The Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo over the countries that supported and supplied Israel on the Yom Kippur war. The OAPEC was the main oil supplier for many occidental countries, so when the embargo took place, the dependent countries suffered a very serious effects on their oil-based economy. The affected countries started to promote different initiatives to decrease their oil dependence (Ruiz, 2004). On this international juncture, the Occidental governments and companies promoted alternatives to the oil that just few years before would have been ruled out.

The second step of the *ARI model* is defining the breakthrough innovation. The 1973 oil crisis created a market opportunity for the non-fossil electric power sources. Some companies, especially in Denmark, identified the necessity of “non dependent” power generation and started to work on innovative wind turbines designs. The Danish government and, after, the United States government, invested heavily on the wind power generation allowing to the emergence wind power companies to grow and improve their efficiency.

The third, fourth and fifth steps are identifying the grand challenges, the key hurdles and assessing these hurdles respectively. Those steps were partially completed during the first implantation stage of the 80’s decade but as the industry evolves there are new challenges and new solutions for them. The main challenges that the wind industry has overcome are:

- *MW-sized wind turbines*: The development of new materials allows to make bigger turbines with more generating capacity (Dismukes et al., 2008)

- *Adaptative turbines*: The manufacturing companies offer wind turbines for low, medium and high wind (Vestas, 2010).

- *Prejudices:* Until the last ten years the wind energy was not seriously considered for the massive electricity generation (Navarcorena, 2004)

- *Off-shore wind farms*: The offshore wind production has revolutionized the wind power market (BWEA, 2005).

- *Cost reduction:* Nowadays the price of the wind energy is 8 times cheaper than in 1980 (US D.O.E., 2010)

And the challenges that the industry will face in a near future are:

- *Size increase:* Although the current biggest turbines reach 4.5 MW (Gamesa, 2010), the power produced by each wind turbine should reach 10 MW.

- *Part manufactured:* The blades of the biggest turbines are too big to be transported by road so the future models will have to be part manufactured and assembled on the final placement (Gamesa, 2010).

- *Silent generators:* The wind turbines have to avoid the acoustic impact over the environment and over the civil population. There are already some alternatives as the low speed generators (THE SWITCH, 2010).

- *Adapted to the location:* The wind turbines must be designed to extract the maximum power from the wind in every location. The development of new theories about wind currents behavior can help to achieve this objective.

The fourth and fifth step were identifying and assessing the hurdles that threatened the future development of the industry. Those hurdles were identified by the middle of the 90's decade, just when the big companies entered into the wind market and the business opportunity became very clear. Some of the most important hurdles for the industry are :

- The cheaper energy sources as cogeneration

- Change of policy trends towards nuclear (de Esteban, 2004)

- Local resistance to wind farm implantation (NIMBY)

- The efficiency limits of the dominant model

- Lack of versatility of the dominant design

The sixth step it is considered as the end of the inception period and the beginning of the grow stage. On this step, the companies establish an innovative system based on the challenges and hurdles for the industry. The following steps, 7th, 8th and 9th, are the innovative system creation, the accelerate prototyping and the incremental innovation launch respectively. Eventually, the standard design emerges. This last point is the 10th step and marks the beginning of the maturity stage. Currently the industry is reaching this 10th step but due to the long life cycle of the wind turbines this process can take several years and even decades. According to Dismukes(2009), the maturity stage will arrive in 2030 when the global wind power industry reaches its maximum development.

The Figure 5.1. shows the approximate current status of the European wind power industry according to the ARI industry evolution stages.

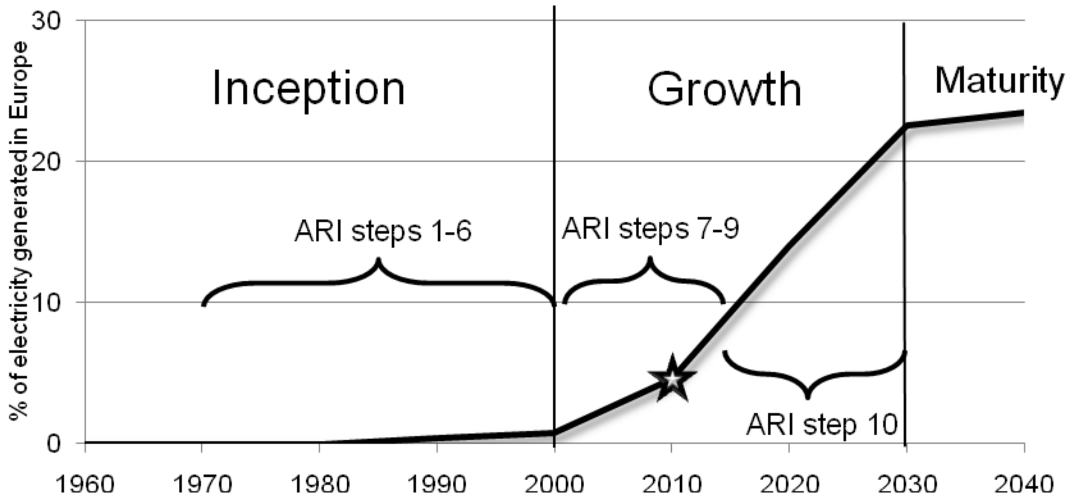

Figure 5.1. *Wind power industry evolution (Dismukes, 2009;Eurostat, 2010)*

5.3. Technology cycles

Probably the” technology cycle” structure is one of the most accurate models of the real process of product evolution and, eventually, product substitution.

The technology cycle theory, explained on the second part of this thesis, is a process divided on four stages starting from a technological discontinuity. This discontinuity, or radical innovation, opens a wide range of technological and market opportunities. Therefore, the technological innovation introduces an era of turbulence also called era of ferment. On the wind power industry the event that is considered as the main technological discontinuity is the evolution from grinding and water pumping windmills to the electricity generating wind turbine designed and built by C. Brush on 1888.

The second stage of the technology cycles is the era of ferment. On this period there is a design competition until one model is set as the dominant design. The period of era of ferment goes from the first wind turbine prototype in 1888 until the apparition of the dominant design. Apparently there is not an exact date of apparition of the current dominant design but this is certainly placed on the first part of the 90’s decade. Notice that the era of ferment covers more than one century.

There are two main reasons that justify the length of the era of ferment. The first one is the very long product lifecycle of a wind turbine and its elevated cost. Currently a wind turbine has a lifecycle from 20 to 30 years and rarely there is any substitution so there is a long time since one technology is able to substitute the existing one. The second fact is that until the decade of the 80’s the wind power was not an economically interesting sector. The industry became profitable on this decade and since then the number of wind farms has been growing exponentially until today. There was an evident necessity of generalizing a wind turbine design in order to improve its efficiency and decreasing the production costs. So, eventually the selected model was the three bladed HAWT with tubular steel tower.

Indeed the onshore wind power industry is certainly going through the Retention stage. This stage is also called the “era of incremental change” and due to the long wind turbine life cycle length, on the next ten to thirty years is not expected a significant technological change, only the improvement of the current designs. However the nature of the Architectural Innovations makes unpredictable the apparition of other “substitutive” technology.

From another point of view there has already been a technological discontinuity: the offshore wind farms. The innovation instead of coming from technological point of view comes from a new approach of the wind power production.

According to this interpretation, the first offshore wind farm built on 1995 on the Danish coast triggered a new technology cycle. The offshore wind farms although sharing great amount of technology with the onshore wind turbines also have their particular characteristics. Those differences are mainly on the structure of the foundations and on the placement. Nowadays there are different alternatives and methods for building offshore wind turbines as deep foundations or even floating platforms but there is not still any dominant design on this topic.

As a result of this technological step we find two different technology cycles which started on the same point but are having different technological paths. Offshore wind turbines can be larger and with shorter towers because the sea wind is more constant at lower altitudes than the inshore wind. There are some other facts that do not affect the offshore wind turbines as the noise that they could produce which does not affect to the local population.

On the other hand, the onshore wind farms are having their own technological path. Although the main trend of making bigger and bigger wind turbines is the same as with the offshore wind farms, the design of these turbines is more focused on adapting their characteristics to the inland placement in order to optimize the turbine's efficiency. The biggest wind turbine manufacturers offer nowadays on their brochures different range of products depending on the final placement. The designs are focused on the average annual wind speed differentiating between high wind and low wind placements.

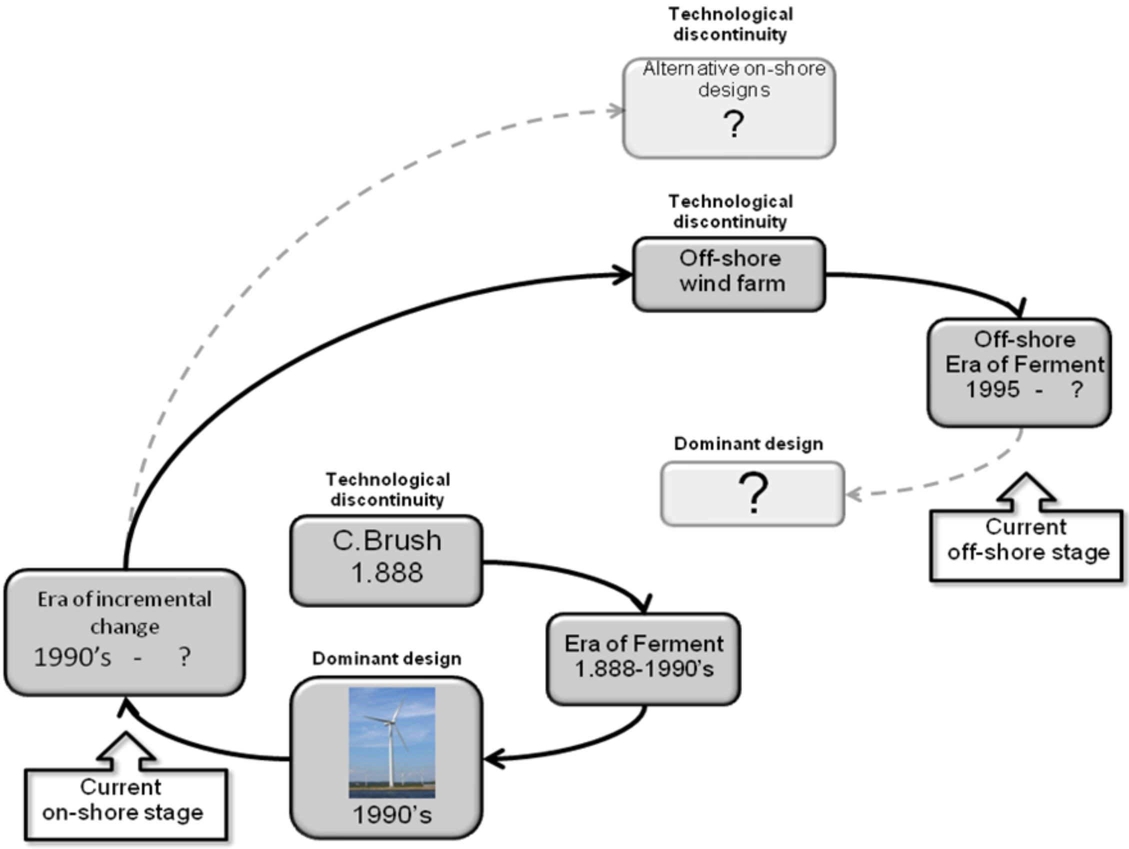

Figure 5.2. *Technology cycles of the large-scale electricity generating wind turbines*

The conclusions of this particular technology cycle analysis showed on the Figure 30. As it can be seen on this figure, although the onshore wind power systems are still on the era of incremental change, the offshore wind farms are starting their own technology cycle independently from the in-land wind farms.

According to the model of the technology cycles a dominant design will emerge on the offshore wind farms. The actual marine wind farms are located in low deepness areas but for continuing the development of these facilities it is necessary the generalization of deep waters foundation systems as floating platforms or other technologies. All these concepts are being developed on the current "Era of ferment".

The next step of the onshore wind turbines would be the substitution by a radical innovation. For the moment this possibility is apparently very small. The current dominant design is being used by the most important wind turbine manufacturing companies. However there are some alternative models which with a proper development and implantation have the potential for entering into the wind power market. The most important alternative projects are studied on the following section.

5.4. Technological substitution

As it has been explained on the previous sections, after a long period of incremental innovations there is always a possibility that a radical innovation enters into the market and starts replacing the dominant design for some uses. Those radical innovations usually are just a combination of the existing technologies but they are not completely developed until they reach a certain share of the market and the companies realize that the design can be profitable. Thus, until there is not a clear market opportunity those designs do not emerge. That is what happened with the current dominant design. The technology needed was already invented, but until a clear market opportunity did not appear until the 70's decade and therefore, the industry did not evolve.

But there are more factors involved in the introduction of a new product inside the market. The dominant design has weaknesses and the new designs must cover these weaknesses with its strengths. As it has been seen on the chapter dedicated to the evolution of the dominant design, the current wind turbine model although being much more developed than any other design it still has certain debilities.

The Table 1 has been built with the objective of comparing the performance of the different models of wind power turbines. Most of the models have not been developed or tested in a big scale yet so the table has been constructed over theoretical results and expectations. However the results provide a general idea of which is the situation of the current wind power alternative models compared with the actual dominant design.

	3-Blade HAWT	Darrieus	Sabonius	Darrieus-Sabonius	MagLev	G-model	Modified Darrieus (H-rotor)	Ducted rotor turbine	Multi rotor turbine	Contra rotating turbine	Magnus turbine	Kite generation	Aerial generation
Power range (kW)	850-4.500	250-1.000	< 1	2 - 15	1.000.000*	?	2 - 15	10	0.4 - 6	5	12	4 – 3.000*	100–1.000*
Low wind conditions (<8m/s)	★★	★★	★★★	★★★	★★★	★★	★	★	★	★	★★★★	★★★★	★★★★
High wind conditions (>35m/s)	★	★	★	★	★★	★	★★	★	★★	★	★★★★	★	★
Land efficiency (KW/m^2)	★	★★	★	★★	★★★★	★★	★★	★★★	★★★★	★★★	★★	★★★★	★★
Maintenance costs (€)	★★	★★	★★★★	★★★	★★★★	★★★	★★★	★	★★	★	★	★★★	★★★
Scalable	★★★★	★★	★	★	★★★★	★★	★★	★	★★	★	★★	★★	★
Visual impact	★★★	★★	★	★★	★	★★	★★★	★	★	★★	★★★	★★★	★★★
Threat to wildlife	★★	★	★★★	★	★★★★	★★	★	★	★	★★	★★★	★★★★	★★★★
Offshore implantation	★★★	★	★	★	?	★★	★	★★	★★	★★	★	★	★
Versatility	★★	★★★	★★★	★★★★	★★	★★★	★★★	★	★★	★★	★★	★★	★★★
Current status	Market Leader	Currently not in use	Small uses (Anemometers)	On market Urban Prototypes	Projected	Not developed	On market Urban Prototypes	On market	On market	Not developed	On market	Prototype testing	On market

Not known ? Not Tested *-Poor ★ - Normal ★★ - Good ★★★ - Excellent ★★★★

Figure 5.3. *Alternative designs table*

The analysis focuses on the principal aspects of the wind turbines and on its critical characteristics. The following sections explain which are the best designs for each characteristic.

5.4.1. Power range

The power range is determinant for the election of a wind turbine model for a specific location. Actually the is a very wide range of wind turbine powers. The common massive dominant design varies from the old 50m diameter, 850 kW turbines to the most evolved models of 128 m diameter and 4.500kW. So, for the substitution of these large wind turbines there are just few models which can compete with the actual dominant design for massive electricity production and they are both still under development. Those designs are the MagLev wind turbine and the Kite generator, but both are in a very early stage of their evolution. In contrast, for the domestic and urban wind energy production, the panorama is completely different. The vertical axis wind turbines offer a great variety of products with better efficiency and much more reliable than the small-scale versions of the dominant design.

5.4.2. Low wind conditions

The first factor of evaluation is the efficiency of the turbines with low wind conditions (<8 m/s). The dominant design is able to work from wind speeds of 4 m/s but the performance is not profitable until speeds of 10 m/s. The other designs of HAWT are not very efficient on this low wind situation except the Magnus model. This is because the Magnus principle allows creating pressure differences from very low wind speeds. The best models on these conditions are the ones based on the drag effect as the Kite wind generator, the Aerial generator and the Sabonius turbines. Notice that the MagLev giant generator although not having the best aerodynamic configuration, thanks to its low friction due to the magnetic bearings that support its weight, it is also able to produce electricity at very low wind speeds.

5.4.3. High wind conditions

The extreme wind speeds (>35 m/s) are also a problem for the usual wind turbines. The pitch control and the active and passive stall designs allow protecting the wind turbines against strong winds but in any case optimizing its performance. On strong wind conditions all the variations of the dominant design have security problems, especially the ducted rotor model because of the terrible drag forces that has to support. Again, the Magnus model is able to work with higher wind speeds because the force done over its blades can be controlled via controlling the rotation speed of its cylindrical “blades”. The VAWT work with multidirectional wind directions, so in the case of very strong winds, they are not able to work because the security reasons and, in addition, they are very difficult to protect. The Aerial and Kite wind generators are susceptible of breaking their anchorage from the ground but they are easy to protect, the operators just have to bring them back to the ground level. The MagLev wind turbine, according to its designers, it is able to work with wind speeds up to 40 m/s, but when the wind speed overpasses this level, the whole structure is susceptible of suffering structural damages and has similar problems as the other VAWT.

5.4.4. Land efficiency

The “Land efficiency” factor refers to the amount of surface that is needed for the generation of a certain amount of electric power. In other words it could be defined as the relation between the surface occupied by the wind turbine and the power generated by it. On this aspect the current dominant design does not have the best behavior. A wind turbine needs to be separated from another turbine between five and nine rotor diameters in the dominant wind direction and between three and five times the rotor diameter in the perpendicular direction to the dominant wind direction (EGA, 2010). According to this information, a medium sized turbine (Vestas V80- 2MW) would need approximately 716.800 square meters to generate 2.000 kW so its land efficiency would be 0.00279 kW/m^2. Notice that in a medium sized cogeneration plant this value would be close to 4 kW/m^2 (Carbonell Figueras, 2004) .The VAWT can be placed closer to each other without interfering on the air flow of the other units but the performance is still not very good compared with other models. A Darrieus turbine needs a separation of 1,5 diameters which is significantly smaller than the three bladed HAWT (Schatzle et al. 1980) . The maximum values for this factor are achieved by the modified HAWT which multiply the efficiency of the wind system. For instance, some experiments done with small multi-rotor prototypes have produced six times the amount of energy that a normal turbine would have produced using the same surface. The contra-rotating and ducted rotor turbines can double the electricity production but only in very favorable conditions. On the case of the MagLev turbine this ratio has not been tested but if the expectations are correct, this factor can multiply several times the amount of energy produced per square meter used. The height and radius of this turbine allows extracting energy from very big air volumes and, in addition, the machinery is concentrated so the power losses on the friction and in the generation and transformation also are lower in average than having the same power distributed in several wind turbines. The Kite generators do not need much space to be placed but they must be separated to avoid the collision between the kites. The Aerial generators have the same problem and in addition they cannot be guided as the kites so their trajectory depends exclusively of the wind making it unpredictable. The final result is that they must operate almost alone or with a long distance between them to eliminate the collision risk.

5.4.5. Maintenance costs

Due to the very long life-cycle of the wind power systems, 20-25 years (Vestas, 2010), the maintenance costs have an important impact on the final profitability of a wind farm. The actual dominant design has a very big disadvantage compared to other models. Operation and maintenance cost easily make up 20-25% of the total cost per kWh produced over the lifetime of the turbine (WETF, 2010). The accessibility of the rotor is reduced because of the big height of the tower. For small maintenance operations the workers can access the nacelle through the tower. But for the substitution of big parts of the turbine as the blades or the gearbox it is necessary a very big external crane which increases notably the costs of the reparation. On the contrary the VAWT have their generators and gearboxes on the ground level which make them much more accessible and decreases substantially the maintenance costs. The MagLev turbine is especially efficient on this aspect. Although the size of its machinery, the overall maintenance costs per kW/h are much lower because the wind production is centralized on one or two turbines instead of being spread over big areas as the conventional wind farms. The Kite wind generation has the same accessibility advantages as the VAWT, and the Aerial generators can also be checked and repaired on the ground level

5.4.6. Scalability

The scalability is the property that allows making bigger and bigger wind turbine models without losing efficiency. The dominant design and MagLev turbine, which is already a big-scale wind turbine, are the models that can be built in larger sizes without decreasing notably their power generated. This characteristic makes them very suitable for the offshore applications where the size of the turbine is a clear advantage. However, the installation of the MagLev turbine on the sea would be very problematic because it needs very big foundations. The most viable way of installing a MagLev turbine on the sea would be making an artificial island with the only purpose of housing the turbine. This alternative would trigger the costs of the project making it clearly unprofitable. The other models are designed for generating power below 1-2 MW so their scalability has a very restrictive efficiency boundary.

5.4.7. Visual impact

The visual impact is a very subjective characteristic of the wind turbines but it is one of the most common arguments against the win power industry. On the countries where there is a big wind power implantation, the turbines are becoming usual and the society is getting used to see them on their landscapes. However each type of turbine has its own visual characteristics. As it has been said the dominant design is the most accepted design but on the case of urban areas there are some very commercially attractive models. In the opinion of the writer, some models of VAWT as the modified Darrieus are very suitable for urban areas. For massive wind power generation the

MagLev turbine creates a huge visual impact but the promoters of this project reply that it is less harmful for the landscape one huge turbine than wind farms with hundreds of wind turbines generating the same amount of electricity. The Aerial and Kite generators operate at high altitudes and would not disturb the landscape in such a big way as the normal turbines.

5.4.8. Threat to wildlife

The other big environmental problem of the wind turbines is the collision of the migrating birds and bats with the blades. Usually this problem decreases when the size of the wind turbines increases in the way that it is easier for the animals to dribble them. There are several reports that evaluate the impact of the wind turbines over the death rates of the birds. Particularly the NRC (National Research Council) released a detailed study that showed very clear results. The report verifies the fact that wind energy development's overall impact on birds is extremely low compared with many other human-related activities. From every 100.000 birds killed only three of those deaths correspond with collisions with wind turbines (NRC, 2007). Surprisingly, the main non natural causes of birds' deaths were collisions with windows and domestic cats. The VAWTs are smaller machines and the shift based models spin with faster speed than the wind; these factors make them extremely dangerous for the wild life. The most respectful models are the Kite and Aerial generators which mobile parts are not as dangerous as the usual blades; and the MagLev turbine, which is so big that it is perfectly identifiable by the entire animal wildlife.

5.4.9. Versatility

During the wind turbines life-cycle, the windmills are exposed to many different atmospheric situations. The versatility category evaluates the capability of the wind turbine to adapt to these different wind conditions. The most problematic cases are: the turbulent airflows, the direction-changing wind and the extreme high and low wind speeds. The most versatile wind turbines should be able to work in all of these cases but not all of the designs are able to do it. The dominant design needs a system for orientating the turbine towards the wind so in changing wind conditions is not able to optimize the electricity production. All the VAWT have much more versatility than the usual HAWT because they do not need to be orientated so they accept wind from any direction. This makes the vertical axis models very suitable for urban areas where the interaction of the wind with the buildings creates non stable wind flows. The Aerial generator is also very adaptable to the different wind conditions and in addition it is portable, so it can be installed and uninstalled rapidly.

5.4.10. Offshore application

The off shore wind farms are becoming more and more important on the wind power industry. For the moment the only model tested on off shore applications has been the dominant design with positive results. During the next years it is expected a proliferation of marine wind farms. The dominant design seems the best option for this kind of facilities. Marine wind turbines do not need to be as high as the normal onshore to have the same efficiency because the marine winds are normally stronger and more stable at low altitudes. From all the alternatives there is not a technology that in a near future could substitute the current dominant design.

6. Conclusion

6.1. Findings and discussion

This section summarizes and extracts the conclusions of the research and analysis work done all over the thesis. Although the wind power industry is a complex and very extensive topic, these conclusions try to make a big picture of the current state of the industry and, through the technology management tools and industry evolution theories, an analysis of which factors will determine the evolution of the industry in a near future. In order to present the conclusions in an organized way, this section divided into three sub sections which are respectively, *current industry status, near future expectations* and *alternatives to the dominant design.*

6.1.1. Current industry status

According to the consulted official sources (Eurostat et al., 2010), the wind power installed capacity is increasing in an exponential way since the beginning of this new century. However it is important to break down this data in order to obtain more specific conclusions. The growth has not been homogeneous from a geographical point of view. There are very big regions with an important wind power potential where the wind power production has not been even considered. These regions are Africa, South America. But there are also some countries inside the "wind developed regions" which do not consider as a serious alternative the wind power generation. On the other hand there are some developing countries, especially China and India, where the increase of the wind power generation has been spectacular during the last five years. For instance, the installed capacity growth rate of China during 2008 was 106.5% (WWEA, 2009). This behavior is expected to continue, thus the most important wind turbine manufacturers as *Gamesa, Vestas* or *Suzlon*, already have manufacturing plants on Asia.

However, the oldest wind power production regions, Europe and North America, still produce the biggest amount of the global wind power energy. The objective of these two powers is to generate the 20% of their electricity needs with renewable power sources by 2020 (E.U. White Paper, 2009). Those sources are mainly solar power, hydropower, geothermic generation and, of course, wind power generation. From all those technologies the most developed are the hydropower and the wind power generation. However the hydropower generation has very limited applications due to the particular geographical and hydrographical characteristics (eg. Rapids, waterfalls, artificial lakes and so on) that are needed for its proper performance. These factors leave the wind power industry as the major player in the actual renewable energies panorama.

For reaching this point the wind power generation has achieved several challenges. The *ARI framework* explained on the first part of the thesis and developed and applied on the *Industry Evolution* section, shows which are the main challenges that the industry has achieved for reaching the current success and growth of the industry:

- *MW-sized wind turbines*: The increase of the size of the turbines, and therefore of the power that they produce, has made the wind power the most developed green energy. The power generated by the modern turbines is in between 0.85 MW and 4.5 MW (Gamesa, 2010).

- *Adaptative turbines*: Nowadays the wind turbine manufacturers offer low and high wind wind-turbines. This distinction allows to the buyers to maximize the electricity production by adapting the technological characteristics of the turbine to the characteristics of the place where they will be installed (Vestas (Vestas, 2010). However, the companies are currently working and improving these aspects of the design.

- *Prejudices:* Until the generalization of the wind-farms the wind power industry was not seriously considered as a reliable alternative for the common fossil electricity sources. Now it is generally considered as an alternative to the most usual ways of electricity generation.

- *Off-shore wind farms*: The offshore wind production offers a huge range of possibilities and opportunities for the expansion of the industry (BWEA, 2005).

- *Cost reduction:* On its beginnings the wind electricity was not profitable but thanks to the economy of scale, the technological development and the wind power boost policies, the actual price of wind power electricity is eight times cheaper than 30 years ago (US D.O.E., 2010)

Comparing the development of the wind power industry with the industry life-cycle frameworks it is also possible to obtain some conclusions.

The most classic industry life cycle theories developed by Abernathy and Utterback (1978) divides the industry life cycle in three stages where the industry is situated according to the number of product and process innovations. The wind power industry is, nowadays, reaching the end of the second stage, the transitional phase. Therefore, the next evolutionary step is finishing this transitional phase and moving into the specific stage, where the product and the process have been mostly improved and the efforts of the companies do not focus on the innovative process. However, due to the length of the wind power industry life cycle stages, the end of the transitional phase is not expected until the year 2020 approximately. This means that the companies will continue the product and mostly the process development on the following years but with decreasing rates.

From the innovative trajectories point of view (McGahan, 2004), the industry is going through the progressive trajectory where the companies invest in incremental innovations with the objective of making high entry barriers and product differentiation. The change of this innovative behavior of the industry is very improbable on the following years. However, according to the McGahan model (ibid.) the next stage of the industry is the creative changing trajectory but this would involve a technological step on the wind power industry evolution.

In order to complete the analysis of the industry it is important to evaluate which are the current technological trends among wind turbine manufacturers.

- *Size increase:* Although the biggest wind turbine in the market generates 4.5MW, almost all the companies are testing nowadays bigger prototypes that reach in some cases 6MW of nominal power (Gamesa, 2010).

- *Part manufactured:* With the growth of the size of the turbines, the process of transporting the blades that, in the new models are more than 60 meters long, becomes a serious problem. The blades of the new turbines are manufactured in two pieces and assembled in the final location of the turbine (Gamesa, 2010).

- *Silent generators:* For the implantation of wind turbines in the rural areas the noise that these turbines generate has to be minimized in order to create a good response from the neighbors. The generator manufacturing companies are building specific low speed generators which produce less noise than the old high speed generators (THE SWITCH, 2010).

- *Adapted to the location:* "*High wind*" and "*low wind*" wind turbines are the first step towards the development of new technological solutions that adapt better to the wind characteristics of the location where the wind farms are (Vestas, 2010).

6.1.2. Near future expectations

According to the wind power associations as AWEA and WWEA (2009), the wind power industry will continue its current expansion with similar or even higher growth rates for, at least, the following 10 years. This growth will be general among the world and with especial importance in some countries as China and India.

In Europe and U.S. the industry is already quite extended and the growth will continue on the following years until the maturity of the industry arrives eventually in

20-30 years (Dismukes et al. 2008). But in the developing regions (China, India) the growth of the industry did not start until the first decade of this new century so the maturity stage might arrive later than in Europe and North America.

However, these predictions are built over hypotheses. Indeed, the wind power industry will have to change and evolve to reach these optimistic predictions. Therefore this thesis points out which are going to be the main challenges that the wind power industry will have to achieve in order to reach the theoretical expectations:

- *Lower the wind electricity costs:* The wind energy must be profitable without subsidies. Until this does not happen the wind power generation will be dependent of the local and regional promotion policies.

- *Minimize maintenance costs:* A considerable amount of the cost of the wind energy is caused by the maintenance costs. Operation and maintenance cost easily make up 20-25% of the total cost per kWh produced over the lifetime of the turbine (WETF, 2010). Manufacturers must develop new turbines that require fewer regular services and more reliable components.

- *Accumulate the spare energy:* During the daily periods of low electricity demand on the grid, the spare energy generated by the wind turbines must be somehow accumulated and not wasted. The actual proposed alternatives, Green power island storage system (Gottlieb Paludan Architects, 2009) and the hydrogen producing wind turbines (NREL, 2003), do not seem realistic projects in a near future.

- *Placement-focused designs:* Turbines must be design according to the wind characteristics of the final placement in order to harness wind power resources.

- *Recyclable turbines*: Currently the most common routes for dismantled wind turbines are landfill (although being banned in several countries as Germany) and incinerated which also cause environmental damage. The only alternative use for a second use of the blades is as filler material in the cement production (Larsen, 2009). The future wind turbines must be built of environmentally friendly materials.

- *Urban solutions:* Following the example of the solar power, the use of small sized turbines on the urban areas must become usual.

- *Deep water solution:* Currently the offshore wind farms are built in low deepness areas therefore limiting the potential off shore zones. With deep water foundation systems there are no practical impediments for the implantation of off-shore wind farms.

However the growth of the industry does not depend exclusively of internal factors. There are some other factors that can damage heavily the opportunities of the sector. These are the main key factors that threaten the future of the industry:

- *Bad implementation:* The locations for the turbines must be carefully selected in order to cause the minimum environmental and social impact and collect the maximum of electricity. The consequences of a bad implementation can be self-destructive for the industry.

- *Change of policy trends towards nuclear:* An extended politic sector believes that the energy of the future is the nuclear power for its lack of CO_2 emissions and its low price (de Esteban, 2004). A change of the political trends toward the actual fission processes and a hypothetical development of the atomic fusion technology (which is in the experimental process) would stop dramatically the wind power energy production.

- *Unsuccessful offshore implementation:* If the developments of the offshore wind farms do not succeed to be reliable and profitable the potential of wind power implantation will be substantially reduced.

6.1.3. Alternatives to the dominant design

The third main topic of the thesis, after the analysis of the current status of the wind power industry and of its future development, is the analysis and evaluation of the alternative wind power generation systems. The objective of this analysis is to measure the potential of each model of entering into the market and, eventually, replacing the dominant design.

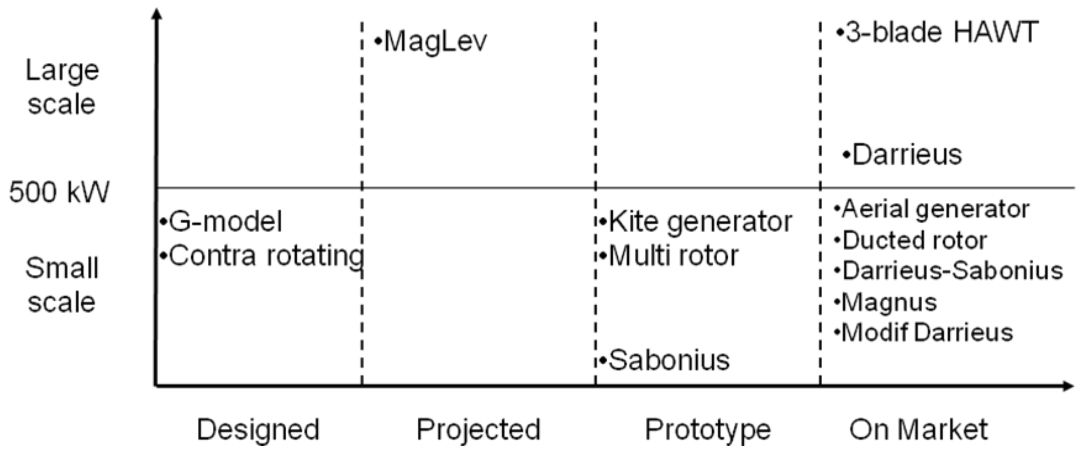

Figure 6.1. *Status of the alternative wind turbine designs*

The wind power systems can be divided in two categories: large and small scale machines. The large scale is usually placed in natural locations and their mission is supplying the electric grid. On the other hand, the small scale generators are placed in urban areas and their purpose is to supply of electricity to private owners. The figure 6.1 shows the current development of the different technologies nowadays.

There are not many alternatives to the large scale electricity generation. Besides from the three bladed HAWT there are only two alternatives. The first one, the Darrieus turbine, was already ruled out on the 80's decade after the implantation of this turbine on several wind farms. The dominant design offered more control over the performance of the turbine and it allowed building larger turbines. The other option is the MagLev wind turbine but, as it can be seen on the Figure 6.1 the design is still under development and has very serious inconvenient despite of being one of the most complete wind turbines according to the Figure 5.3.. The main problems are that it is very difficult to find investors for a project of such size. Each MagLev wind turbine would cost $53 million (Basantani, 2007). In addition is very hard to find a proper location where to install such a colossal structure without disturbing the surrounding environment. In addition the model has not been tested with any prototype of similar size to the projected turbine.

On the small scale wind power production the panorama is very different. There is still not a generalized dominant design and the criterion used for evaluating the models is not the same as in the large size wind turbines. On these turbines some key-features as the appearance, the simplicity and the reliability are determinant. In order to make a brief summary the author has selected three models that for their characteristics are very suitable for the small scale wind production.

- *Modified Darrieus turbine, three helical blades:* These turbines are visually attractive and its simplicity is one of the key points for this model. In addition there are companies that are already commercializing these designs in different sizes (from 2 to 15 kW), and

- *Multi rotor turbine*: Although this design is still in the prototype stage, it has shown very positive results on the test. The appearance of the models is not very attractive for the urban locations but suitable for farms and other rural places. Its high land efficiency is the main strength of this model (Selsam, 2010).

- Magnus wind turbine: Its good performance under low wind conditions makes it very suitable for locations without high speed winds (eg. Finland). For achieving a good efficiency, this model must be medium-sized, which is too large for urban implantations but acceptable in rural areas (Mecaro, 2007).

6.2. Assessment of the study

This section goes through all the validity issues of the thesis. It is very important to understand that the research, analysis and conclusions are linked to the characteristics and limitations of the process. In order to explain the validity of the results, this section exposes the limitations of the theories that have been used to model the industry. In addition it is necessary to examine how adequate are these methods for the study the development of the industry and other important issues about the validity of the research methods and data used during the whole process.

The first step for assessing the validity of the results obtained on this thesis is to analyze which are the objectives of this work and which approach is used on this document for reaching to the conclusions. As it is said on the introduction, this thesis studies the wind power industry evolution with the objective of evaluate its current status, the near future development and the alternatives to the wind turbine dominant design. For the two first objectives the thesis uses the reference of the existing industry life-cycle theories and technological innovation and substitution frameworks. All these theories study the behavior of the industry from an abstract point of view. However, they have been developed through the study and analysis of other industries in the past. This means that these theories assume that the development among industries follow a predictable pattern through different stages. These stages can be identified through the observation of some key-indicators.

The domain of the research has been very well defined from the beginning of the research work. As it is explained on the *Approach* section the thesis studies the wind power industry and, especially, the big wind turbines manufacturers. But inside the domain, the researcher has to choose the key-indicators for his purposes. In this case the purpose is to study the evolution of the industry. The main indicators considered have been: the power installed, the costs of the electricity generation, and the power generated by each turbine. These are the indicators that most of the official sources use for their reports and statistics. However it would be possible to make the same study using other indicators as the number of wind turbines installed. In this case the results would be different because the growth of number of turbines has not been as high as the growth of power installed due to the increase of the wind turbines capacity. Nevertheless, for the achieving the objectives of this thesis, the power installed provides a global information about the wind power evolution and also allows comparing this capacity with other sources of electricity.

Although the comparison of the wind power industry with the industry evolution theories provides a rational prediction of the future behavior of the industry, it is important not to forget that the future of this specific industry depends, also, on many random and unpredictable factors. So the results of the thesis must be considered as rational predictions and not as absolute truths. This thesis indicates which is most probable behavior of the industry on the following years according to the data collected, the theories considered and the interpretation of both data and theories. The wind power industry will follow a very determinate path that probable will differ in some aspects to the prediction done. However this fact does not subtract credibility to the study which has been done with the maximum seriousness following the analytical methodology that this kind of work requires.

In order to assess the reliability of the study, in first place it is necessary to determine the validity of the theories used to model the development of the industry. The life cycle theories are not universal laws, and the characteristics of the industry object of the study and of the surrounding environment can limit the grade of applicability of the models. In some cases (Abernathy, 1978) the own authors set the limits of the applicability of the theories. In the case of case Abernathy (Ibid.) his life-cycle model is not applicable to the industries which development is very rapid and also to the industries where the product is heavily standardized. The industries where the products and processes are too simple are also ruled out from the scope of this theory. Teece (1986) limit the life cycle model to industries where the customer needs are relatively similar. The industries where the niche markets have importance and do not take advantage of scale economies do not follow the industry life-cycle dynamics. From the technology cycle point of view (Anderson and Tushman, 1990), the industries where the technological discontinuities happen every few years, the different models do not have time to establish themselves as dominant designs. During the *era of ferment the* next technology discontinuity appears before the dominant design emerges (see Peltoniemi, 2009).

As it can be observed, the wind power industry fits into the range of validity of these theories. Wind turbines are not a completely standardized product and complex from the manufacturing point of view. In addition the needs of the customers are quite similar, good performance and low costs. On addition the technology cycle has been long enough time to have a clear dominant design.

From all the theories used on the thesis, the youngest one is the recently developed ARI model (Dismukes, 2005). As its own name indicates, accelerated radical innovation, this theory focuses particularly on the radical innovations which are developed in a short period of time. This framework can be used both as a model and as a tool for managing the industrial development of a radical innovation.

This model of development, ARI, does not fit perfectly on the trajectory of the wind power industry, mainly because the wind power industry did not behave according to the model on the very first steps of the ARI methodology. In addition the wind turbines are not considered as radical innovations even if the current model of industry development is similar to the structure of the growth stage of the ARI model. This factor limits the use of the ARI model, and makes it unnaccurate to descrive the whole process of the evolution of the wind power industry. However the model fits perfectly with the actual situation of the industry and that is why it has been considered for this study. In addition the model provides an organized framework in order to detect the challenges and hurdles for the industry and its development which is a very important point of this thesis.

The reliability of the data used on the thesis is generally high. The sources are mainly databases as the Eurostat or the US DOE (Department of Energy) which use reliable methods for the data collection. However, there is other information that, although being valid for a period of time, might change with the time. For instance the E.U. White Paper establishes certain objectives for the year 2020 and the predictions of this thesis have been made according to this document. But in the current global economic situation these objectives might be changed or, at least, updated. The results of the thesis have to be interpreted according to the wind power industry situation on spring of 2010 and cannot be extrapolated to a future where some structural conditions might have changed.

Although the data collection method used, *secondary analysis*, in most of the cases has provided quality data, in the section about the alternative designs the information found was not completely trustable and very incomplete due to the small interest of the big companies on these designs. In most of the cases the information comes from small companies which are looking for investors in order to develop their ideas. This situation involves that some of the estimations about the performance of the wind turbines have not been tested and seem to incur into exaggerations. An academic primary source of data would have been very useful, therefore providing trustable data from prototype tests and digital simulations of the models. However, the technical information acquired during the research work combined with the information provided by the companies has allowed making a qualitative analysis of the main characteristics of the turbines.

The conclusions are very clear about the challenges that the wind power industry will have to overcome in order to achieve the most positive expectations. All the conclusions are written according to the fact that the industry overcomes them. But there are other possible interpretations of the results in the case that the industry does not succeed to overcome the hurdles and achieve the challenges. In these cases the industry would reach an early maturity and would not get to the objectives of being the most important renewable source of energy. The development of the industry would be drastically stopped. The possibility of an early decline of the industry must be considered as an alternative interpretation of the industry evolution. However, in this case, the thesis exposes the possitive alternative basing its choice on technological factors and on the information acquired on the research process, assuming that the wind power industry is ready for overcoming the future challenges.

6.3. Implications

6.3.1. Recommendations for further research

For this study the wind power industry has been treated like a global business with global characteristics. The result shows a big picture of the industry and identifies several trends on the future development of the industry. However for a deeper analysis of the wind power sector, the industry should be divided into smaller parts. This way it is possible to obtain more specific and accurate conclusions. In the opinion of the author, the development of the industry on India and China is a very interesting topic for a deeper analysis.

In addition, the utilization of primary data sources extracted through personal interviews from personnel from the wind turbine manufacturing companies, environmental and energy responsible of the national governments and wind-farms owners; would provide to the study a more accurate and updated point of view: It would also point out some practical problems and key-factors that are difficult to identify with the secondary data analysis.

From the technological point of view, this thesis points out some fields with high potential for academic research on the field of the mechanic, aerodynamic and fluid behaviour. The study of the efficiency of the different alternative models of wind turbine is a very adequate and interesting topic for the development of Master of Science Thesis on the speciality of Mechanical design. In the opinion of the author the models with more academic interest are: the Magnus turbine, the multi-rotor turbine and the g-model turbine.

6.3.2. Policy making and management practice

The companies that are in the sector of wind turbines manufacturing are experimenting a very important grows. The results of this M.Sc thesis show that this grow will continue but the companies should not stop investing in R&D in order to create product differentiation towards winning market share and loyal customers with the objective of maintain their position until the era of maturity. The introduction of incremental innovations via R&D will create very high entry barriers on the developed markets as Europe and North America and will reduce substantially the threat of new entrants. In addition the existing manufacturing companies should consider the penetration on new markets as the South American market where the wind power generation is controlled by small and regional companies.

The off-shore market is a very promising sector. The manufacturing companies should make an effort in developing new solutions for the off-shore wind farms in order to simplify their structure so the turbines can be maintained consuming less money. The foundation of the marine turbines is also a very interesting topic for the R&D investigations that can generate important returns to the investing firms.

Due to the high rivalry in the sector of wind power generation on the developed regions as Europe and North America, the only chance for the companies that want to enter into the market of large scale wind power generation is the specialization of their products. The products offered by the large manufacturers are usually very generic so there might be a place on the market share for specific solutions. The other chance for the entrant companies is to enter into new and developing markets. Nowadays the business potential in China and India is very big so the new companies would have an opportunity in those markets. In addition the South American markets also have a lot of growth potential.

There are companies that do not take part directly on the wind turbine manufacturing process but have interests on the industry. The business of recycling components of old wind turbines has a very promising future. On the next 5 to 10 years the wind turbines of the wind farms installed during the decade of the 90’s will have to be replaced for newer and more efficient models. This means that there will be a great amount of wind turbine blades and, therefore, a big business opportunity for the companies that specialize on this recycling process.

From the policy making point of view there are some recommendations for the authorities for achieving a healthy grow and adaptation process of the wind energy into the energy generation system. First of all the subsidies should not be given unconditionally and in a uncontrolled way. The authorities must make sure that the money used for promoting wind power companies is used to increase the efficiency of the equipments and not to make richer the shareholders of these firms. One way of achieving this objective is obligating to the companies to expend a certain percentage of their capital into R&D activities. In addition the government should penalize the companies that do not implement correctly the wind turbines damaging the environment and without studying if the characteristics of the location that allow to have a profitable wind production. These activities damage seriously the image of the wind power industry and must be heavily punished.

The offshore wind power production is a sector with huge possibilities that must be subsidized to achieve a certain level of efficiency. The national governments must promote this kind of facilities which do not affect to the environment in such a way as the inshore wind farms and, in addition, do not damage so heavily the landscapes.

Finally, the small scale urban production should be promoted from two different approaches. One is by making the turbines visually attractive and socially accepted via publicity campaigns and, second, by subsidizing the use of these turbines among the private users both in rural and urban areas.

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