MSc in Applied Environmental Economics Dissertation 2005

# A model to explain investment decisions in renewable energies with a case study for the Chilean wind energy industry

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I herby declare that this Dissertation has not been submitted, either in the same or different forms, to this or any other university for a degree. I also declare that this Disssertation does not draw from any other work prepared under consultancy or other professional undertaking, by myself or jointly with other authors in any way other than duly and explicitly acknowledged herewith.

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Date:...........................................................

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**Acknowledgements**

To my family which has always supported me in every possible manner and which has provided essential data for this work, revised my English and given me technical advise. Specially to my brother Carlos, who was born an engineer and has become a visionary.

**Abstract**

A model to explain the investment decisions in renewable energies is proposed and illustrated with a case study for a future wind energy industry in Chile. The model can be applied to predict the geographical location, investment's amount and total capacity of wind, solar and biomass based industries. It is based on the concept that the marginal efficiency of capital in these industries can be explained by the energy transport distance and the productivity of the site for any given production technology and project size. The case study demonstrates the use of cash flows defined in variable energy transport distance and productivity of the site, to produce the data needed by the model. The results of the case study suggest the existence of favourable conditions for the development of a wind energy industry in the central part of Chile and define the magnitude of the trade-off between power transmission distance and mean wind speed that result in constant levels of marginal efficiency of capital. The model is appropriate to predict and understand the expansion of a future industry producing hydrogen from renewable energies.

## 1. Introduction

Investment decisions in the energy sector have a significant influence on economic growth, environmental quality and political stability. The long periods needed to recover the investments on energy related capital and the long lasting environmental effects associated to its operation, give further evidence of their importance and strategic nature.

For these reasons, the regulation of the energy sector has attracted much attention from economists and policy makers. Taxes, subsidies, standards, emission markets and quotas have been applied in an effort to direct its expansion and control its increasing external costs. The relevance of this attempt is evident when we look at the growth in energy demand that we should observe over the next years and the prodigious investment amount that it would encompass[1].

Although its development has taken place under generous incentives in most parts of the world, some renewable energy technologies have gradually become cost effective means of satisfying part of that demand. Driving forces of this phenomenon are the economies of scale that manufacturers of renewable energy equipment are starting to experience, constant technical developments, and the increasing private and social costs related to the utilisation of fossil fuels.

[1] The Group of Eight Nations (2005) suggests that US$16 trillion would need to be invested in the world's energy systems over the next 25 years in order to satisfy the 60% demand growth that they expected to take place in the same period.

The fastest growing renewable energies are based on wind, solar radiation and biomass. How much of them can we produce? How much of them do we want? What are the proper levels of intervention, if any, that should be applied to these emerging industries in order to achieve those desired quantities? What is the economically useful potential of a given region for the development of new projects? What is the opportunity cost of preserving an area with potential to produce renewable energy? These are momentous questions that applied economists need to answer promptly and wisely.

The present work contributes to this quest by proposing a model to explain investment decisions in those technologies and by providing a case study of its application to a future wind energy industry in Chile.

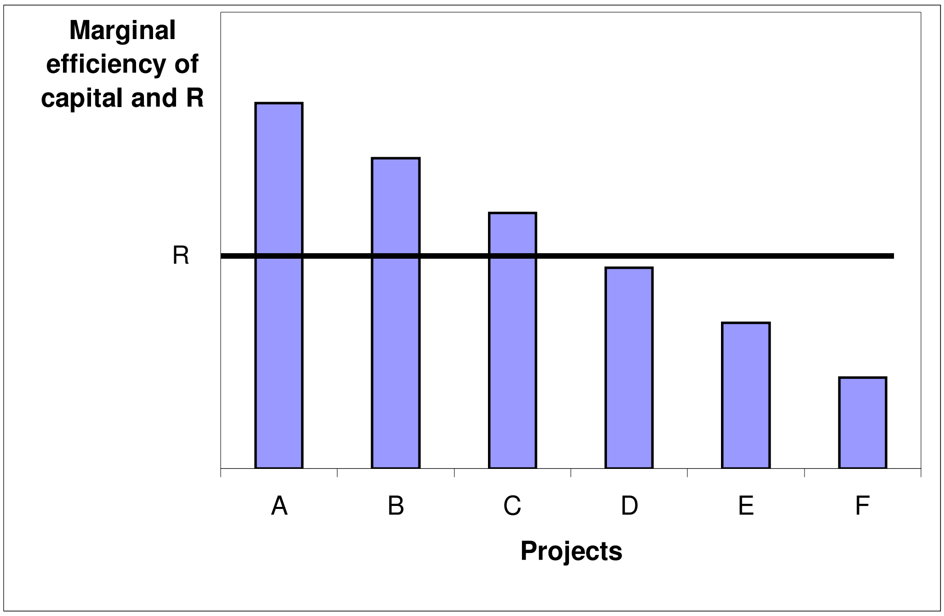
### 1.1. Background

The theory of investment is built over the coincident reflections of John M. Keynes, Alfred Marshall and Irving Fisher regarding interest rates and what they call "marginal efficiency of capital", "marginal net efficiency of a factor of production" and the "rate of return over costs", respectively[2]. Keynes (1942) defines the concept as "that rate of discount which would make the present value of the series of annuities given by the returns expected from the capital-asset during its life just equal to its supply price". He then proposes that investors would rank their projects according to their expected marginal efficiency of capital and they would decide to invest in those that offer a marginal efficiency of capital

[2] The reader may want to refer to Keyne's (1942) "General Theory of Employment Interests and Money", Marshall's (1890) "Economic Principles" and Fisher´s (1930) "Theory of Interest".

greater than the current available rate of interests. He recognises the intuitive fact that "if there is an increased investment in any given type of capital" "....the marginal efficiency of that type of capital will diminish as the investment in it is increased". He proposes a schedule by which the marginal efficiency of capital falls with increased investment. **Figure 1.1** illustrates the concept.

**Figure 1.1**. Diminishing marginal efficiency of capital with increasing investment.




In **Figure 1.1.**, project A is the first to be executed by a profit maximising investor because it has the highest marginal efficiency of capital above the current rate of interest (R). Projects B and C are also above R and therefore are also implemented. But projects D, E and F are discarded because the investors would be better off by putting their resources to grow at the current rate of interest. As can be easily seen, sufficient decreases in R would spring up the construction projects D, E and F.

Among the determinants of a decreasing marginal efficiency of capital, Keynes proposes that the added pressure on facilities producing a specific “type of capital will cause its supply price to increase”. And he points out that this effect may be of importance in producing  equilibrium in the short run. Although this may be a good reason to explain the decrease in the marginal efficiency of capital in the presence of a mature supply industry, it may not yet be applicable to the present supply industry of renewable energy capital-assets. In fact, we have seen constant drops in the supply prices of wind, biomass and solar generating equipment along with increasing demand. The reason for this drop may well be because this supply industry is still immature and as such, still experiences a relatively fast technological development and economies of scale that are just starting to show up.

But then, Keynes turns to the possible long run cause for a decreasing marginal efficiency of capital: that “the prospective yield will fall as the supply of that type of capital is increased”. Keynes does not elaborate further on this point, as his concern was the aggregate level and rate of investment for the whole economy. But, as I explain in **Section 2.1**, wind, biomass and solar based renewable energies have a fundamental characteristic that allows us to make a useful generalisation when it comes to understanding how this prospective yield falls affecting the marginal efficiency of capital [3].

[3] For simplicity, I would like to limit the meaning of a biomass renewable energy project to the production of biomass for energetic purposes. How this biomass is converted into usable energy will generally fall out of the boundaries of the analysis in this work. Similarly, I would like to limit the meaning of a solar project to the generation of electricity using photovoltaic panels.

## 2. Objectives and methodology

The objectives of this dissertation are:

a) To develop a model to explain investment decisions in wind, biomass and solar based renewable energies.

b) To illustrate the application of the model with a case study of a wind energy industry associated to the main electric system of Chile.

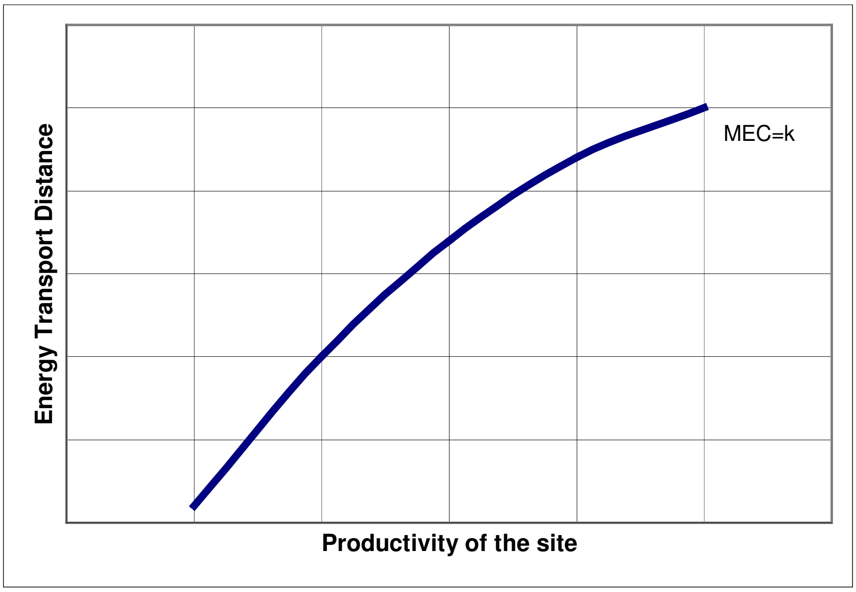
As will be explained in **Sections 2.1** and **2.2**, the application of the model requires the selection of a representative project used as a proxy of the real projects to be built by a future Chilean wind energy industry. This representative project will be the basis of a cash flow analysis, to be defined on variable wind speed and energy transport distance. Microsoft Excel spreadsheets will be used to set up these cash flows. The assumptions for the formation of the cash flows and the detailed description of the representative project, will be addressed along **Section 3**.

The data required by the model will be obtained by evaluating iteratively the cash flows at different combinations of mean wind speeds and energy transport distances, subject to the achievement of fixed levels of profits. The results are presented in **Section 4**.

### 2.1. Theoretical approach

We can describe any wind, solar or biomass based energy project in terms of the productivity of it's site and the distance from that site to the energy consumption centre. In general, the higher the site's productivity[4], the higher the marginal efficiency of capital we could expect because every unit of capital produces a correspondingly "higher yield". On the other hand, the higher the energy transport distance, the higher the transport costs will be and thus, the lower the marginal productivity of capital we could expect. We could derive a curve in the distance-productivity space for which the marginal efficiency of capital (MEC) remains constant. **Figure 2.1.** illustrates the concept.

**Figure 2.1.** Constant marginal efficiency of capital (MEC) curve MEC=k.




A family of similar curves could be drawn to the right and to the left of MEC=k indicating combinations of productivity and distance with higher and lower constant MEC, respectively. In the rest of this work, these curves with constant marginal efficiency of

[4] By productivity of a site, I mean its natural availability of energy, such as annual solar radiation received per unit of area, annual mean wind speed or mean annual increment of biomass per unit of area achievable with a given specie.

capital may be called Isoprofit curves, because they indicate points of equal discounted profits to investors. The marginal efficiency of capital may be simply called internal rate of return (IRR).

In line with Keynes's rule, profit maximising investors would choose to build first the projects with higher IRR, located in the lower right corner in **Figure 2.1**. From that region, they should continue to colonise the rest of the productivity-distance space until they reach the Isoprofit that corresponds to the current available rate of interest, where they should stop.

Knowing that in any region there is a finite available area for the construction of projects to the right of the Isoprofit of current available rate of interest, we can estimate the economically installable capacity (Ec) by that industry as follows:

$$Ec = AR * Sa \qquad \textbf{[Eq.2.1.]}$$

where,

$AR$ is the total area available to the right of the Isoprofit of current rate of interest, expressed for example in hectares and;

$Sa$ is the specific area required by the relevant technology expressed for example in mega watts per hectare.

Similarly, total investment in that industry and region (INV) can be obtained as follows:

$$INV = Ec * Si \qquad \textbf{[Eq.2.2.]}$$

where,

$Si$ is the average specific investment cost for power in that technology, expressed for example in $ per mega watt.

It is easy to gather empirical evidence showing that at least for wind energy, $Sa$ has continuously risen during the last decade, a tendency that could be well explained by **[Eq.2.1.]** as an effort to increase installed capacity and total investment in the presence of a limited area AR[5]. In the same way, we could obtain empirical evidence of a continuous drop in $Si$, a tendency which could be interpreted to the light of **[Eq.2.2.]** as an effort to increase $Ec$ for any fixed INV.

## 2.2. Assumption for the application of the model

The model will explain the investment in a renewable energy industry as long as the cash flows used to obtain the Isoprofits are representative of that industry. In line with this assumption, here follows a brief description of the considerations that should be observed for the correct application and interpretation of the model.

### 2.2.1. Homogenous technology

Implicit in the model is the notion that there is a cost-revenue relation that varies mainly with the energy transport distance and productivity of the site. If one suspects that in a

[5] Particularly in Britain, environmental pressures help to reduce AR.

given renewable energy industry, the shape or horizontal position of the family of Isoprofit curves varies, for example as a result of several different production technologies being used (e.g. different vegetable species or cultivation regimes, fundamentally different types of wind turbines or solar panels), then the researcher should obtain the corresponding representative Isoprofits for each technology variant separately. Each technology will have its own total area available to the right of the Isoprofit of current rate of interest (AR), its own specific areas (Sa) and specific investments (Si).

### 2.2.2. Constant returns to scale

Even though we could expect the renewable energy projects addressed in this work to exhibit almost constant returns to scale, the family of Isoprofit curves should be considered valid within a certain project size range. The fact that wind, solar and biomass based technologies should exhibit nearly constant returns to scale is evident when we consider that an increase or decrease in production requires the addition or removal of a wind turbine, a unit area of energy crop or a unit area of solar panel, an operation which can be considered fairly equivalent to varying the number of plants that a firm operates. Nevertheless, we could expect some economies of scale to arise with an increasing size of the project due to the utilisation of common roads, administration personnel, etc. Other sources of economies of scale may be given by the possibility of a better utilisation of an electricity transmission line or the possibility to obtain lower financial costs when negotiating larger loans, etc. If the assumption of constant returns to scale does not hold, then representative project size classes should be identified and their Isoprofits should be derived separately.

### 2.2.3. Uncertainties

Any effect that a cash flow analysis fails to give account for will affect the predictions of the model. These effects may include reduced or increased productivity of a plot of land (e.g. due to erosion, fertility loss or gain), changes in the patterns of winds or solar radiation (e.g. due to climate change), variation of the energy transport distance due to movement of the consumption centres (e.g. a significant growth of a city in the direction of the project site), unpredictable price changes that distort the relation between revenues and costs, etc.

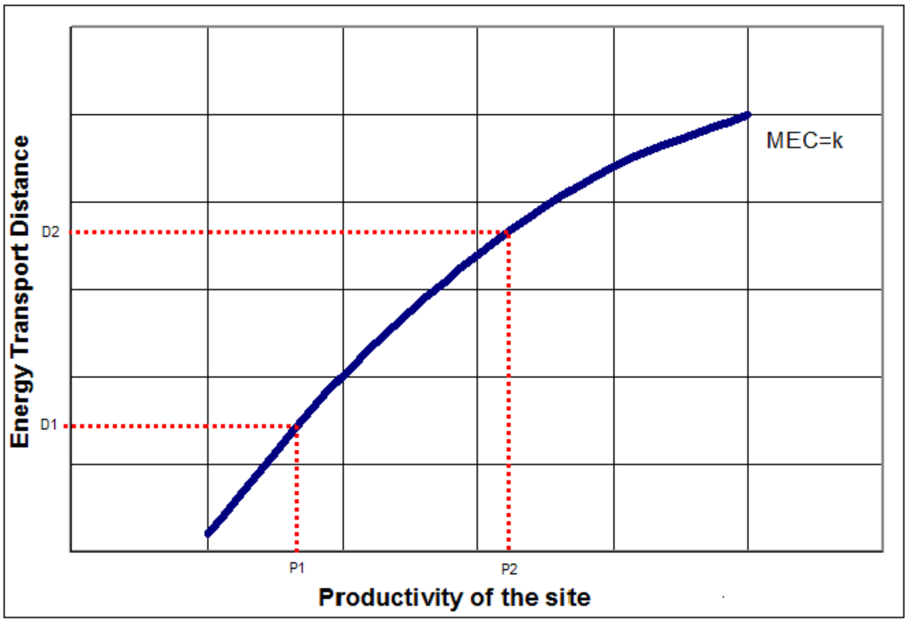
## 2.3. Further interpretations and applications of the Isoprofit curves

### 2.3.1. Derived demand for sites

The Isoprofit curves represent the trade off of distance to the consumption centre and productivity of the site for constant profits. **Figure 2.2** shows two combinations of distances and productivities ([D1,P1], [D2,P2]) investors should be indifferent to choose from. This dissertation assumes that the prices of sites are not related to the demand of sites for renewable energy projects. Although this is a simplification that may be applicable in some parts of the world[6], we could expect that in the future, as sites become scarce and energy demand grows, a derived demand for sites could be explained on the basis of this trade off between distance and productivity.

[6] As will be shown in Section 3.2, at least for the case of wind energy, the cost of the land remains a very small proportion of the total investment costs, even when considering countries like Denmark where one could expect that land has a high opportunity cost.

**Figure 2.2**. Energy transport distance / productivity of the site substitution along the Isoprofit curve (MEC=k).




### 2.3.2. Site screening

The application of the model to the screening of sites by an investor that perceives a given current available rate of interest, is straight forward. Specifically, it allows the investor to concentrate its search only in a determined region of the distance-productivity space. The integration of the model to a Geographical Information System where the distance-productivity layers of information could be analysed simultaneously may be interesting.

### 2.3.3. Incentives and prices of energy in the long run

If society at any moment decides to have a given proportion of the wind, biomass or solar energy, that is higher than the one associated to the area AR in **[Eq. 2.1]**, then it could provide the right incentives to incorporate the relevant additional area to production. This would 'artificially' allow the existence of a bigger economically installable capacity, with the Isoprofit curves moving to the left in **Figure 2.2**.

If incentives are not to last indefinitely, in the long run, when the supply of energy is dominated by renewables and a few other sources, the given desired proportion of renewable energy could become the source of definition of the price of energy. A higher price of energy will increase AR and a lower one will decrease it.

### 2.3.4. Royalty

The fact that a site has a certain mean wind speed, a certain capacity to produce biomass or receives a determined solar energy radiation, could be thought of as a property analogous to the existence of a given amount of a mineral in the soil. In many states, a charge or "royalty" is levied on companies that extract those minerals. Therefore, it would not be too strange to observe in the future a similar charge being applied to a renewable energy industry. This charge would move the Isoprofits to the right, diminishing the area AR, and could be used to restrict the expansion of the renewables industry.

### 2.3.5. Opportunity cost of preserving a site

By checking a site's energy transport distance and productivity, and finding the corresponding Isoprofit curve for it, a quick estimate can be obtained of the opportunity cost of not developing a renewable energy project.

## 3. Case Study

### 3.1. General description of the model project

The model project will use state of the art industrial size wind turbines to generate electricity for the main electric system of Chile. It will consist of wind turbine generators with their towers, control and monitoring systems, transmission line, power conditioning and management gear.

The wind turbines selected for this case study are manufactured by the German Nordex AG. The Nordex N90 will be used to evaluate the model project in sites of mean wind speed in the range of 4 to 8 meters per second. The Nordex N80 will be used to evaluate the model project in sites with mean wind speeds in the range of 8 to 12 meters per second[7]. Technical details of these machines can be found in **Annex 1**.

[7] Different turbines are used for each wind range because their design is optimised for different mean wind speeds. The term model project is used to address the plants based on the N80 and N90 generically.

The model project based on the Nordex N90 will have 22 wind turbines with a rated output of 2.3 MW each, yielding a total installed capacity of 50.6 MW. In the case of the Nordex N80 based project, 20 wind turbines will be used, yielding a total installed capacity of 50 MW.

The model project will deliver three-phase electricity at 50 Hz frequency to the main electric system of the country. The length of the transmission line will vary according to the distance from the plant to the point of delivery.

The life of the electrical and mechanical components of the plant is expected to be 20 years, which is the evaluation period minus 1 year of construction.

**3.1.1. Representativeness of the model project**

The total inexistence of a wind energy industry in the region under study makes it hard to predict how representative this model project may prove to be. Nevertheless, as explained below, this fact may not hinder the validity of the results to be obtained.

Even though the market of wind turbines is varied, the tendency in the world is to use large size wind turbines with similar specifications, design features, performance and cost structures to those of the Nordex N80 and N90. As a result of this, we could expect that the Chilean wind energy industry will be developed on this type of homogeneous technology.

It is equally difficult to comment on how representative the chosen project size may prove to be. But a multiple regression analysis of the impact of project size on the cost of wind energy, gives us grounds to believe that its effect is modest at least in the range of 10 to 80 MW of installed capacity[8]. Several studies addressing the development of wind energy projects owned by local communities arrive to similar conclusions[9]. These studies suggest that the assumption of constant returns to scale may hold for a large range of project sizes.

### 3.2. Investment cost structure

Based on data from Germany, Denmark, Spain and the U.K. collected during 2001 and 2002, for wind turbines of up to 1.5 MW, the European Wind Energy Association (EWEA) suggests that a typical wind farm will have the investment cost structure shown in **Table 3.1**.

**Table 3.1**. Cost structure for a typical medium-sized wind farm.

| Investment item | Share of total investment cost (%) |
|---|---|
| Turbine (ex-works) | 74-82 |
| Foundation | 1-6 |
| Electric installation | 1-9 |
| Grid connection | 2-9 |
| Consultancy | 1-3 |
| Land | 1-3 |
| Financial costs | 1-5 |
| Road construction | 1-5 |

Source: EWEA (2004).

[8] Work being carried at the Lawrence Berkley National Laboratory. Preliminary results provided to the author on August 2005 by Ryan Wiser, coordinator of Wind Power Economic, Market and Policy Analysis Activities of that institution.
[9] See for example Bolinger et al. (2004).

Considering that the Nordex N80 and N90 wind turbines are larger than those accounted for by EWEA (2004), slight savings in some of the items could be expected. For example, as fewer turbines would be installed for any given power capacity, less land would be used and shorter roads would need to be built. Similarly, it is reasonably to expect some savings in foundations, consultancy and electric installations. For this reason, the model project will use as a representative share of the investment cost in turbines, the upper limit shown in **Table 3.1**, equal to 82% of the total investment cost. At the same time, it may be expected that the cost of land in Chile would be lower than in Germany, Denmark, Spain and the U.K., so the lowest limit shown for this item in **Table 3.1**, will be used as a representative value. The investment cost for the rest of the items, will follow the mean value of the range indicated in **Table 3.1**, except for the financial and grid connection items which are considered separately in **Sections 3.11** and **3.6**, respectively.

According to Nordex[10], the Free On-Board German port[11] indicative price for their N90 model is US$ 2,296,843 per turbine, whereas for the N80 the same price is US$ 2,225,673 [12]. The scope of supply includes the complete turbine with tower, individual step up transformer and its control and monitoring hardware and software.

Starting from these reference prices and assumptions, and knowing that the number of turbines for the plants based on the Nordex N80 and N90 are 20 and 22 respectively, **Table 3.2** sets out the investment costs per item used to evaluate the model project.

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[10] Personal communication with Norbert Dwenger, director of Nordex Energy Ibérica S.A. in April 2005.
[11] The reader may want to see the definition of this term at http://www.iccwbo.org/incoterms/preambles.asp .
[12] The monthly average exchange rate for April 2005 informed by the Bank of England at http://www.bankofengland.co.uk/statistics/index.htm equal to 0.7728 [€*US$^-1] is considered in these figures.

**Table 3.2**. Investment costs per item (April 2005 US$).

| Investment item | Share of total investment cost (%) | Investment cost | |
|---|---|---|---|
| | | Project based on Nordex N90 | Project based on Nordex N80 |
| Turbine (ex-works) | 82 | 50,530,546 | 44,513,460 |
| Foundations | 3.5 | 2,156,792 | 1,899,965 |
| Electric installation | 5 | 3,081,131 | 2,714,235 |
| Consultancy | 2 | 1,232,452 | 1,085,694 |
| Land | 1 | 616,226 | 542,847 |
| Road construction | 3 | 1,848,679 | 1,628,541 |

Import duties are not applicable to exports from the EU to Chile, but a 17% value added tax will have to be paid. A charge of 1.5% over the price of the wind turbines will be considered to cover sea freight and insurance costs. **Table 3.3**, gives account of these additional investment costs.

**Table 3.3**. Additional investment costs.

| Additional investment cost item | Rate over turbines' total costs (%) | Total cost (US$) | |
|---|---|---|---|
| | | Project based on Nordex N90 | Project based on Nordex N80 |
| Value added tax over wind turbines | 17 | 8,590,193 | 7,567,288 |
| Sea and land freight plus insurance | 1.5 | 757,958 | 667,702 |
| Total | | 9,348,151 | 8,234,990 |

### 3.3. Prices of electric energy and power

There are three different types of prices for electricity in the Chilean market; the spot prices, the node prices and the unregulated prices.

The spot prices are the prices used by generating companies to exchange electricity in their respective systems. The necessity of this exchange arises when, following the instructions of their system operator[13], generating companies produce less energy and/or power than they sell to their customers thus having to make up for the difference by purchasing from other generating companies. In the main electric system of Chile (the SIC[14]), the spot price of energy is equal to the opportunity cost of the water stored in the Laja Lake[15], as determined by a dynamic programming model[16] that trades off the benefit of using water today to generate electricity displacing the more expensive thermal generation, against the cost of not having water in the future (Fischer, Galetovic, 2000), thus forcing the use of thermal power plants. Power exchanges take place when generating companies experience capacity deficits or surpluses during the period of peak demand. In this period, as the demanded power capacity approaches the installed power capacity, the system experiences a higher risk of being unable to carry its load. As a result, power capacity may become scarce and a subject for trade. The spot prices of power are valued at the marginal cost of increasing generating capacity in each of the basic substations of the system using the latest available technology, as calculated by the government[17]. **Figure 3.1.** shows the weekly average of the spot price of energy at one of the substations of the main electric system of Chile.

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[13] Known in Chile as "Centro de Despacho Económico de Carga" (CDEC), is the organisation that coordinates the operation of the electrical installations in a given system in order to ensure its most efficient use.

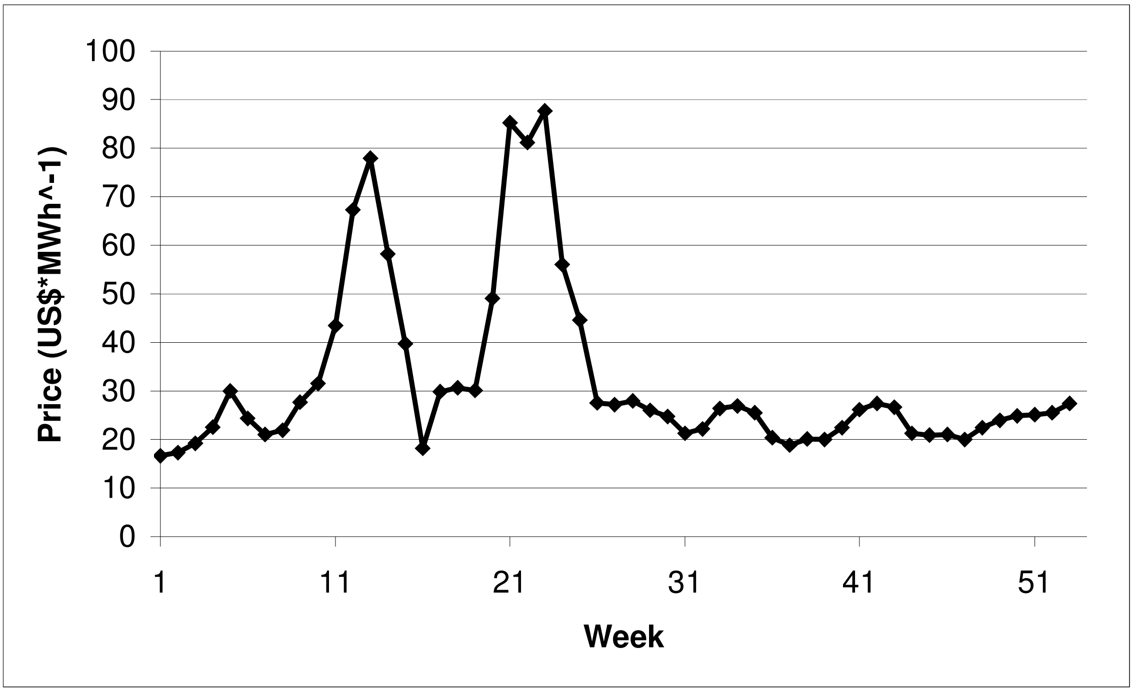
[14] SIC is the acronym for "Sistema Interconectado Central". According to CNE (2005), SIC provides electricity to over 90% of the population and has over 60% of the total generating capacity of the country.

[15] When this lake is full, it can hold enough water to generate around one fourth of the annual energy consumption in the system (Fischer, Galetovic, 2000).

[16] The name of this model is OMSIC, the acronym for "Operación Mensual del Sic".

[17] The agency that sets this value is the National Energy Commission (or CNE according to its initials in Spanish).

**Figure 3.1**. Weekly average of the spot price of energy at Alto Jahuel Substation (2004 US$).




Elaborated using CDEC-SIC 1 (2005) data.

As the spot prices are highly variable over time, policy makers foresaw that they would bring about too much uncertainty to allow optimal decisions on how much energy to use and how much capital to spend in new generating capacity. To overcome this problem, generating companies were required to sell electricity to distributing companies at the expected spot prices averaged over the next four years (Pollit, 2004). These prices are calculated by a simpler version of the model used to obtain the spot prices and are set by the National Energy Commission each six months. The price is then adjusted to take account of system losses at each of the basic substations of the system (or "nodes"), and the results are referred to as the node prices of energy. To these are added the marginal costs of increasing the generating capacity in each node using the latest available technology. These additional components are referred to as the node prices of power. Node prices of energy and power are expected to reflect the marginal costs of supply at the different nodes of the system. **Table 3.4** shows the node prices of energy and power valid from April to October 2005 at all the substations of the SIC in which the node price is calculated.

**Table 3.4**. Node prices of energy and power for the substations of the SIC (May 2005 US$).

| SUBSTATION | Power (US$*MW^-1*month^-1) | Energy (US$*MWh^-1) |
|---|---|---|
| D. DE ALMAGRO | 6,837.96 | 45.23 |
| CARRERA PINTO | 6,925.48 | 45.94 |
| CARDONES | 6,934.30 | 45.62 |
| MAITENCILLO | 6,616.78 | 43.56 |
| PAN DE AZUCAR | 6,857.63 | 44.89 |
| QUILLOTA | 6,674.45 | 42.99 |
| POLPAICO | 6,784.36 | 43.48 |
| CERRO NAVIA | 6,892.91 | 45.06 |
| ALTO JAHUEL | 6,764.01 | 43.88 |
| RANCAGUA | 6,911.23 | 46.01 |
| SAN FERNANDO | 6,439.03 | 44.45 |
| ITAHUE | 6,298.61 | 44.57 |
| PARRAL | 6,377.97 | 43.91 |
| ANCOA | 6,266.71 | 42.06 |
| CHARRUA | 6,208.36 | 41.93 |
| CONCEPCION | 6,476.35 | 44.79 |
| SAN VICENTE | 6,534.02 | 44.84 |
| TEMUCO | 7,400.31 | 47.58 |
| VALDIVIA | 7,312.53 | 47.59 |
| PUERTO MONTT | 7,314.73 | 47.53 |
| PUGUEÑUN | 9,412.59 | 61.16 |
| Average | 6,868.59 | 45.57 |

Elaborated using CNE (2005) data.

According to the current regulations[18], consumers with a maximum power consumption of over 500 kW are free to negotiate their supply directly with generating companies. These unregulated prices are supposed to be a good approximation of the marginal benefits and marginal costs of electricity consumption and production. For this reason, these prices are used as a reference to adjust the node prices if the two values differ by more than 5%.

As a representative price for energy, the model project will use the average node price of energy for the substations of the SIC equal to 45.57 US$*MWh^-1 (see **Table 3.4**).

Choosing a representative price for power requires a consideration of the power demand of the system and the power offer of the model plant over time. The present Chilean regulations dictate that capacity payments are perceived according to the power that a generating unit can offer only during periods of peak demand[19]. Such power capacity is referred to as "firm power" and is determined by the system operator (CDEC) taking into account the availability of the generating unit during these periods. The determination of the firm power for thermal and hydroelectric plants is straightforward. It considers that the rated capacity of a generating unit should be weighted by factors such as their mechanical availability, reliability, fuel availability, their speed to pick up loads, the quantity of water stored, etc. At the moment, no procedure is in place to calculate the firm power of wind farms in the SIC. Nevertheless, wind farms are similar to the ubiquitous run-off-the river

[18] Mining Ministry of Chile Law Decree No. 1 of 1982: "General Law for Electric Services" and its modification by Ministry of Economy and Reconstruction Law 19940 of 2004 on Energy Transport and Tariffs.
[19] Article 261 of the "General Law for Electric Services".

hydroelectric plants[20] in that their operators have little or no control over their source of energy. For this reason, a new procedure to calculate the firm power of wind farms could be based on the one used for run-off-the river hydroelectric plants (see for example Mohr, Lira 2005).

Ultimately, the power that a wind farm will be able to offer during peak demand periods, and therefore its ability to receive capacity payments, will be a characteristic highly specific to the site of the project and to the power demand pattern of the grid to which it is connected. The statistical study of macro and micro meteorological fluctuations could help to predict the output of a wind farm with a degree of confidence that will be proportional to the quantity of data available. The actual operation of the wind farm could be used to validate such predictions and assign to each project a definite capacity value.

Because of its importance for the economic viability of wind energy projects, and because of the effect over the performance and operation of electric systems, the determination of the power that a wind farm can offer during peak demand periods (or capacity credit), has received extensive attention in the literature. Due to the diversity of the methodologies used, purposes of the studies, level of wind power penetration, geographical locations, total areas covered and realities of the electric markets they address, it is difficult to make direct comparisons of the published figures. Nevertheless, the information is useful in order to make a rough estimate of the capacity credit that the model project should have.

[20] As opposed to dam regulated hydroelectric plants, run-off river plants usually have a very limited capacity to accumulate water and therefore, their output at any moment depends heavily on the instantaneous upstream flow.

For example,  Demeo et al. (2004) report that the in the United States of America, the Pennsylvania-New Jersey-Meryland Regional Transmission Organization (PJM) uses a capacity value for new projects of 20% of the net plant rating until actual operating data becomes available. The same authors indicate that the New York Independent System Operator (NYISO) uses a historic capacity factor adjusted for maintenance. In the same country, Milligan and Porter (2005) point out that the Electric Reliability Council of Texas (ERCOT) assessed the contribution of wind plants during 4PM and 6PM in August and July, the peak period for this system, obtaining and average output of wind of 16.8% of rated capacity. **Table 3.5** shows the capacity credit given by different organisatons in the United States of America as reported in the same paper.

**Table 3.5**. Capacity credit as a percentage of nameplate output given by several organisations or studies in the United States of America for on-shore wind power plants.

| Organisation or Study | Capacity Credit (% nameplate capacity) |
|---|---|
| Southwest Power Pool (SPP) | 3-8 |
| Rocky Mountain Area Transmission Study (RMATS) | 20 |
| General Electric Energy Consulting study for New York State Energy Research and Developmet Authority | 9 |
| Minnesota Department of Commerce using a Sequential Monte Carlo approach | 26.7 |
| Minnesota Department of Commerce using a load modifier method | 32.9 |
| PacifiCorp using a Sequential Monte Carlo approach | 20 |
| Portland General Electric (PGE) | 33 |
| Idaho Power | 5 |

Elaborated using Milligan and Porter (2005) data.

Giebel (2000) using a model developed to assess the value of renewable sources of energy for Europe[21] found out that a capacity credit of wind plants as a whole should be 19.3% of the installed capacity.

When considering the figures mentioned above to assess the capacity credit of wind, one should bear in mind that in many of the studies cited, more than one wind farm was included and these were separated by varying distances. The greater the area considered, the higher are the chances that at least one plant will be generating at any moment, including the peak demand periods. The risk of using these data for a single plant to be built in a small area such as the model project is therefore to overestimate its capacity credit.

A 20% of the installed power will be chosen as a representative capacity credit for the model project and will be valued at the average node price of power of 6,868.59 (US$*MW^-1*month*^-1) as shown in **Table 3.4**. The yearly revenues for the model project will be calculated as follows:

$$CR = 6{,}868.59 * 12 * 0.2 * ICAP \qquad \textbf{[Eq. 3.1.]}$$

where,

CR are the capacity revenues in US$ per year;

6,889.59 is the constant of the node price of power in (US$*MW^-1*month*^-1);

12 is the number of months per year;

[21] The National Grid Model, developed by the Energy Research Unit (ERU) of the UK's Council for the Central Laboratory of the Research Councils (CCLRC).

0.2 is capacity credit constant;

ICAP is the installed capacity in mega watts;

### 3.4. Estimate of electric energy production and sales

Because power plants in the SIC are dispatched by the electric system operator (CDEC) in merit order of increasing marginal costs[22] and the marginal cost of wind is zero[23], the model plant will be dispatched as long as there is enough wind for its operation. Therefore, the sales of electricity will only depend on the energy input to the wind turbines, the capacity of the plant to transform that input into electricity, and the losses associated to electricity transmission and voltage transformation which are considered in **Section 3.5**.

The energy input to a wind turbine depends on the kinetic energy of the air that passes through the area swept by its rotor. The kinetic energy (KE) of a given mass of air (m) depends on the square of the speed (v) at which it moves, as follows

$$KE = \frac{1}{2} * m * v^2 \qquad \textbf{[Eq. 3.2.]}$$

[22] The application of this principle ensures the least costly supply of electricity in the system. The principle is defined in the Mining Ministry of Chile Law Decree No. 1 of 1982: "General Law for Electric Services".
[23] The marginal cost of wind is zero because there is no cost associated to the use of one additional unit of wind for generating electricity. The assumption also implies that there is no opportunity cost associated to extracting energy from the wind, which is an idea that may be disputed on the grounds of neglected and non-priced services that wind may provide.

If we substitute the mass (m) in **[Eq. 3.2]** by the mass flow of air ($\dot{m}$), the expression becomes the dynamic power ($P_d$) equation, that indicates the wind's kinetic energy input by unit of time,

$$P_d = \frac{1}{2} * \dot{m} * v^2 \qquad \textbf{[Eq. 3.3.]}$$

The mass flow of air ($\dot{m}$) passing through the area (A) swept by the wind turbine's rotor depends on the density of air ($\rho$) and the speed at which the air is crossing that area. This relation is given by:

$$\dot{m} = A * \rho * v \qquad \textbf{[Eq. 3.4.]}$$

Substituting **[Eq. 3.4]** into **[Eq. 3.3]** we have,

$$P_d = \frac{1}{2} * A * \rho * v^3 \qquad \textbf{[Eq. 3.5.]}$$

As this expression shows, the dynamic power available for the transformation of wind energy into electricity depends on the cube of the wind speed. Nevertheless, because of an aerodynamic constraint known as the Betz limit, a wind turbine has an upper theoretical limit to capture the dynamic power available in the wind. **[Eq.3.6]** takes account of this limitation by incorporating the power coefficient $C_p$

$$P_d = \frac{1}{2} * C_p * A * \rho * v^3 \qquad \textbf{[Eq. 3.6.]}$$

According to Betz (1926), the maximum power coefficient for a disk-like rotor has a value of 16/27. Real wind turbines have power coefficients well below this theoretical value. **Table 3.6** shows the power coefficients and the power output at different wind speeds for the turbines used by the model project including losses related to the mechanical power transmission system and electricity generation system.

**Table 3.6**. Power curve and power coefficients ($C_p$) for the wind turbines used by the model project.

| Wind speed (m*s^-1) | Wind turbine | | | |
|---|---|---|---|---|
| | Nordex N80 | | Nordex N90 | |
| | Power (kW) | Cp | Power (kW) | Cp |
| 4 | 15 | 0.076 | 70 | 0.281 |
| 5 | 120 | 0.312 | 183 | 0.376 |
| 6 | 248 | 0.373 | 340 | 0.404 |
| 7 | 429 | 0.406 | 563 | 0.421 |
| 8 | 662 | 0.420 | 857 | 0.430 |
| 9 | 964 | 0.430 | 1225 | 0.431 |
| 10 | 1306 | 0.424 | 1607 | 0.412 |
| 11 | 1658 | 0.405 | 1992 | 0.384 |
| 12 | 1984 | 0.373 | 2208 | 0.328 |
| 13 | 2269 | 0.335 | 2300 | 0.269 |
| 14 | 2450 | 0.290 | 2300 | 0.215 |
| 15 | 2500 | 0.241 | 2300 | 0.175 |
| 16 | 2500 | 0.198 | 2300 | 0.144 |
| 17 | 2500 | 0.165 | 2300 | 0.120 |
| 18 | 2500 | 0.139 | 2300 | 0.101 |
| 19 | 2500 | 0.118 | 2300 | 0.086 |
| 20 | 2500 | 0.102 | 2300 | 0.074 |
| 21 | 2500 | 0.088 | 2300 | 0.064 |
| 22 | 2500 | 0.076 | 2300 | 0.055 |
| 23 | 2500 | 0.067 | 2300 | 0.049 |

| | | | | |
|---|---|---|---|---|
| 24 | 2500 | 0.059 | 2300 | 0.043 |
| 25 | 2500 | 0.052 | 2300 | 0.038 |

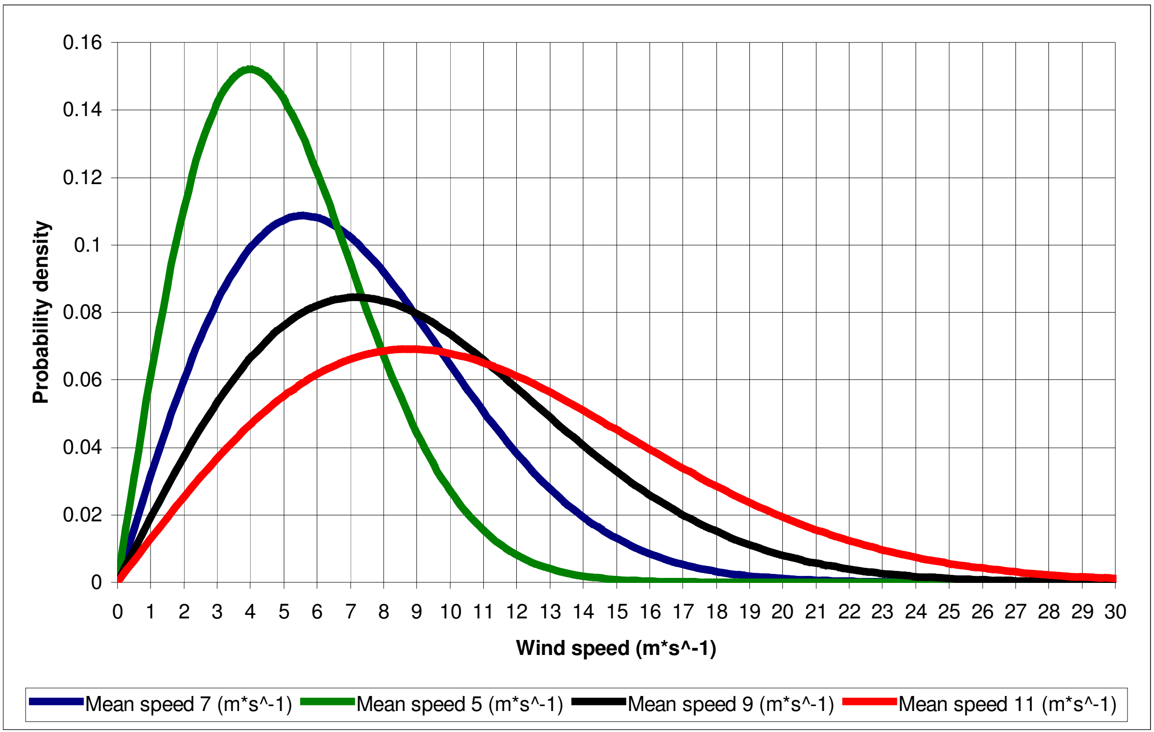
Source: Manufacturer's brochure for the Nordex N80 and Nordex N90 wind turbines.

Wind speed is usually considered to be a random variable that, in the absence of historic measurements, can be explained by a special case of the Weibull probability density function called the Rayleigh distribution (Frost and Aspliden, 1994). Shenck (2005) provides a variant of the Rayleigh distribution ( $f(v)$ ) where the mean wind speed ( $\bar{v}$ ) is explicitly expressed,

$$f(v) = \frac{\pi}{2} * \frac{v}{\bar{v}^2} * e^{-\frac{\pi}{4} * \left(\frac{v}{\bar{v}}\right)^2} \qquad 0 < v < \infty \qquad \textbf{[Eq. 3.7.]}$$

**Figure 3.2.** shows this distribution for sites with mean wind speeds of 5,7, 9 and 11 m*s^-1.

**Figure 3.2**. Rayleigh probability density functions for the wind speed at sites of different mean wind speeds.




The probability of wind speed occurring in any particular range can be calculated by integrating the corresponding probability density function between the upper and lower limits of that range. Alternatively, an approximation can be obtained by multiplying the probability density of the central value of the wind speed range by the width of that range. The smaller the width, the better the probability approximation will be. In this study, the probability was estimated using 2100 ranges of 1/100 (m*s^-1) width for wind speeds between 4 and 25 (m*s^-1) which are the cut-in and cut-out wind speeds for the turbines used by the model project. This procedure was done for sites with mean wind speeds between 4 and 8 (m*s^-1) for the Nordex N90 turbine and between 8 and 12 (m*s^-1) for the Nordex N80, with increments of 1/4 (m*s^-1), giving a total number of mean wind speeds of 17, in each case.

Annual electricity production figures for each turbine were estimated by multiplying the probability of wind speed occurring in each wind speed range and site by the number of hours available per year to obtain the corresponding expected annual generating times. Then, the expected generating times were multiplied by the respective power output of the relevant turbine model obtained from the power curves shown in **Table 3.6**. As the power curves in this table only indicate values for wind speeds each 1 (m*s^-1), a linear interpolation was used in order to add 100 extra points between those values. **[Eq. 3.8]**, summarises the procedure used to predict the annual energy output per wind turbine.

$$PE_{M,N} = \sum_{R=1}^{2100} (\Pr[V_{R,M}] * 8765 * P_{M,N,R}) \qquad \textbf{[Eq. 3.8.]}$$

R=1 to 2100

M=1 to 17

N=1, 2

where,

$PE_{M,N}$ is the predicted energy output in kWh*year^-1 for all ranges of wind speed for turbine model N at site M;

$\Pr[V_{R,M}]$ is the probability that wind speed will be in the range R at site M at any moment;

R is the wind speed range index;

M is the site's annual mean wind speed index;

8765 is the total number of hours available in one year;

$P_{M,N,R}$ is the expected power output of the wind turbine model N (N=1 for Nordex N80 and N=2 for Nordex N90), at wind speed range R and site M.

**Table 3.7** shows the results obtained from the application of **[Eq. 3.8]**.

**Table 3.7**. Predicted energy production per wind turbine according to mean wind speed of the site.

| Mean wind speed (M) (m*s^-1) | Predicted energy per wind turbine ( $PE_{M,N}$ ) (kWh/year) | |
|---|---|---|
| | N=1 (Nordex N90) | N=2 (Nordex N80) |
| 4 | 1,532,739 | - |
| 4.25 | 1,876,169 | - |
| 4.5 | 2,249,567 | - |
| 4.75 | 2,649,943 | - |
| 5 | 3,072,207 | - |
| 5.25 | 3,512,381 | - |
| 5.5 | 3,966,058 | - |
| 5.75 | 4,428,971 | - |
| 6 | 4,897,126 | - |
| 6.25 | 5,366,892 | - |
| 6.5 | 5,835,040 | - |
| 6.75 | 6,298,751 | - |
| 7 | 6,755,598 | - |
| 7.25 | 7,203,513 | - |
| 7.5 | 7,640,741 | - |
| 7.75 | 8,065,792 | - |
| 8 | 8,477,400 | 7,576,922 |
| 8.25 | - | 7,998,084 |
| 8.5 | - | 8,407,875 |
| 8.75 | - | 8,804,868 |
| 9 | - | 9,187,793 |
| 9.25 | - | 9,555,527 |
| 9.5 | - | 9,907,101 |
| 9.75 | - | 10,241,690 |
| 10 | - | 10,558,621 |
| 10.25 | - | 10,857,366 |
| 10.5 | - | 11,137,539 |
| 10.75 | - | 11,398,892 |
| 11 | - | 11,641,307 |
| 11.25 | - | 11,864,793 |
| 11.5 | - | 12,069,469 |
| 11.75 | - | 12,255,561 |
| 12 | - | 12,423,387 |

**Appendix 1** contains tables used for the calculation of $PE_{M,N}$ for both wind turbine models at selected sites[24]. These tables also contain columns regarding the transmission losses which will be explained in **Section 3.5**.

The net electric energy production ($NP_{M,N}$) by the project was obtained by multiplying the predicted energy per turbine by the number of turbines in the model plant and subtracting the transmission losses ($L_{M,N}$), as follows

$$NP_{M,N} = T_N * PE_{M,N} - L_{M,N} \qquad \textbf{[Eq. 3.9]}$$

where,

$NP_{M,N}$ is the gross electric energy production per turbine in kWh/year at site M with turbines N;

$T_N$ is the number of turbines of model N. $T_N$ is equal to 22 for the plant using the Nordex N90 and is equal to 20 for the plant using the Nordex N80 wind turbines.

### 3.5. Transmission losses

Transmission losses will occur as a result of the resistance of the electrical conductors according to the Joule's law:

$$PD = I^2 * R \qquad \textbf{[Eq. 3.10.]}$$

[24] It is not possible or useful to include in **Appendix 1** the tables for all the sites because of their large extension and because all of them follow the same structure. All the tables are included in the electronic version of this dissertation.

where,

$PD$ is the dissipated power in watts;

$I$ is the current transmitted in amperes;

$R$ is the resistance of the conductor in ohms.

These losses will subtract from the total energy produced by the model plant reducing its sales. There will also exist minor losses due to step-up transformation from the wind turbines' generators voltage into the transmission line's voltage, which will be neglected here in favour of brevity.

For any given power to be transmitted, the main factors determining the transmission losses are the transmission's voltage, current, and conductor's length, material, sectional area and temperature.

As a simplification, it will be assumed that the transmission losses are explained by the following expression:

$$PD = I^2 * C * R_L * L \qquad \textbf{[Eq. 3.11]}$$

where,

$PD$ is the power dissipated in watts;

I is the effective current of the circuit in amperes;

C is the number of conductors in the circuit;

$R_L$ is the linear resistance of the conductor in ohms per kilometer;

L is the length of the line in kilometers.

The model project will use a copper conductor with a cross sectional area of 300 thousand circular mils[25] (otherwise known as Cu 300) and a linear resistance ( $R_L$ ) of 0.132 Ohms per kilometer. The line will consist of one circuit with one conductor for each phase and will be rated for an effective current (I) of 0.405 kilo ampere. The transmission voltage will be 154 kilo volts[26].

As the power output of the wind farm will be variable depending on the wind conditions, and the delivery voltage is fixed at 154 kilo volts, the current will vary according to the following expression:

$$I_{M,N,R} = \frac{P_{M,N,R}}{154} \qquad \textbf{[Eq. 3.12.]}$$

where,

$P_{M,N,R}$ is the expected power output of the wind turbine model N (N=1 for Nordex N80 and N=2 for Nordex N90), at wind speed range R and site M and expressed in kWh;

$I_{M,N,R}$ is the current associated to that power.

To calculate the energy losses the following expression was used:

[25] One circular mil is the cross sectional area of a wire one mil in diameter. One mil is 1*10^-3 inches.
[26] This is a common specification for electrical conductors in Chile and elsewhere in the world. The same specifications are used in the SIC for transmission distances of up to 80 km.

$$L_{M,N} = \sum_{R=1}^{2100} (I_{M,N,R}{}^2 * T_N * R_L * GT_{M,N,R}) \qquad \textbf{[Eq. 3.13.]}$$

where,

$L_{M,N}$ is annual dissipated energy in kWh per kilometer at site M with wind turbine model N and;

$GT_{M,N,R}$ is the generating time in hours at wind speed range R, site M and model turbine N.

**Table 3.8** shows the energy losses obtained with **[Eq. 3.13]**. The lasts 4 columns of **Appendix 1** show the current and dissipated power by wind speed range for selected mean wind speeds[27].

**Table 3.8**. Annual transmission losses for the model project per kilometer according to mean wind speed of the site.

| Mean wind speed (M) (m*s^-1) | Wind farm's annual losses ( $L_{M,N}$ ) (kWh*km^-1*year^-1) | |
|---|---|---|
| | (N=1) Nordex N90 | (N=2) Nordex N80 |
| 4.00 | 8,851 | - |
| 4.25 | 12,229 | - |
| 4.50 | 16,317 | - |
| 4.75 | 21,132 | - |
| 5.00 | 26,606 | - |
| 5.25 | 32,698 | - |
| 5.50 | 39,339 | - |
| 5.75 | 46,446 | - |
| 6.00 | 53,937 | - |
| 6.25 | 61,727 | - |

[27] All the tables are included in the electronic version of this dissertation.

| | | |
|---|---|---|
| 6.50 | 69,735 | - |
| 6.75 | 77,886 | - |
| 7.00 | 86,111 | - |
| 7.25 | 94,346 | - |
| 7.50 | 102,538 | - |
| 7.75 | 110,636 | - |
| 8.00 | 118,599 | 87,043 |
| 8.25 | - | 94,035 |
| 8.50 | - | 100,954 |
| 8.75 | - | 107,761 |
| 9.00 | - | 114,421 |
| 9.25 | - | 120,904 |
| 9.50 | - | 127,182 |
| 9.75 | - | 133,231 |
| 10.00 | - | 139,032 |
| 10.25 | - | 144,566 |
| 10.50 | - | 149,820 |
| 10.75 | - | 154,784 |
| 11.00 | - | 159,451 |
| 11.25 | - | 163,815 |
| 11.50 | - | 167,875 |
| 11.75 | - | 171,630 |
| 12.00 | - | 175,082 |

### 3.6. Investment and maintenance costs estimates for the transmission line

In order to estimate the payment that generating companies have to make to the owners of transmission infrastructure due to energy transporting services, the Chilean government regularly collects information regarding the costs of replacement and maintenance of power lines, transformers and related gear. **Table 3.9** shows the replacement value and annual maintenance costs of selected SIC's transmission lines with the same specifications as the one used by the model project. These costs include their respective rights of way payments, power conditioning, switching and protection gear. Lines shorter than 5 kilometers are taken out of the sample because they correspond to special cases, such as lines built inside a power plant or built to connect two nearby substations, etc. which for the purpose of the model project, would impose a bias on the averages.

**Table 3.9**. Annual maintenance costs and replacement value of single circuit, copper (Cu 300), 154 kilovolts, 0.405 kilo amperes transmission lines longer than 10 kilometers (December 2004 US$).

| Lines' starting and ending places | Length (km) | Replacement value (US$) | Maintenance cost (US$*year^-1) |
|---|---|---|---|
| Abanico – Charrúa | 80.4 | 11,942,000 | 281,000 |
| Arranque Chillán – Parral | 65.1 | 6,091,000 | 139,000 |
| Charrúa - Arranque Chillán | 57.8 | 6,144,000 | 147,000 |
| Itahue – Maule | 42.95 | 4,857,000 | 118,000 |
| Linares – Maule | 42.65 | 3,781,000 | 85,000 |
| Parral – Linares | 36.8 | 3,394,000 | 76,000 |
| Charrúa – Concepción | 72 | 7,445,193 | 193,000 |
| Total | 398 | 43,654,193 | 1,039,000 |
| Averages per kilometre | | 109,767 | 2,613 |

Source: Elaborated using CDEC-SIC 2 (2005) data.

As representative values for the investment and maintenance costs for the transmission line, the model project will use the averages per kilometre of the sample shown in **Table 3.9**. The equations used in the cash flow are the following:

$$ITL = 109{,}767 * L \qquad \textbf{[Eq. 3.14.]}$$

$$MTL = 2{,}613 * L \qquad \textbf{[Eq. 3.15.]}$$

where,

ITL is the investment in the transmission line in US$;

MTL is the annual maintenance cost in US$ per kilometre and;

L is the length of the transmission line in kilometres.

### 3.7. Wind farm's operation and maintenance cost estimate

In this study the operation and maintenance costs include insurance, regular maintenance, repair, spare parts and administration. Based on experiences from Spain, Denmark, Germany and the U.K., EWEA (2004) estimates that the operation and maintenance cost for the latest generation of large size wind turbines is in the range of 0.007 and 0.008 US$*kWh^-1 [28]. The model project will use the mean value of this range equal to 0.0075 US$*kWh^-1. The following expression is used in the cash flow to take account of the maintenance costs:

$$MC_{M,N} = 0.0075 * NP_{M,N} \qquad \textbf{[Eq. 3.16.]}$$

where,

$MC_{M,N}$ are the total maintenance costs in US$ associated to the production of $NP_{M,N}$ kWh of electricity at site M with turbine model N.

### 3.8. Price of emission reduction certificates

By avoiding the utilisation of fossil fuels to generate electricity in Chile, the model project should be able to offer emissions reduction certificates into the carbon market. The sale of these instruments should signify an additional source of income into the model project's

[28] The average spot exchange rate for June 2004 of 0.8153 [€*US$^-1] informed by the Bank of England at http://www.bankofengland.co.uk/statistics/index.htm is considered in these figures.

cash flows, influencing the position of the Isoprofit curves in the distance-wind speed space.

The carbon market arises from the commitment of several states and firms willing to reduce their emissions of greenhouse gases. Since these gases are uniformly mixed in the atmosphere, the emission reductions can take place anywhere in the world regardless of territorial jurisdictions. The main commitment is the 1997 Kyoto Protocol (in force since February 16, 2005) which emerged from the 1992 United Nations Framework Convention on Climate Change (UNFCCC). The commitment consist in the reduction of greenhouse gases emissions of at least 5.2% below the levels of 1990. The Protocol creates the possibility for the committed parties to trade emission reductions between them through a mechanism called Joint Implementation (JI), and with non committed parties to the treaty through a mechanism called Clean Development Mechanism (CDM).

The CDM allows for the implementation of projects oriented to reduce emissions and/or enhance the capacity of carbon sinks in developing countries. These projects would produce Certified Emission Reductions (CERs) that could be purchased by parties needing to achieve their individual reduction targets as set out by the Kyoto Protocol[29].

There are other similar greenhouse gases regulatory schemes at the international, national, and sub-national levels with varying degrees of linkage to the Kyoto Protocol. For example, the European Union Emissions Trading Scheme (EU-ETS) which started to operate in January 1st 2005, puts ceilings on the emissions of 12,000 large scale point sources within

[29] Individual targets can be found at http://unfccc.int/essential_background/kyoto_protocol/items/3145.php.

the European Union and allows the use of Kyoto emission credits to count against its emissions reduction targets[30]. According to Lecocq and Capoor (2005), Japan and Canada are developing national plans to meet their Kyoto obligations, whereas in some states of countries that didn't ratify the Kyoto Protocol such as the United States of America and Australia, regimes that limit carbon emissions and allow for carbon transactions also exist. Nevertheless, according to the same authors, it is unclear how these regimes will be ultimately linked with the Kyoto Protocol.

In the study of Lecocq and Capoor we can find one of the few comprehensive studies regarding atmospheric carbon prices[31] available in the public domain. The study includes prices for Kyoto Protocol targets and for other schemes. Because the Kyoto Protocol rules that valid emission reductions are only those that are additional to what otherwise would have occurred in the absence of the project[32] as deemed by the CDM Executive Body, three categories of prices are identified:

1- Verified Emission Reductions (VER): These prices include transactions in which getting the recognition of the emission reductions by the CDM Executive Board is the responsibility of the buyer;

---

[30] The relationships between the (EU-ETS) and the Kyoto Protocol is governed by Directive 2004/101/EC of the European Parliament and of the Council available from http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=32004L0101&model=guichett.

[31] The emissions reductions of other global warming gases with different greenhouse effect potential are usually converted to equivalent tonnes of carbon dioxide emission reduction $(tCO_2e)$, using factors defined by UNFCCC. These transformations allow for a direct comparison of prices and were used in the study by Lecocq and Capoor (2005).

[32] This concept is usually referred to as "environmental additionality".

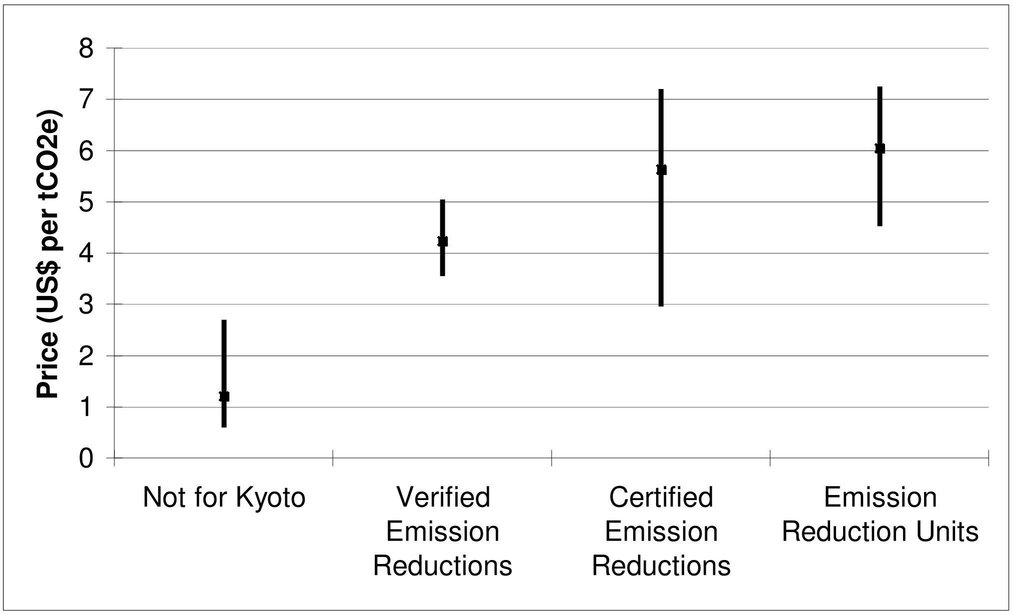
2- Certified Emission Reductions (CER): These prices include transactions in which the recognition of the emission reductions by the CDM Executive Board is the responsibility of the seller;

3- Emission Reductions Units (ERU): These prices include transactions of emission reductions originating through JI projects, which are considered the less risky because they do not need to gain the CDM Executive Board approval among other reasons.

**Figure 3.3** shows the minimum, average and maximum prices observed from January 2004 to April 2005 on a sample that accounts for 53.5% of the volume of project based[33] transactions exchanged during the period.

[33] As opposed to transactions of allowances, project based transactions originate in projects that reduce greenhouse gas emissions.

**Figure 3.3**. Prices for project based emission reductions from January 2004 to April 2005.




Source: Lecocq and Capoor (2005).

Several factors suggest that these average prices observed during the last months are not representative of the prices that our model project would perceive. For instance, The Economist (July 9, 2005) indicates that there is still a structural imbalance between supply and demand because many companies from new European Union member states have not joined the carbon market as allocation registries have not yet been set up for them. Other commentators have pointed out that there is still a great deal of regulatory uncertainty, particularly on behalf of the CDM Executive Board, which has prevented to a great extent the materialisation of the bulk of transactions needed by states to comply with their cap targets. There are also uncertainties regarding how much of the emission reductions burden committed by the different states will be directly passed on to the private sector, which in turn does not have a clear indication on how much to buy.

But perhaps the clearest hint suggesting the need to interpret past prices with care is the present difference between the prices observed for CERs and EU-ETS allowances. As indicated earlier, CERs and EU-ETS are interchangeable emission reductions, so it could be expected that their prices should to some extent be similar. Nevertheless, these prices differ greatly[34].

In the absence of a better forecast, the model project will use as a representative price for its CERs, the average price observed by Lecocq and Capoor (2005) during the last 16 months which is equal to 5.63 US$ per $tCO_2e$.

### 3.9. Eligibility of the model project to issue CERs

The main criteria considered by CDM Executive Body when it endorses project based certificates of emission reduction is the project's additionality with respect to a base line. As already noted when analysing the price of the project's emission reduction certificates, additionality refers to the idea that valid emission reductions are only those that are additional to what otherwise would have occurred in the absence of the project. In other words, if the project were not implemented then, no emission reduction would take place and greenhouse gas emissions would follow a baseline pattern.

[34] For instance on August 8, 2005 Point Carbon (www.pointacrbon.com) indicates that EU-ETS emission allowances are being sold at 25.19 US$ per $tCO_2e$, whereas the same day, the World Bank Community Development Carbon Fund (http://carbonfinance.org/cdcf/home.cfm) announces that it is buying CERs from Hondura's "La Esperanza" hydro power project at 4.5 US$ per $tCO_2e$.

The baseline pattern in the SIC consists in the expansion of the generating capacity to match a growing demand for electricity by means of power plants that represent minimum costs for their developers and thus maximise private benefits. In theory, such expansion could take place in the form of power plants based on any technology including hydraulic turbines, gas turbines in simple (Brayton) or combined (Brayton-Rankine) cycles using liquid or gas fuel, steam turbines (i.e. a Rankine cycle powered by coal, oil, gas, atomic radioactivity or biomass), wind turbines, photovoltaic solar panels, etc. CNE (2004) has determined that the least cost option for the addition of new power into the SIC are the combined cycle and hydroelectric power plants. This means that the model wind farm is not part of the base line scenario and therefore possesses additionality.

There are other aspects that the CDM Executive Board considers when endorsing project based emission reductions such as the technical feasibility of the project, the certitude associated to the estimate of emissions reduction quantity and country related risks that could threaten the delivery of emission reductions. Technical feasibility of the model project is out of the question considering that wind energy is already a widespread technology in the world. Country related risks for the model project are considered to be very low as demonstrated by the fact that Chile is among the three largest suppliers of project based emissions reductions (Lecocq and Capoor, 2005) and it is ranked 2$^{nd}$ by the May 2005 CDM Host Country Rating developed by Point Carbon (Point Carbon, 2005). The estimate of emissions reduction quantity can be measured to a high degree of certitude as explained below.

### 3.10. Estimate of CERs sales

The amount of CERs to be produced by the model project will depend on the amount of fossil fuel generated electricity displaced by its operation. After the project starts to operate, an ex-post observation of the amount of fossil fuel generated electricity displaced by the model project could be done by analyising the dispatch instructions of CDEC. By multiplying the corresponding emission factors of the displaced fossil fuel power plants by the quantity of electricity displaced by the model project according to CDEC instructions, a very precise estimate of the avoided emissions can be obtained.

The World Bank (2001) found that a new 25 mega watt run-off-the-river power plant to be connected to the SIC would displace only coal-based generation. The same source assigned to this type of generation an emission factor of 860 tonnes of CO2 per gigawatt-hour of electricity.

We will use these same assumptions to calculate the potential sales of CERs by the model project. **Eq. [3.17]** is the expression incorporated in the cash flows to calculate the CERs annual sales.

$$CERs = 5.63 * 0.86 * NP_{M,N} \qquad \textbf{[Eq. 3.17.]}$$

where,

CERs are the sales of certificates of emission reduction in US$ per year;

5.63 is the price of CERs in US$ per $tCO_2e$ as indicated in **Section 3.8**;

0.86 is the emission factor of the SIC's coal-based generation in $tCO_2e * MWh^{\wedge}{-1}$ and;

$NP_{M,N}$ is the net amount of electricity produced by the model project at site M with turbines N expressed in $MWh * year^{\wedge}{-1}$.

### 3.11. Financial structure and costs

The total investment will vary according to the wind turbine model and the length of the transmission line. 30% of this total investment will be the investor's equity and the remaining 70% will be covered by a 20-year loan at 5.5% interest rate to be paid back in annual installments of the same amount. The actual financial structure that any particular project would have will be determined by an optimization process, which considers characteristics of the borrower and the lender. Nevertheless, according to the author's experience, the financial structure chosen here is commonly used by companies working in the Chilean energy sector. Also, the discount rate of 5.5% is a common discount rate for the evaluation of projects in the sector, but the actual rate would only be determined on a case by case basis[35].

To calculate the annual principal payments, the following expression was used:

$$PP = \frac{PVL}{20} \qquad \textbf{[Eq. 3.18]}$$

[35] It should be noted that the ability of the project to raise loans is strongly tied to the mean wind speed of the site. For example, the debt coverage increases with increasing mean wind speeds.

where, PP are the annual principal payments and PVL is the present value of the loan, both in US$.

To calculate the annual interests (INT) in US$, the following expression was used in the cash flow:

$$INT = \frac{PVL}{\frac{1}{(1+0.055)^1} + \frac{1}{(1+0.055)^2} + ... + \frac{1}{(1+0.055)^{20}}} - PP \qquad \textbf{[Eq. 3.19]}$$

**3.12. Depreciation and resale value**

A straight line depreciation in 10 years was considered for the wind turbines and electrical installation. A straight line depreciation in 15 years was considered for the transmission line and civil works (i.e. foundations and roads).

A zero resale value for the whole investment was considered after the 20 years of operation.

**3.13. Income tax**

The state of Chile charges companies a 15% tax over their income after depreciation has been deducted.

## 4. Results of the case study

**Appendix 2** contains the cash flows that originate the Isoprofit coordinates. These cash flows accounted for:

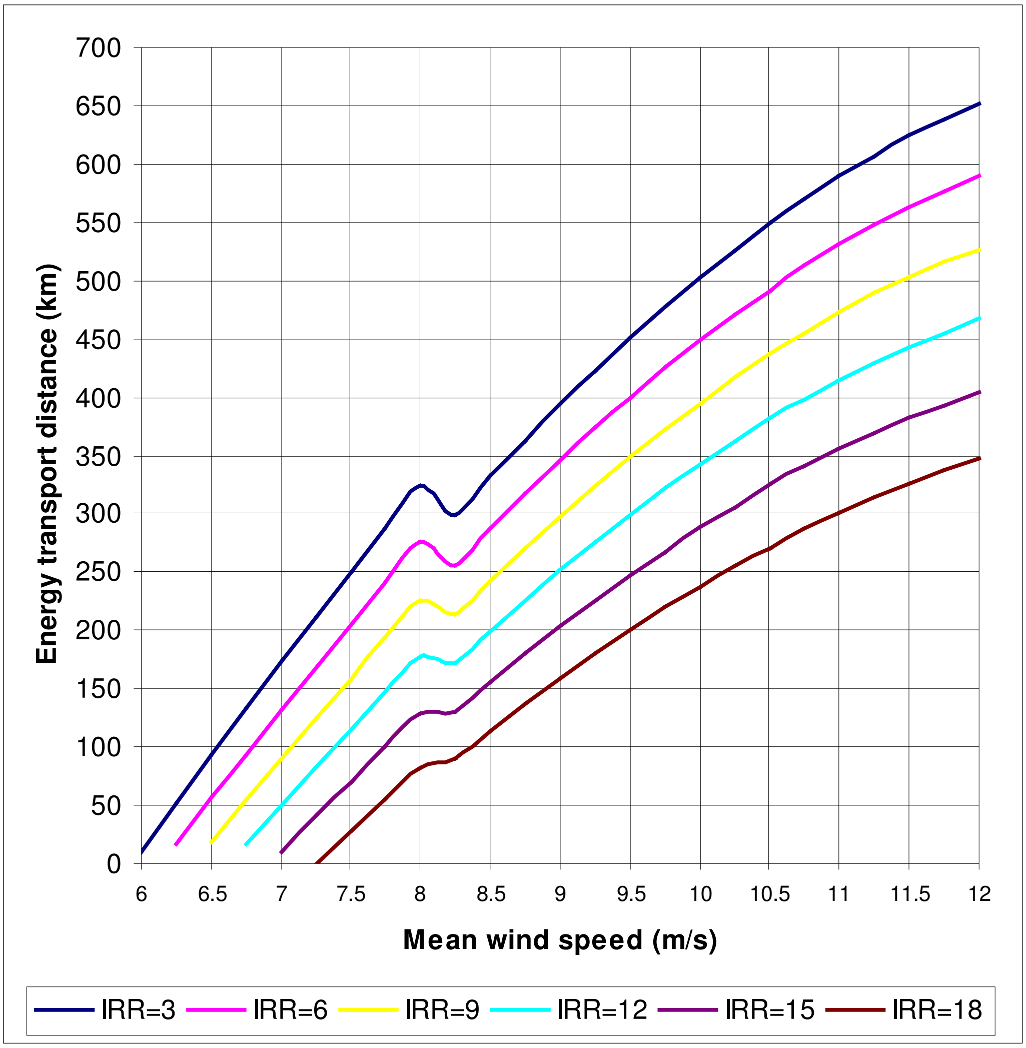
- Variable sales of electricity due to mean wind speed variations
- Variable investment cost due to variable length of the transmission line
- Variable financial costs due to the investment in a transmission line of variable length
- Variable equity due to variable investment in the transmission line
- Variable sales of emission reduction certificates due to variable quantities of electricity produced
- Variable operation and maintenance cost due to variable quantities of energy produced
- Variable costs associated to the maintenance of a transmission line of variable length
- Variable depreciation due to a variable investment in the transmission line
- Variable dissipated power in the transmission line due to variable currents being exported from the site at different wind speeds
- Variable income tax due to variable depreciation associated to the transmission line and variable sales resulting from wind speed variations

**Table 4.1** shows the Isoprofit coordinates plotted in **Figure 4.1**.

**Table 4.1**. Isoprofit coordinates.

| Mean wind speed (m/s) | Energy transport distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | IRR=3 | IRR=6 | IRR=9 | IRR=12 | IRR=15 | IRR=18 |
| 6 | 10.0 | | | | | |
| 6.25 | 51.0 | 17.0 | | | | |
| 6.5 | 93.0 | 56.0 | 18.0 | | | |
| 6.75 | 133.0 | 94.0 | 55.0 | 17.0 | | |
| 7 | 173.0 | 132.0 | 90.5 | 50.0 | 10.0 | |
| 7.25 | 212.0 | 169.0 | 125.0 | 83.0 | 41.0 | 0.5 |
| 7.5 | 251.0 | 205.0 | 159.0 | 115.0 | 71.0 | 28.0 |
| 7.75 | 288.0 | 240.0 | 193.0 | 147.0 | 100.0 | 55.0 |
| 8 | 324.0 | 275.0 | 225.0 | 177.0 | 128.0 | 82.0 |
| 8.25 | 299.0 | 256.0 | 214.0 | 172.0 | 130.0 | 90.0 |
| 8.5 | 332.0 | 287.0 | 242.0 | 199.0 | 155.0 | 113.0 |
| 8.75 | 363.0 | 317.0 | 270.0 | 226.0 | 180.0 | 137.0 |
| 9 | 394.0 | 346.0 | 298.0 | 252.0 | 204.0 | 159.0 |
| 9.25 | 423.0 | 374.0 | 324.0 | 276.0 | 226.0 | 180.0 |
| 9.5 | 451.0 | 400.0 | 349.0 | 299.0 | 248.0 | 200.0 |
| 9.75 | 477.0 | 426.0 | 373.0 | 322.0 | 268.0 | 220.0 |
| 10 | 503.0 | 450.0 | 395.0 | 343.0 | 289.0 | 238.0 |
| 10.25 | 527.0 | 471.0 | 417.0 | 362.0 | 306.0 | 255.0 |
| 10.5 | 549.0 | 492.0 | 437.0 | 382.0 | 325.0 | 271.0 |
| 10.75 | 569.0 | 513.0 | 455.0 | 398.0 | 340.0 | 287.0 |
| 11 | 589.0 | 531.0 | 472.0 | 415.0 | 356.0 | 301.0 |
| 11.25 | 606.0 | 548.0 | 489.0 | 430.0 | 370.0 | 314.0 |
| 11.5 | 624.0 | 563.0 | 503.0 | 442.0 | 382.0 | 326.0 |
| 11.75 | 638.0 | 577.0 | 516.0 | 455.0 | 393.0 | 337.0 |
| 12 | 651.0 | 589.0 | 527.0 | 467.0 | 404.0 | 347.0 |

**Figure 4.1**. Isoprofits graph.




## 5. Discussion and conclusions

### 5.1. Regarding the case study

Given the present prices of energy, power and the investment costs for a wind farm in the range of around 50MW, and considering that the current available rate of interest for any person in the country is around 4%[36], we can conclude that economically viable projects for private investors operating in the studied region, should exist only above wind speeds of 6.25 m/s.

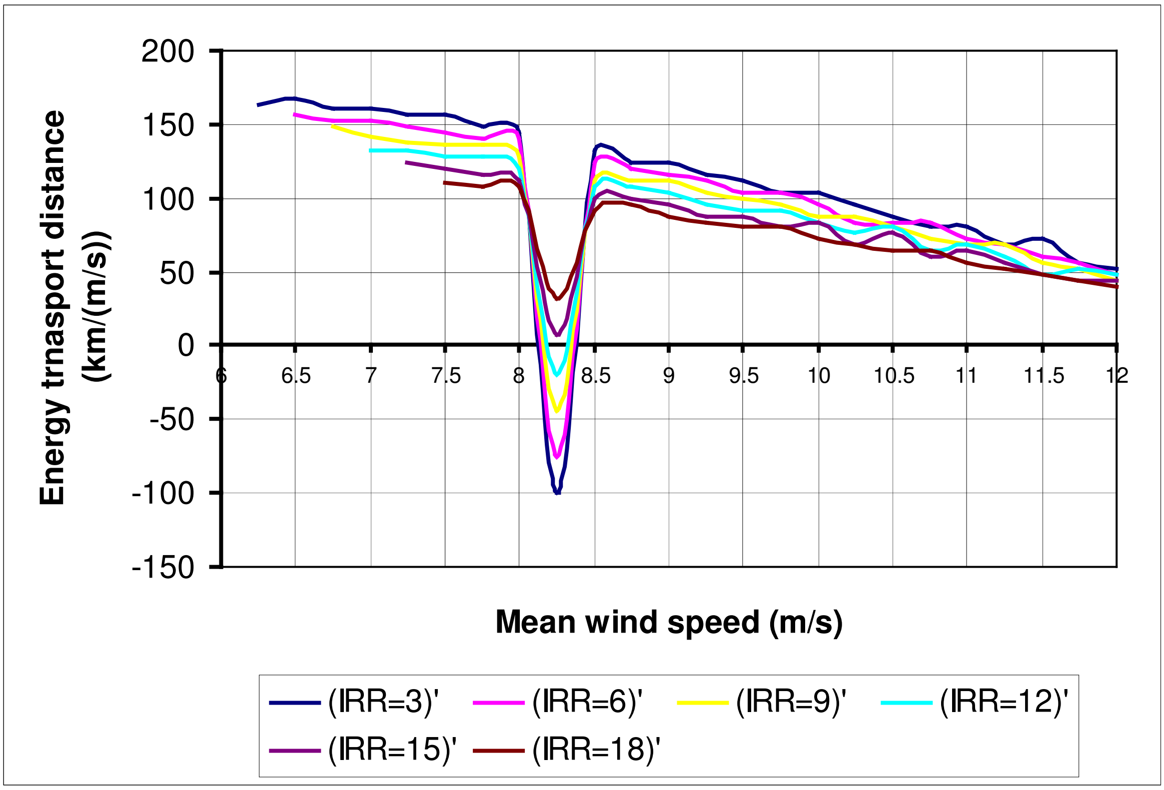
Considering that the average distance from the coastline, a zone exposed to strong winds coming from the Pacific Ocean, to the main electric system of the country is probably lower than 100 km[37], we can presume that almost any project similar to our model project located at a site with a wind speed of over 7.75 m/s, would have an IRR of over 15%.

The substitution of energy transport distance by wind speed for constant marginal efficiency of capital varies between Isoprofits and along them. **Figure 5.1** shows this variation obtained from **Table 4.1**. **Appendix 3** contains the same information in table form. For example, in order to keep a constant marginal efficiency of capital of 12% when reducing the wind speed from 7.75 to 7.5 m/s, the energy transport distance should be reduced approximately 130 km. But if the reduction of wind speed is from 10 to 9.75 m/s, then the energy transport distance should be reduced in 84 km.

[36] This is the approximate average rate of interest given by the pensions fund system since its creation in 1981.

[37] The average total width of the country is under 180 km and the main electric lines run roughly through the middle of the territory.

**Figure 5.1**. Slopes of the Isoprofit curves.




The discontinuity in the slopes of the Isoprofits at 8 m/s is explained by the change of wind turbine model. Apart from that, the variation in slopes is governed by all the factors for which the cash flows account for. The great number of equations (many of them non-linear) in which these cash flows originate, the fact that the cash flows were run for discrete wind speeds increments (of 0.25 m/s) and the many round-up approximations involved, may be responsible for the uneven variation of these slopes.

Regarding the economically installable capacity predicted by the model, it would be interesting to analyse the effect of changing prices and the effect of the application of different types and levels of incentives or disincentives. This analysis could be easily performed using the cash flows used to plot the Isoprofits.

The verification of the constant returns to scale assumption, would tell us the project size range to which the family of Isoprofits obtained can be applied to, and therefore it is an important task that should be carried out.

The determination of the physical area available to the right of the Isoprofit of current rate of interest, would allow the determination of the economically installable capacity and total investment for a future wind energy industry in Chile, according to equations 2.1 and 2.2. That information would probably be useful to enhance the National Energy Policy.

**5.2. Regarding the model**

The Isoprofit model provides a way to estimate investment's amount, capacity and geographical location of wind, biomass and solar based technologies. The model can be applied having in mind private, social or both kinds of benefits, as long as they can be accounted for by a cash flow analysis.

According to the model, the first projects to be implemented should be able to select the best sites being able to have the highest marginal efficiency of capital in a given industry.

The model is appropriate to predict the locations and conditions under which the production of hydrogen for energetic purposes by a renewable energy industry could start to take place.

It has been envisaged by many that this form of harnessing renewables represent an unquestionable way of providing energy in a sustainable manner, and may denote the beginning of a new era.

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