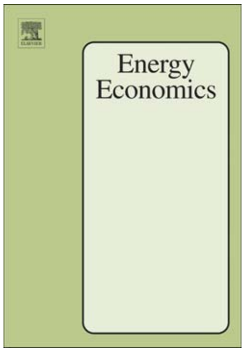

Energy
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Renewable energy in the equilibrium mix of electricity supply sources

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Renewable energy in the equilibrium mix of electricity supply sources

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Abstract

A method to derive the long-run supply curve for a given renewable energy source and technology is proposed. The method accounts for the spatial complexity arising from the distribution of the energy source and the energy transport infrastructure of the territory. The use of the resultant supply curve within the partial equilibrium competitive model for the design and evaluation of renewable energy support schemes and for the determination of optimal supply mixes is illustrated. A case study with the application of the method for wind energy in Rapa Nui (or Easter) Island is presented.

Keywords: support schemes, renewable energy, supply curve, partial equilibrium, ISOPROFIT model

1. Introduction

Anthropogenic climate change has been called the greatest market failure the world has ever seen (Stern, 2007). It has been characterised as the greatest threat to future generations (Obama, 2015) and is viewed by the public as a top global concern second only to terrorism (Pew Research Center, 2015). Renewable energy support schemes are one of the main interventions undertaken by countries to address the problem. This is because the world's energy sector is the largest contributor to greenhouse gas emissions (IPCC, 2014), it is expected to continue growing with economic development (Bruns et al., 2013), and the belief exists that there is ample space in it for efficient emission abatement (IPCC, 2011). But the unexpected termination or drastic curtailment of national schemes in countries like Spain, the UK and Germany in the last years endorse the view that an improved method to set up such schemes is needed. Misleading regulation signals brought about by inadequate support schemes result in sub-optimal levels of renewable energy infrastructure investment, of fiscal expenditure, of technical development efforts, of carbon reduction targets and of energy prices, bringing economies farther away from the economically efficient energy matrix.

Increasing international pressure for energy subsidy reform (Coady et al, 2015), growing hunger for energy of developing economies (Wolfram et al., 2012; King et al., 2015), the advent of the electric car and the pressing commitments made at the 2015 UNFCCC Paris conference foretell demanding times for policy makers working on renewable energy schemes. The IPCC (2014) estimates that fulfilling by 2100 the main goal of the Paris Agreement[1], would require anthropogenic greenhouse gas emissions to be by 2050 in the range of 60 to 30% those of 2010. There is little doubt that these challenges require major transitions in the worldwide energy system (van Vuuren et al., 2015), a key outcome to our subsistence on Earth.

Energy supply can be classified as coming from non-renewable and from renewable sources. The supply mix of the non-renewable part can be optimised using a set of criteria based on least cost or profit maximisation. However, the optimal supply mix of the renewable part is more complex to determine, as it depends on each territory's potential for that kind of generation. It is here where energy policy may fail to provide proper regulation, hence one of the reasons for the constant need for revision of support schemes. In fact, the territorial potential for incorporating renewable energy becomes the central problem when studying policy interventions to favour the

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[1] The main goal of the Paris Agreement consists in "holding the increase in global average temperature to well below 2°C above pre-industrial levels" (UNFCCC, 2015).

development of some generation means over others. The knowledge of this territorial potential should enlighten society's decision about what policy objectives (e.g. emission targets, supply cost, or the proportion of energy to be imported) are desirable, achievable and optimal.

In this article, I propose a way to determine the supply-demand equilibrium composition of the electricity generation mix of a territory in the presence of renewables that need to be "harvested" over large areas such as wind or solar energy. The model proposes a “positive” approach to solve the problems of how much "green" energy is achievable under a given set of prices and where it should be located. By capturing the effect of incentives at the investor's cash flow level and working its way up to the supply-demand equilibrium, the model also provides a base for evaluating policy interventions that should be done (if any) to market-based economies in order to achieve the policy objectives set out by society. I also put forward the idea that support schemes should be designed taking into account the long-run supply curve of renewables which is highly specific to each territory or country.

Although the model is of greater use when applied to large regions or complete countries, where it could help refine policy schemes that affect the allocation of larger investment amounts, a case study of its application to the isolated electrical system of Easter Island is presented due to its reduced size and simplicity.

2. Theoretical framework

Modelling the expansion of generating infrastructure has been traditionally approached by solving an operation and investment cost minimisation problem subject to meet demand. Later, as electricity markets were liberalized, modelling development efforts shifted towards a profit maximisation approach. Game Theory has been especially useful for this approach as it allows to investigate the strategic behaviour of generation companies as they try to maximize their profits affecting each other. Among the most urgent improvements to these tools and procedures, is the incorporation of the geographical scope in order to account better for the fastest-growing low-CO2 generation technologies such as wind and solar photovoltaic (Ryan et al., 2011; Power Systems Engineering Research Center, 2009).

Other methods such as portfolio theory, scenarios and investment rate projections can be used successfully for various purposes within the energy sector, but they are limited when it comes to predict the growth of renewables as they don't attend properly the geographical constraints in which renewables develop.

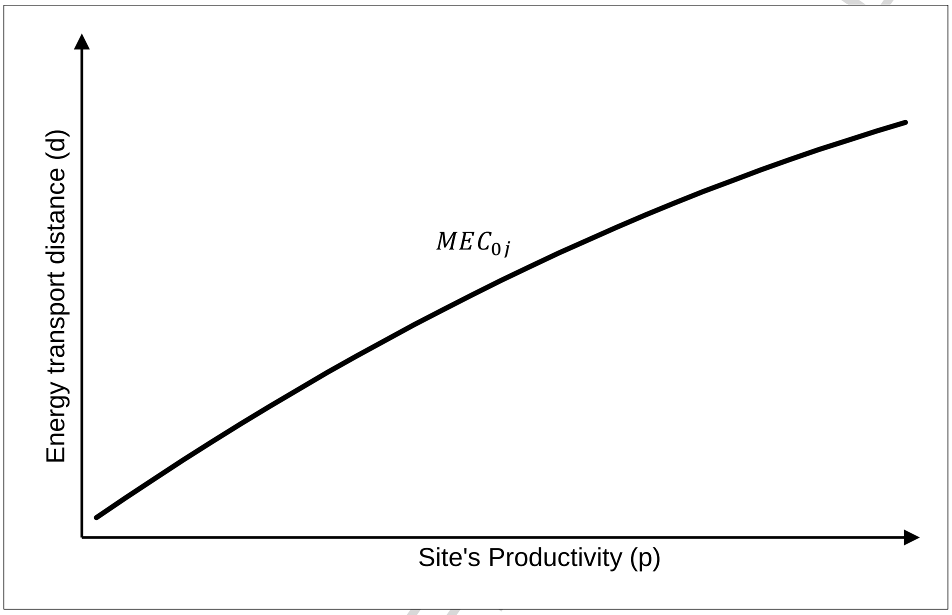
The partial equilibrium competitive model is probably the most widely used tool to study prices and it provides a framework to the problem of determining optimal sets of electricity supply sources and support schemes for renewables. A territory-specific long-run supply curve for a given renewable source is a result of the spatial complexity arising from the distribution of the energy source and the energy transport cost, themes central in classic spatial economic theory.

If we derive such long-run supply curves for the different renewable energy technologies in a territory, we could obtain a set of supply-demand equilibrium quantities of electricity to be provided by say wind, photovoltaic, biomass or ocean derived energy technologies. The gap between the sum of renewable energy supply and total demand could be met by traditional means of generation, after giving attention to the relevant (technical, environmental, social, etc) restrictions. In this way, it is possible to obtain an economically efficient energy matrix.

2.1 The ISOPROFIT Model

The ISOPROFIT model (Faúndez, 2007) says that for a fixed set of prices “i=0”, a given renewable energy technology and source “j” (such as wind, biomass, solar radiation, etc.) and a given region, the space available for the development of renewable energy projects can be delimited by a curve of constant marginal efficiency of capital (MEC_{0j}) in the energy transport cost - productivity space. This MEC_{0j} corresponds to the current available rate of return available to investors, and can be called isoprofit MEC_{0j} curve. Using transport distance as a proxy for transport cost, **Figure 1** shows the hypothetical isoprofit curve MEC_{0j}.

Figure 1. Hypothetical isoprofit MEC_{0j} curve.



Distance "d", may be expressed for example in kilometres and is the distance that energy should be transported from the source to the selling point[2]. Depending on the source, productivity "p" may be expressed as an average wind speed or solar radiation per unit of area, kilograms per hectare of biomass or, more generally, as a measure of energy per unit of area (MWh*m^-2) that is possible to extract in a given period.

In line with investment theory, investors should "colonise" the space available for development of new projects starting from the lower right corner of **Figure 1** and continue until they reach isoprofit MEC_{0j}. Spatial economists would say that rent of projects located over MEC_{0j} is zero.

Each point along the isoprofit MEC_{0j} can be obtained by trying combinations of productivity and energy transport distance iteratively in a cash flow model of the renewable energy technology under study, until MEC_{0j} is reached.

If for example, we vary the set of prices "i=0" to reflect an increase only in the selling price of energy, we should observe a displacement of MEC_{0j} to the left and upwards to accommodate a bigger area available for development of projects by profit seeking investors. Let us denote the new set of prices by the sub-index "i=1". **Figure 2** shows the new curve MEC_{1j} and MEC_{0j}.

Figure 2. Displacement of the isoprofit curve as a result of an increase in the selling price of energy.

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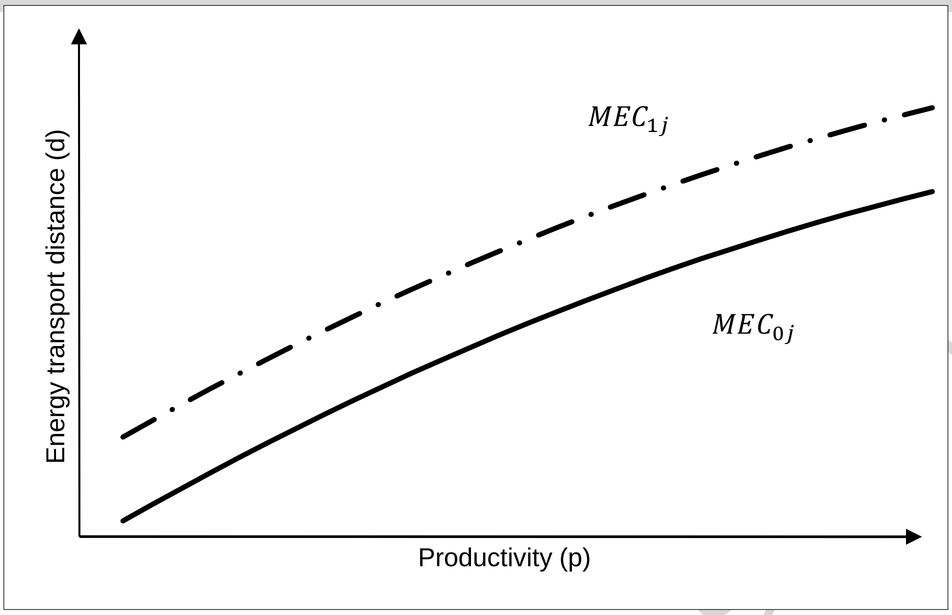
[2] The use of Euclidean transport distance as a proxy for energy transport cost is made in order to keep this presentation simple, but it's not a requisite for the application of the model.



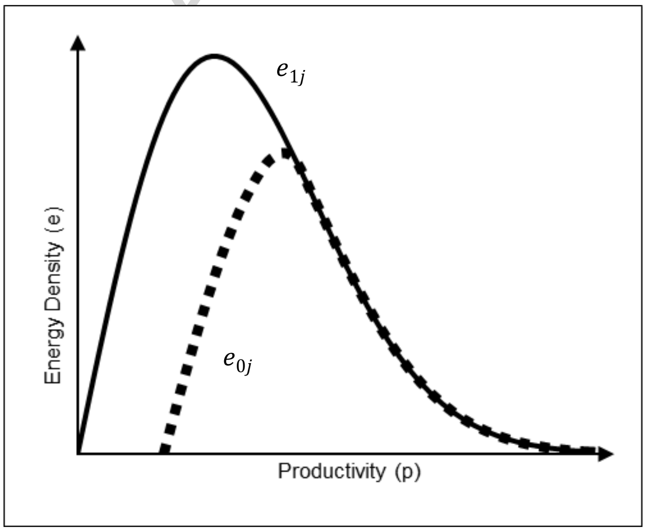
2.2 Relating the ISOPROFIT Model to a geographical area

Let the productivity "p" over a territory be a continuous random variable. Then, for every isoprofit ($MEC_{i,j}$) it is possible to derive a probability density function of productivity "$f_{i,j}(p)$" that returns the likelihood of finding area in the territory to the right of each isoprofit. Multiplying "$f_{i,j}(p)$" by the total area available to the right of isporofit $MEC_{i,j}$ ($A_{i,j}$) and by productivity "p" we get,

$$e_{i,j}(p) = A_{i,j} * f_{i,j}(p) * p$$ **Equation (1)**

Let us call $e_{i,j}(p)$ the "Energy Density Function" for isoprofit $MEC_{i,j}$. In our example, e_{0j} relates to MEC_{0j} and e_{1j} relates to MEC_{1j}. **Figure 3**, shows these two hypothetical Energy Density Functions.

Figure 3. Hypothetical Energy Density Functions e_{0j} and e_{1j}.



Integrating the Energy Density Function $e_{i,j}(p)$ over productivity we obtain:

$$Q_{i,j} = \int_0^{\infty} e_{i,j}(p)\, dp$$ **Equation (2)**

Where "$Q_{i,j}$" is the total energy available to the right of $MEC_{i,j}$ for the territory considered.

In our example,

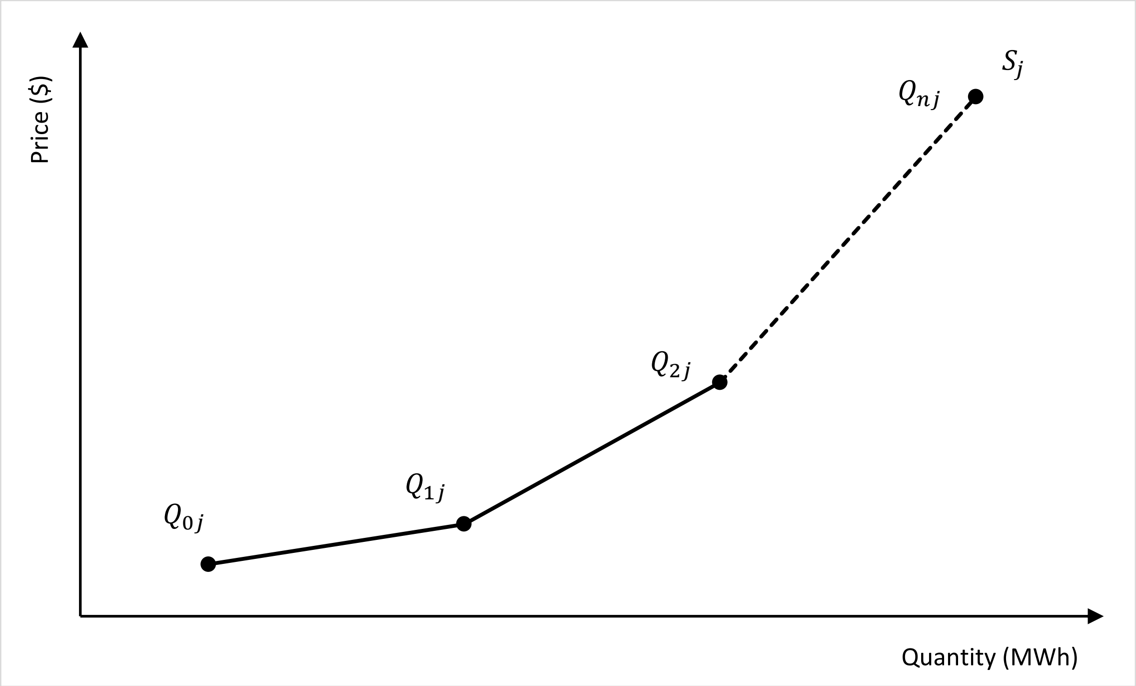
$$Q_{0j} = \int_0^{\infty} e_{0j}\, dp \qquad \textbf{Equation (3)}$$

$$Q_{1j} = \int_0^{\infty} e_{1j}\, dp \qquad \textbf{Equation (4)}$$

Where Q_{0j} and Q_{1j} are the quantities of renewable energy (e.g. in MWh) that investors should be willing to supply under the set of prices $i = 0$ and $i = 1$ related to MEC_{0j} and MEC_{1j}, respectively.

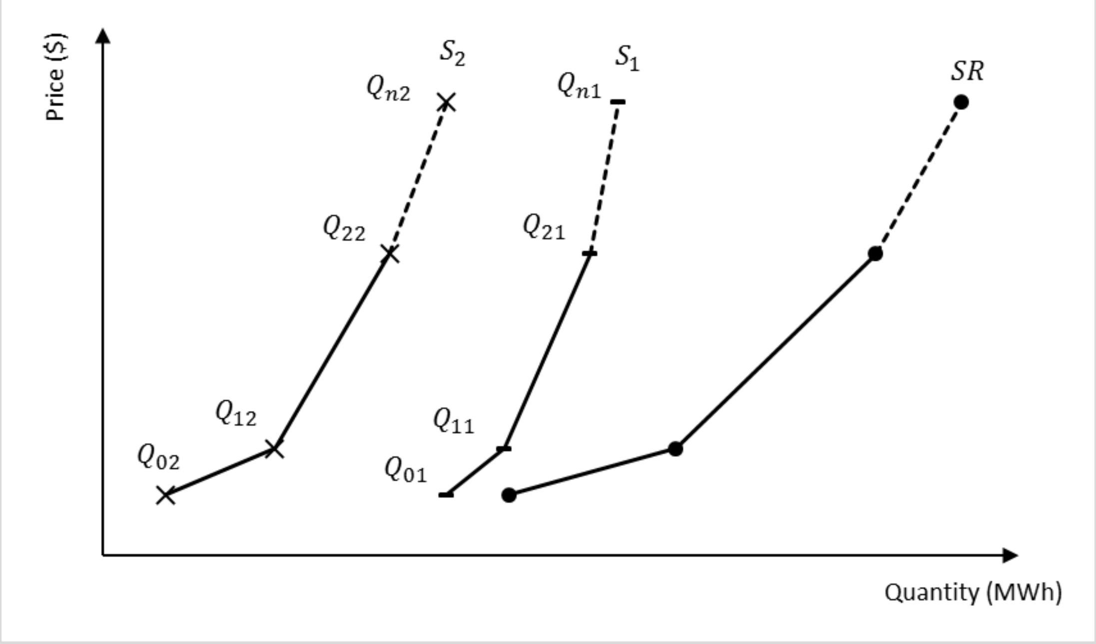
Extending this process to MEC_{nj}, e_{nj} and Q_{nj} the market supply curve "S_j" of the renewable technology "j" can be obtained. **Figure 4** illustrates the hypothetical result of this process.

Figure 4. Hypothetical market supply curve for technology "j" (S_j).



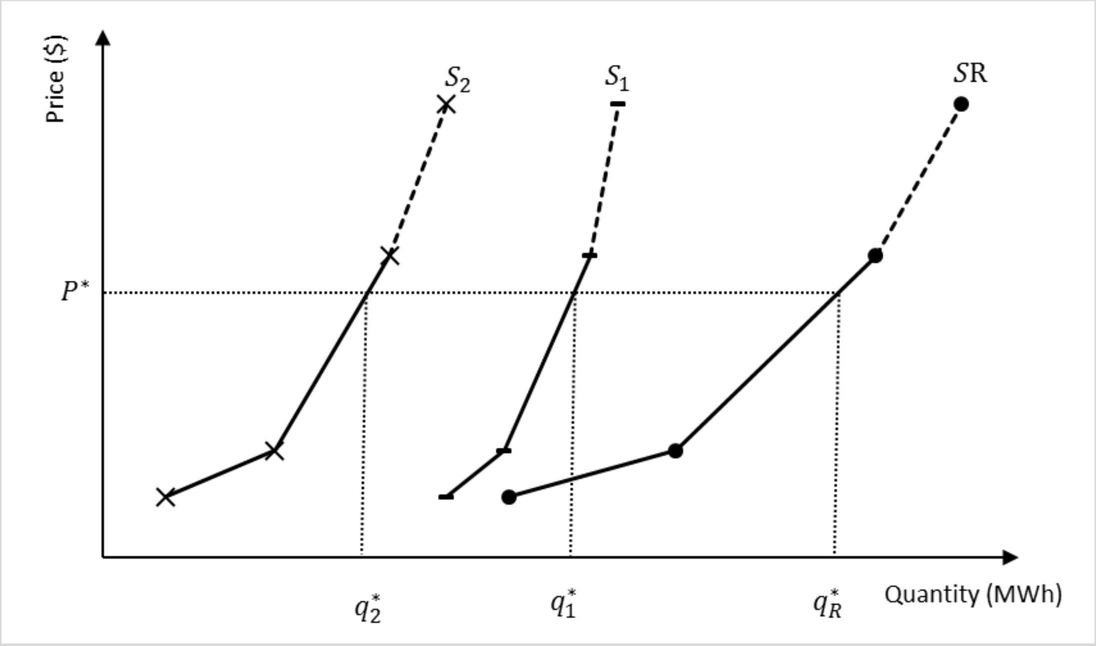
If we do the same for all the energy sources and technologies "j" we could obtain by addition of the individual Q_{ij} along their supply curves at the same price level, the market supply curve of renewables (SR) for the region under the energy selling prices defined by "i=0,1,2,3,...,n". **Figure 5**, shows this process considering the existence of only two technologies, "j=1" and "j=2" (say wind and solar photovoltaic).

Figure 5. Derivation of the market supply curve of renewables (SR) in the presence of two generation technologies.



The equilibrium composition of energy sources for the renewable part of the supply is now easy to obtain provided we have already derived a demand curve. **Figure 6**, shows this process considering the existence of two technologies ("j=1" and "j=2") and an equilibrium price P*.

Figure 6. Market allocation of renewable energy supply among technologies j=1 and j=2.



For a market equilibrium price P^*, quantities q_2^* and q_1^* would be produced by renewable sources j=1 and j=2, respectively, giving a total renewable supply of q_R^*.

When other components of the set of prices or the technology are varied (such as the conversion efficiency of the technology, investment cost, tax incentives, etc), the model can be used to predict the effect of support schemes, technological improvements, etc., over the quantity of renewable energy that should be provided by the market.

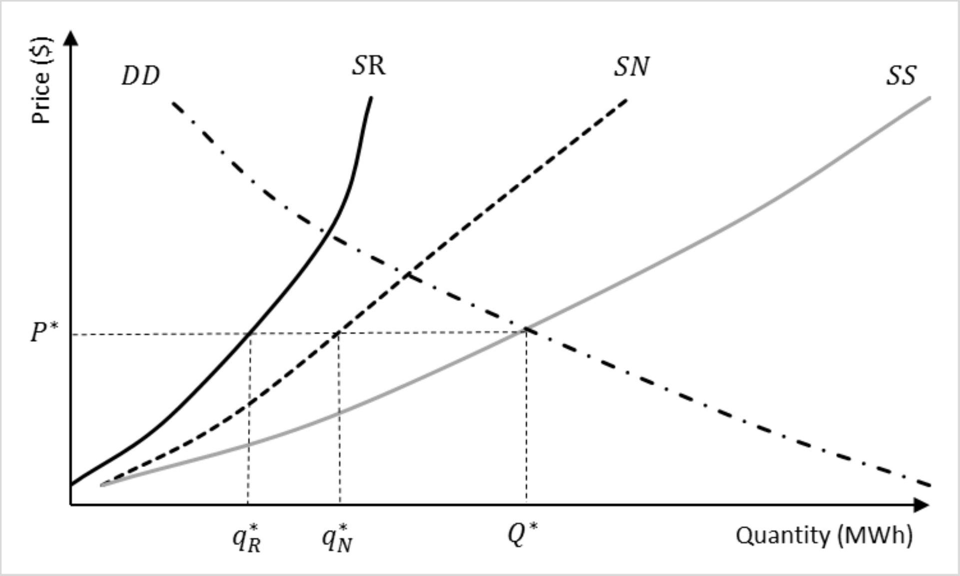
2.3 Allocation of renewable and non-renewable sources in the generation mix

As expected from the partial equilibrium model, the economically optimal supply of renewables is reached when it equals its equilibrium quantity (q_R^*), after attending for all the grid related, environmental, social and similar constraints. Economically suboptimal supply quantities of renewables are observed under and over q_R^*. The remaining portion of total demand (Q^*), should be supplied by non-renewables at their equilibrium quantity (q_N^*) such that for any given equilibrium price (P^*)

$$Q^* = q_R^* + q_N^* \qquad \textbf{Equation (5)}$$

Let DD be the aggregated demand for electricity, SR be the aggregated supply of renewables, SN be the aggregated supply of non-renewables and SS be the total supply, then **Figure 7** shows the supply-demand equilibrium quantities q_R^* and q_N^*.

Figure 7. Optimal allocation of supply sources.



Supply-side interventions to the market solution in favour of renewables generally fall in three categories; those that artificially displace SR to the right (i.e. investment or tax incentives, feed-in tariffs above the equilibrium price, energy transport incentives, etc.), those that artificially displace SN to the left (i.e. renewable energy obligations) and those that have both effects.

3. Case study

Rapa Nui (or Easter) Island is a Chilean territory located over 3,500 km away from the South American Continent. It has a population of approximately 6,000 people and a total area of roughly 16,000 hectares, around half of which is a National Park. Electricity demand growth is mainly driven by tourism. Generation and distribution of electricity is done by a state owned company that operates the approximately 40 km long grid including the only power plant in the island. This power plant consists of several reciprocating Diesel generating sets. The electricity company estimates that total generation in the Island is around 9.9 GWh per year (SASIPA, 2016). A high cost of electricity results from the inherent high cost of Diesel as a means of electricity generation[3] and from the need to transport it from continental Chile. This generating scheme is also associated with a high carbon footprint of the islanders and with a high dependence of the island from the Chilean state, which subsidises the price of electricity heavily.

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[3] Reciprocating Diesel generating sets operating in continental Chile, similar to those in Rapa Nui, have a variable cost of 148 to 160 US$*MWh^-1, as can be verified in Coordinador Eléctrico Nacional (2017). To estimate the total cost of electricity in the island, externalities and freight cost from Valparaíso port should be added.

Following the methodology proposed by Faúndez (2007), the isoprofits for wind energy in Rapa Nui were obtained for selling prices of electricity of 100, 125, 150 and 175 US$*MWh^-1 and 11% Marginal Efficiency of Capital (MEC). For this purpose a cash flow model that gave account of the economic performance of a 1.6 MW windfarm consisting of two Enercon E53 wind turbines was done. This small windfarm was supposed to use a site of 25 hectares of land and given the size, demand growth rate and infrastructure of the island, can be considered to be the Minimum Efficient Scale for the expansion of wind energy in the territory. Investment cost assumptions were as representative as possible of the investment costs that the wind farm would encounter if it were built today in Rapa Nui. The cash flow was set up in variable energy transport distance and wind climate regime. So, whenever the wind climate was varied the following changes took place in the cash flow: variation of sales of electricity according to the power curve of the wind turbines; variation of transmission losses and; variation of operation and maintenance costs. In the same fashion, whenever the energy transport distance was modified, the model took account of: the variation in the transmission line's investment cost; the variation in transmission losses according to the length of the conductor and; the variation in the transmission line's maintenance cost. The project's transmission line consisted of a 6.6 kV, three phase, single circuit copper conductor with a resistance of 0.2766 Ohm*km^-1. Energy transport distance was used as a proxy for the energy transport cost. **Figure 8** shows the isoprofits obtained.

In order to obtain for each isoprofit the Energy Density Functions as per **Equation 1**, it was necessary to make assumptions regarding energy transport distance and wind resource availability over the territory. Energy transport distance was assumed to be the Euclidian distance between the windfarm and the geometrical centre of gravity of the 6,600 to 220 V transformers located throughout the island's grid. Wind climate over the island was modelled from data obtained by the meteorological station at Mataveri Airport[4] using DTU's "Wind Atlas Analysis and Application Program" Version 10. The software was also fed with a digital terrain model of the island with height contour lines every 5 metres. The software was then set to calculate the shape and scale parameters of the Weibull's probability distribution of wind mean speed in a 500 by 500 metres square grid at 50 m above terrain level. A total of 640 grid elements fell on land, giving account of an area of 16,000 ha. **Figure 8** also characterises in terms of productivity and energy transport distance all the projects of 25 hectares and 1.6 MW possible to build in the island.

Figure 8. Isoprofits for Rapa Nui Island for various selling prices and 11% Marginal Efficiency of Capital (MEC) and projects possible to build.

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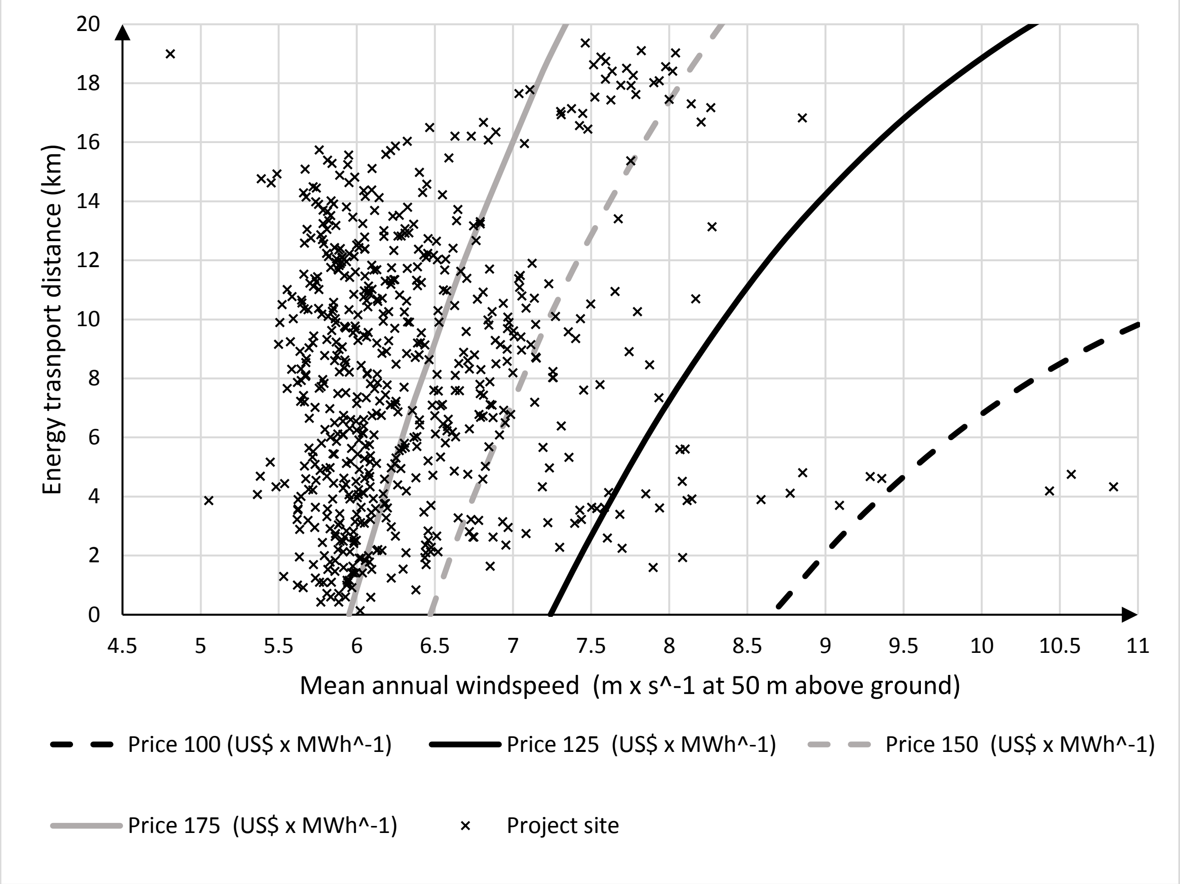
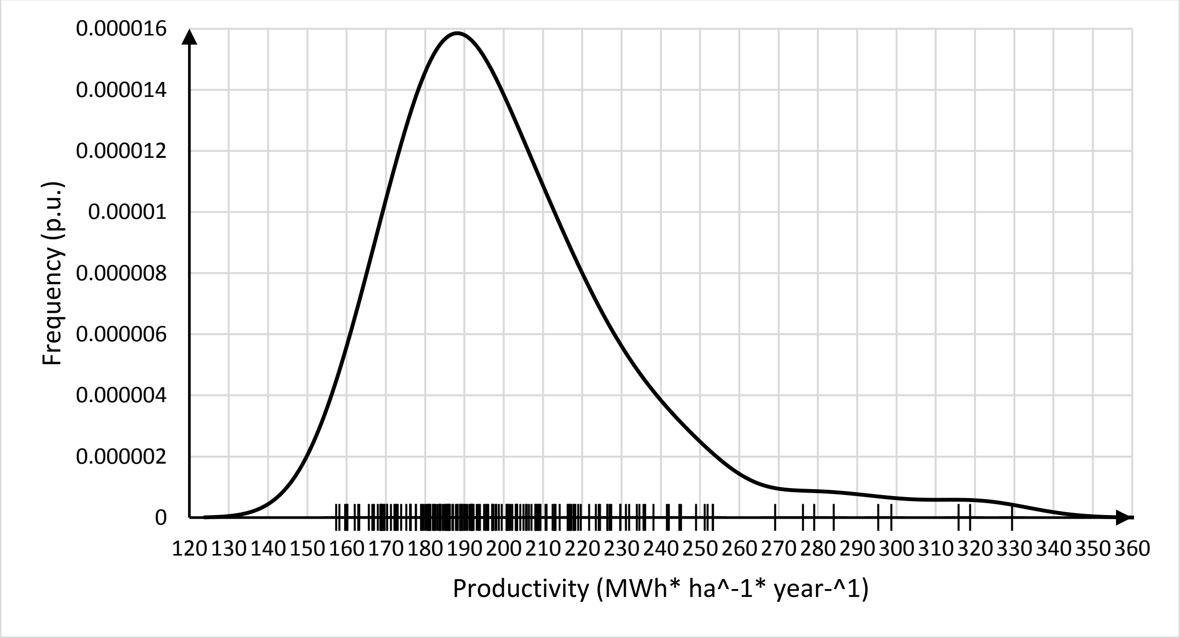
[4] This meteorological station does not comply with the standards accepted by the wind industry. A proper wind resource assessment should be carried out in order to improve the reliability of the wind climate simulation.



The probability density function of productivity over the territory "$f_{i,j}(p)$" was obtained for each isoprofit by a kernel density estimate using Royal Society of Chemistry's software "AMC Kernel Density" Version 1.0e for MS Excel. As an example, **Figure 9**, shows the rug plot of the productivities obtained from the wind climate simulation and the kernel density estimation of the Energy Density Function associated to the 175 US$ x MWh ^-1, 11% MEC isoprofit.

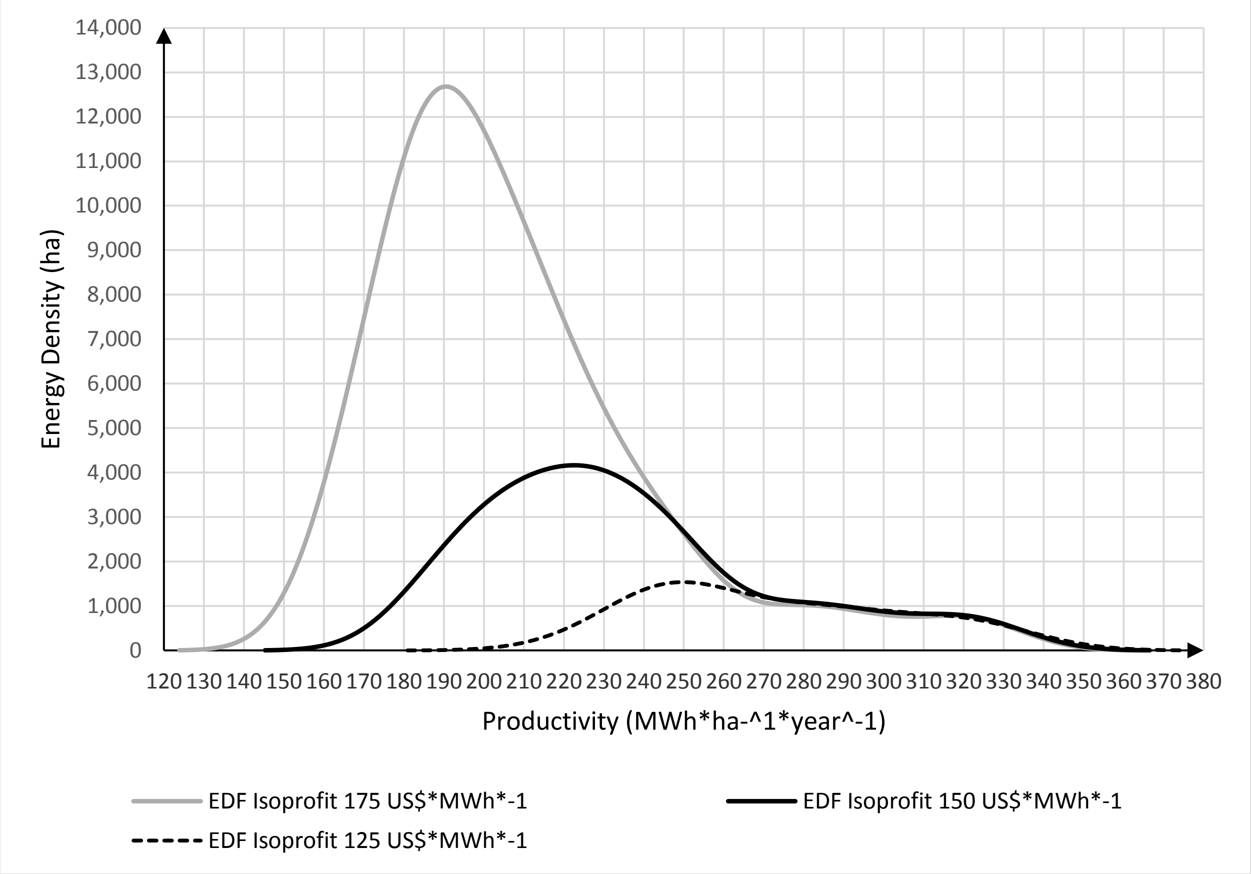
Figure 9. Productivities (crosses over the horizontal axis) and kernel density representation (line) of the probability density function "$f_{i,j}(p)$" associated to the 175 US$*MWh ^-1, 11% MEC isoprofit.



Total area to the right of isoprofit 175 US$*MWh^-1 resulted to be $A_{1,j} = 4{,}225\ ha$; total area to the right of isoprofit 150 US$*MWh^-1 resulted to be $A_{2,j} = 1{,}500\ ha$; total area to the right of isoprofit 125 US$*MWh^-1 resulted to be $A_{3,j} = 475\ ha$ and; total area to the right of isoprofit 100 US$*MWh^-1 resulted to be $A_{4,j} = 75\ ha$.

Figure 10, shows the Energy Density Functions (EDF) associated to the 125, 150 and 175 US$*MWh ^-1, 11% MEC isoprofits. The 100 US$*MWh ^-1 EDF is not shown because it requires a different scale to be seen appropriately.

Figure 10. Energy Density Functions (EDF) associated to the 125, 150 and 175 US$*MWh ^-1, 11% MEC isoprofits.



Integrating over the EDFs we obtain the energy quantities that producers should be willing to provide in Rapa Nui if their target Marginal Efficiency of Capital were 11% and the complete area of the island were available for developing projects. But roughly speaking, half the land in the territory is a National Park, and let us assume that only half of the remaining area is available for the development of windfarms due to other constraints[5]. Using these assumptions, **Table 1** shows the energy quantities that profit-seeking wind farm investors in Rapa Nui should be willing to produce at various energy selling prices in the constrained and unconstrained cases.

Table 1. Expected wind generation at various energy selling prices.

	Energy Production (MWh per year)	
Energy Selling Price (US$*MWh^-1)	Unconstrained	Constrained
100	24,103.1	6,025.8
125	127,736.0	31,934.0

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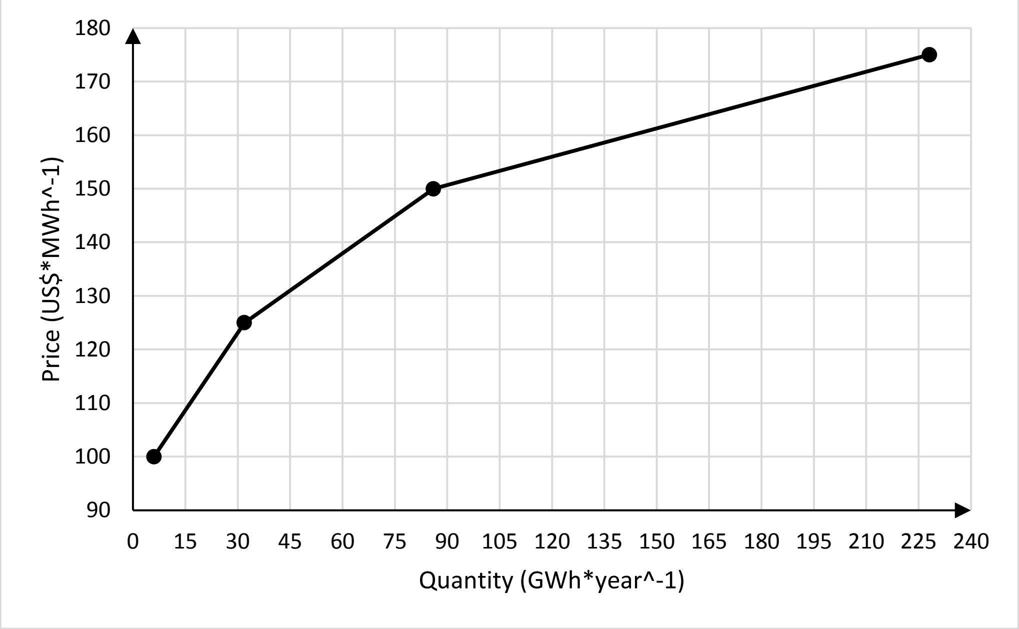
[5] Other constraints such as social, cultural, technical, environmental, economic, etc. Of course this a great simplification done for illustration purposes only. The proper use of the model requires overlapping a map of constrained areas with the wind resource and electric grid related layers of information.

150	344,497.6	86,124.4
175	912,666.5	228,166.6

Figure 11, shows the constrained market supply curve of wind energy predicted by the model in Rapa Nui Island.

Figure 11. Market supply curve of wind energy in Rapa Nui Island.



Suppose that in a particular moment in the future a market-based energy generation mix were in place in the island. Suppose also that the equilibrium price of electricity were 110 US$*MWh^-1. According to **Figure 11**, wind energy should account for approximately 15 GWh of the total supply each year. Let's assume that the people of Rapa Nui wanted to increase the share of wind generated electricity from 15 to 45 GWh per year. Then they should be ready to see an increase in the equilibrium price of electricity to approximately 130 US$*MWh^-1, or the local government should be ready to put a subsidy of 20 US$*MWh^-1. This is a basic supply analysis but there are other ways to apply the model in order to help to solve some of the difficult problems of renewable energy. For example we could be interested in knowing the effect on supply of technological improvements of wind turbines or incentives such as tax exemptions for windfarms, or energy transmission toll reductions. All these changes would be associated to supply curve shiftings, requiring the derivation of new isoprofit curves and EDFs.

4. Conclusions and discussion

The spatial structure arising from a particular energy resource distribution and the electricity consumption areas over a territory are represented in the supply curve of that energy resource. This representation is useful for evaluating energy policy interventions. It also helps the public to have clear expectations regarding the capacity and costs associated to low-CO2 generation technologies beyond the temporary equilibria of interests groups and the sometimes opposed opinions of successive governments.

As it can be seen from **Figure 10**, the larger the area $A_{i,j}$ under an EDF, the more it resembles a Normal distribution. It is my contention that under the normality assumption and for sufficiently large areas $A_{i,j}$, (such as complete countries) EDFs can be quickly estimated with enough accuracy as to yield supply curves that are useful for energy policy intervention evaluation. Such estimation could be done by similarity between sites based on site complexity (topography, surface roughness, temperature, altitude, etc.) and resource mean value (geostrophic wind or mean annual solar radiation), which are the defining elements of the expected value of productivity ($f_{i,j}(p) * p$) in Equation 1. For wind and solar resources, the high quality and quantity of information today available about their distribution over the Earth, guarantees this process to be possible. For other resources, such as dendroenergy, tidal or wave energy, more effort may be required in most countries in order to get reasonably accurate resource distribution patterns necessary to feed the model.

If there were no cost increases or technical restrictions associated to the operation of 100% wind isolated electrical systems, and considering that the assumptions contained in the isoprofits shown in **Figure 8** are correct, the energy demand in Rapa Nui (9.9 GWh per year) could be fulfilled at a price of under 110 US$*MWh^-1, as shown in **Figure 11**. As the present supply cost is at least 148 US$*MWh^-1 (see footnote N°3), it can be deduced that wind energy has ample space for development in the island, even without a support scheme.

From **Figure 11** it can also be deduced that the price elasticity of supply in the range from 6 to 30 GWh per year (which contains the present and near future electricity demand level in Rapa Nui), is quite encouraging as small increases in price have a rather large effect on supply. This characteristic of the territory promises a high efficiency of potential incentives that may be applied to favour the development of wind farms in the future.

It would be of interest to incorporate into the model the dynamic aspects of the supply-demand spatial phenomenon to deal for example with the change of shape, magnitude and location of consumption and with the growth of electricity transmission infrastructure.

It would also be of interest to apply the model to cases where energy transport cost is no longer spatial invariant and where transportation routes need not to be straight lines. This should shed light on the optimal expansion of transmission infrastructure.

To generalise the use of the model to obtain supply curves of non-energy resources that need to be harvested over large areas seems to be an interesting step forward.

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Highlights

- A method to derive supply curves of renewable resources is proposed.
- The method is territory-specific and produces long-run supply curves.
- It's suitable for resources that need to be harvested such as wind or solar energy.
- A case study of wind energy in Easter Island is presented.
- The use of the method for the evaluation and design of support schemes is shown.