Levelized Cost of Energy: a new estimation considering GHG emissions

Mario Villone

Universidad Nacional de Luján, Argentina

e-mail: mariovillone@gmail.com

Abstract

The aim of this paper is to enunciate a new way to estimate levelized cost of electric energy (LCOE), considering emission of greenhouse gases cost, by taking the theoretical cost of avoiding pollution as the emission cost. In this way, it would be comparable LCOE from different sources of electrical generation with different GHG emission, in addition, with this way to calculate it could be possible to determine more efficient Pigouvian taxes (knowing the full cost of avoiding emission) and it could be possible also to generate an Economic-Ecological optimization Models for the electrical generation.

Resumen

El objetivo de este trabajo es el de enunciar una nueva forma de estimar el costo nivelado de la energía eléctrica teniendo en cuenta el costo de las emisiones de Gases de efecto invernadero (GEI) tomando el costo teórico de evitar la polución como el costo de la emisión. De esta manera se harían comparables costos nivelados de energía provenientes de distintas fuentes de generación eléctrica con distintos niveles de emisión. Adicionalmente, con esta manera de calcularlo se haría posible determinar impuestos del tipo “pigouvianos” más eficientes ya que se conocería el costo completo de evitar las emisiones. Además, sería posible también generar un modelo de optimización económico – ecológico para la generación eléctrica.

Key words: Electricity, Levelized cost of energy, GHG, CCS.

JEL: Q49, Q52, Q54

1. Introduction[1]

One of the characteristics in modern societies is high energy consumption, and especially for electric energy. To produce electricity is necessary not only natural resources as energetics (uranium, wind, petroleum, etc.) but an atmospheric one also as a waste deposit (in such a case of electrical generation which emits Greenhouse gases -GHG)

When an environmentally responsible producer increases its private costs to reduce social cost of pollution, it exists an ecological dumping (Martínez Alier 2014 [2011]) between producers.

The situation would be in the following way: generator who has lower private costs, even thought, higher social costs, it could have a higher private rentability at the expense of higher social costs than its ecologically responsible competitor. Then, it is configured a private saving for producer against a damage for the whole society (Kapp 2000 [1968]).

It is possibly to find a similar case from theory of games, in the well-known case of "Tragedy of Commons" where it can be seen that by using a natural resource a producer who does not pay a cost for it, producer will tend to overuse it to maximize his private profit (Hardin 1968)(Don't matter if final profit is lower than it would potentially be). For a more stylized externalities game see Miklós-Thal and Shaffer (2017)

From previous situation, it can be deduced the need of assigning an economic (monetary) value to deteriorated natural resources. In the same line from accounting amortization used for capital goods (Richard 2012).

If emissions are not valued, there is no charge either to producer or consumer for their proportional responsibility in resource deterioration. Pigouvian tax rate (if it exists where power plant is allocated) could not be optimal, as it is mentioned in a Norwegian study based on a simulation model by Greaker and Midttømme (2016).

For the aim of this paper, interest is focused on a single emission: Greenhouse gases (GHG) emitted in electrical generation.

GHG are also expressed in the literature as carbon dioxide equivalent (CO2-E), this is so because CO2 is the most relevant GHG.

[1] I would like to thank two anonymous reviewers for their valuable constructive contributions.

Gases Considered in this paper are the six greenhouse gases contained in Kyoto Protocol (Naciones Unidas 1998): Carbon dioxide (CO2), methane (CH4), nitrogen oxide (N2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC) and Sulphur Hexafluoride (SF6).

There is a link between CO2-E and the economy, since its greatest generation is produced by human productive activity, it has an anthropogenic origin.

Energy sector generates 35% of anthropogenic GHG, resulting in a great contribution to global warming (Rubin, Davison and Herzog 2015).

Related to preceding statement, there is a high degree of agreement, with a high level of statistical confidence, with a future perspective of high growth (in order of 14.4 GTn-Giga tons- of CO2 by year in 2010, against a forecast of 24 to 33 GTn of CO2 by year in 2050, measured between the 25th and 75th percentiles) (Bruckner T. *et al* 2014, 418).

Fossil fuels are expected to be very important in electricity generation over the next years (IPCC 2005). Increasing global demand for electric energy makes it necessary to produce more and will bring consequently greater GHG emission22-12- (Ghobadi *et al* 2018).

2. CO2-E, climate change and market failures

In nineteenth century, as in subsequent years, economic science developments contemplated natural resources only in terms of productivity and optimal moments for extraction in terms of prices, costs and resource scarcity (Hotelling 1931), but not its environmental effects.

This paper considers that global warming effects due to anthropogenic causes are market failures. This is so, because goods in question (atmosphere and its regulatory effect) are public goods, using Samuelson criterion, which is that goods individual consumption does not generate subtraction to another people consumption for the same good (Samuelson 1954 and Hueting 1991). According to Godard classification (Godard 2004) these assets should be in a class of "Not exclusive-not Rival", I.e. A pure common good.

Face to impossibility to reverse immediately global warming effects, mitigation option is proposed. It consists in producing with a lower CO2-E emission level, to avoid reaching an atmospheric concentration such as it raises average global temperature by more than 1.5 °C (IPCC 2018).

For this, there are different tools proposed for different types of production. Since this paper focuses on emissions generated for electricity generation, only the carbon capture and storage option (CCS) will be enunciated.

Unlike most of agencies reports such as the IPCC, this paper proposal considers two different processes for capture and storage: industrial and forestry.

Only a synthesis of Capture and Storage of Carbon (CCS) methods will be summarized.

For more information on this topic see IPPC reports (IPCC 2014b and 2005), Rubin, Davison and Herzog (2015), Rubin *et al.*(2013) (especially for methodology) and reports of the Global CCS Institute (Global CCS Institude 2017 and 2013).

2.1. CCS

Industrial CCS consists in capturing CO2-E generated by industrial processes and storing it. For this purpose, there are different technologies, not all of them applicable to the same type of production.

Process consists in CO2-E separation, its capture and the storage during a long-term period (until losing its greenhouse-effect generation potential).

CO2-E is compressed and transported to underground deposits (geological formations), the ocean or for another industrial use (although it is the least used). Storage in geological deposits can be in oil and gas fields or underground saline formations. (IPCC 2005)

A capture plant can capture and store between 85% to 95% of emission, and It needs between 10% to 40% more energy than a generation plant which does not use the capture and storage system (IPCC 2005).

There are different types of capture systems: Afterburn, Combustion chamber and Oxyfuel Combustion. Concentration of CO2-E and pressure are fundamental factors. Together with the type of fuel (solid, gas) for choosing most efficient method (IPCC 2005).

Absorption capture process using solvents is the most mature and capable method for capture just to 90% of emissions (Nwaoha *at al.* 2018)

Transportation is essentially made by pipes in distances that can reach up to 1000 kilometers in most of cases with differences of pressure between the beginning and the end and in some cases needing for Intermediate compression (IPCC 2005).

Capture after burned in power generation plants is economically feasible only under specific conditions. Technology required for capture in pre-combustion is widely applied in fertilizer production (IPCC 2005).

For storage in geological formations underground or overseas, technology and knowledge that comes from oil and gas activity is already available.

Ocean storage can be done in two different ways: dissolving CO2 in water (below 1000 meters) via pipelines or ships or depositing via platforms (below 3000 meters). When CO2 is denser than water, it is expected to form "lakes" that would delay dissolution in the environment (the impact of this last process is under study) (IPCC 2005).

Without using CCS technology mitigation impact of CO2-E would be around 140% more expensive than with it (Hu and Zhai 2017). Thus, CCS systems are fundamental tools in mitigating (Rubin, Davison and Herzog 2015).

Impurities in CO2-E are an important factor in transportation cost (Porter *et al.* 2017). While CO2 concentration is very important to determine investment (the higher it is, the higher the investment) (Garðarsdóttir *et al.* 2018).

3. Proposal

3.1. First: Introduction

Two large capture and storage groups are considered here (as mentioned above), an industrial one, consisting in several options, called generically carbon capture and storage technologies (CCS), and another one called forestry group, considering the trees carbon absorption capacity according to Stavins and Richards (2005).

In this last case, as trees capture only CO2, and not the other greenhouse gases, by working with CO2-E concept, investment considered will be the necessary to capture a CO2-E level composed only of CO2.

3.2. Second: Levelized Cost of Energy

Levelized Cost of Energy, known by LCOE is a cost of the electricity generation that incorporates all expenditures in infrastructure and operation for a generation power plant throughout its economic cycle of life (including fuel cost), with an expected rate of return of capital normalized on total energy generated.

It could be redefined more briefly, as the present value of sum of discounted costs divided by the total production adjusted to the value of economic time (Rubin *et al.* 2013 and Global CCS Institute 2015)

LCOE most utilized formula is:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + C_t + F_t}{(1+i)^n}}{\sum_{t=1}^{n} \frac{KWh}{(1+i)^n}} \quad (1)$$

Where: I_t: Expenditure on investment in period t; C_t: Costs in the t period; F_t: Expenditure on fuels in period t; *i*: Interest rate; n: power plant economic life; KWH: Electricity generated in period t.

This formula only considers the measure of payments, i.e. it is a private measurement.

Current way of measuring LCOE cannot make any comparable measure from countries or regions with different regulations in taking measures against CO-E emissions (due to cost of avoiding).

LCOE cannot correctly compare generation cost between sources that are not ecologically equivalent (different CO2-E emission level) or sources with different variability in generation (coal, nuclear with wind or solar, for example) (Global CCS Institude 2017).

This paper only deals with the first class, the lack of comparability between generation sources with different degree of CO2-E emission.

3.3. Third: Formula Proposal

$$LCOE_{env.var} =$$

$$\frac{\sum_{t=0}^{n}\frac{I_t+C_t+F_t}{(1+i)^t}}{\sum_{t=0}^{n}\frac{kwh_t}{(1+i)^t}} + \min\left[\min\left(\min_\alpha\left(\frac{\sum_{t=0}^{n}\frac{Iccs_{t\alpha}+Cccs_{t\alpha}+Fccs_{t\alpha}}{(1+s)^t(1-find_\alpha)}}{\sum_{t=0}^{n}\frac{Kwh_t}{(1+i)^t}} + \frac{\sum_{l=1}^{lim}\frac{CAlmac_{l}\alpha}{(1+s)^l(1-find_\alpha)}}{\sum_{t=0}^{n}\frac{Kwh_t}{(1+i)^t}}\right);\ \min_\beta\left(\frac{\sum_{t=0}^{n}\frac{If_{t\beta}+Cf_{t\beta}+Ff_{t\beta}}{(1+s)^t\left(1-ffor_\beta\right)}}{\sum_{t=0}^{n}\frac{Kwh_t}{(1+i)^t}} +\right.\right.\right.$$

$$r=1\infty CResgforr\beta 1+sr1-ff\beta rt=0nKwht1+it;\min zCRefz \qquad (2)$$

with:

$$\int_0^t Cap\ \ e^{-st}\,dt \geq \int_0^t Emis\ \ e^{-st}dt \qquad (3)$$

Acronyms used:

LCOE $_{env.\ var}$: LCOE considering CO2-E emission

I_t: Investment at time *t*

C_t: Operating cost at time *t*

i: interest rate

F_t: Fuel cost at time *t*

$Iccs_{t\alpha}$: Investment in carbon capture and storage technology at time *t* and corresponding to α technology used

$Cccs_{t\alpha}$: Operating cost at time *t* for α technology

$Fccs_{t\alpha}$: Fuel cost at time *t* for using CCS system

Kwh_t: Kilowatt hour produced at time *t*

$Calmac_{l\alpha}$: Cost of carbon storage at *l* period for the α technology used

$Find_\alpha$: Industrial CCS correction factor for α technology

Lim : weighted average life time for CO2-E emission in power plant generation

If_β: Forest investment for carbon capture at time *t* for the β option

Cf_β: Operational costs for the maintenance of forest plantation for forestry CCS

Ff_β: fuel cost for maintenance of forest plantation at time *t* and for β forestry option

$ffor_\beta$: Forest correction factor for β alternative

s: Discount Social rate

$CResgfor_{r\beta}$: Forestry cost of maintenance for β option for time *r*

ffβr: Correction factor for Forestry maintenance for β option for time r

t= period of time

$Cref_z$: Reference cost for the *z* option

r: time for maintenance of forestry plantation

capt: CO2-E Capture (physical amount)

emis: CO2-E emission (physical amount)

Proposed formula for $LCOE_{env.var}$ is a levelized cost of electric energy considering carbon dioxide equivalent (CO2-E) emission.

$LCOE_{env.var}$ is composed of traditional formula of the levelized cost of energy (LCOE) and the theoretical costs of electricity generation with no CO2-Emmission.

Thus, to the already calculated LCOE, will be added the cheapest option for producer, which would have avoided emission, therefore, the addition to traditional formula is a theoretical cost of avoiding those emissions assigning investing (in a full sense, including operating costs) as the cost of emission.

3.3.1.Some considerations about the formula

Both terms represent levelized costs, i.e. assigned to Kwh produced and given the time value effect, temporal periods for both are different, this is because *n* represents operating period of the given power plant, while in storage case, time arrives up to the technical limit of weighted average life of greenhouse gases.

This is because of power plant life could reach (for example) to 40 years while the CO2-E has effects for many years, ranging from very short periods in some cases for the CO2 up to 50,000 years for the CF4 and with different intensity in greenhouse effect (IPCC 2014a, 124).

If CO2-E is issued to the atmosphere, assuming 100 years after the plant's closure, it would generate a greenhouse effect (with the corresponding contribution to the average global temperature rising), and all previous investment would only have served to defer greenhouse effect.

Interest rate used is not that of market, and in no way could it be in the case of storage, because the temporary limit considered exceeds in several generations the life of a potential investor (Krutilla 1967).

In addition, a concept called "industrial factor" is included. This term reference to a necessary correction factor, since the use of a capture and storage system involves the use of more energy (IPCC 2005, 28). Therefore, to be able to sell the same amount of energy as if industrial method of capture and storage should not be used, more electricity should be generated, and starting this process would directly and indirectly demands more CO2-E emissions.

So, to capture these new emissions would emerge a process like the previous one, although smaller, and then another and so on. Thus, an adjustment (or correction) factor is to consider in addition to all the emissions mentioned above.

As it proposed here, it is assumed a constant industrial factor, however, with statistical data, it could be used a non-constant non- linear factor according to real statistical distribution.

Finally, all these costs are assigned to electricity what power plant will produce in its useful life. In this paper, it is considered not only consistent with cost concept, but ethical also, because production is responsible for these emissions, thus, in electricity generation is where it should be reflected.

By using "minimum" function in the formula, producer will choose technology which minimizes the assignable portion to levelized cost, always considering the same technical efficiency.

For forestry is used an analogous to the "industrial factor" that is called in the present paper "forestry factor", and conceptually represents the same idea as the industrial one.

It is a correction factor, due to a new forest plantation capable of assimilating CO2-E would generate new emissions (for example, could be caused by : fuel of trucks and machinery, transport of people to carry out the work, etc.).

Also, in this case, expenditures that are to be paid during the project useful life those of maintaining forest plantation have been separated.

Here, the difference with industrial case is remarkable, since that what is absorbed by forestry in case of release to the atmosphere (by burning wood) would alter CO2-E concentration because of it is not affected by time. That is the reason by which temporal variable tends to infinity, since it does not matter when the wood is burnt, in this state, it does not lose its potential greenhouse effect.

There are also several forest options, called here with β, and the company will consider the cheaper one from all those which have the same efficiency degree.

Due to the scope of this work, it is not under consideration potential use of wood that does not involve its burning (such as uses in construction, furniture, etc.). This approach is called *Inside the Fence* (Global CCS Institute 2013).

At this point, the minimum cost of industrial options and the minimum cost of the forest options is already at the minimum.

3.3.2.Reference cost

$CRef_z$ (4)

For an electricity generator, fixed costs could become very expensive for investment in capture and storage, or for most of them, it could be technically impossible accessing to any of the industrial alternatives (for example, a solar, eolic or nuclear generator) or forestry alternative.

For this reason, minimum cost between industrial and forestry options is compared to a reference cost, which is a cost that other companies have taken or it is issued from internationally recognized agencies reports (as IPCC, Global CCS Institute, IEA, etc.).

Contemplating potentiall investments and costs in different places of the world do not affect the given treatment that in the formulae. As many types of pollution have primarily a local effect, but global warming from anthropogenic origin affects globally.

Producer who chooses a geographical location instead of another because of the economic cost (in investment, maintenance, fuel, etc.) does not make a difference in terms of environmental impact (related to global warming).

3.3.3. Condition

$$\int_0^t Cap \;\; e^{-st} dt \geq \int_0^t Emis \;\; e^{-st} dt \quad (3)$$

In CCS by industrial means, capture and emission process is simultaneous. However, in forest capture, there is a gap between both, it depends *grosso modo* on: electric energy produced on one hand and forested species, forestry management, decisions of pruning and investments over time on the other hand.

That is why condition proposed, although valid for both capture groups, becomes more relevant in forestry alternative.

Thus, the integral of emission and the integral of capture, both with respect to time represent volume emitted and captured respectively of CO2-E.

However, it could happen that even though the accumulated volumes are equal at a certain point of time, it could have been accumulated in a different relationship.

In that case, it would not be the same for society if capture was given towards the end of power plant life time, in that case, for many years the CO2-E contributed to greenhouse effect.

Whereas, in the other hand, it might be that capture is produced before emission time, in this case, the whole society has a benefit until emissions compensate.

Because of this, it is proposed to recognize the "time value of equivalent carbon dioxide", using the same social rate that was used for the entire analysis. As both are continuous variables, an instant social discount rate has been applied.

Although actualization methodology is the same as for the " time value of money", and although the concepts are linked, it should not be confused actualization of CO2-E which is a homogeneous measure of benefit to society with financial actualization.

Therefore, it is assigned a value associated with time (the closer, the greater) to each tonne of CO2-E either emitted or captured.

If net emission is greater than capture, the chosen model of capture is inefficient, so that, it could not be applied. Generator should choose a model that, at least, captures what it emits (in actual terms).

On the other hand, when it captures more than it emits (measured in actual terms), there would be a benefit for society, but this analysis is beyond the aim of this paper.

3.3.4.Considerations, assumptions and estimates

It is proposed here using original costs adjusted by inflation (deflation) effect, instead of adopting the replacement cost approach, an alternative that considers the cost of re-making at the time of measurement the necessary expenditures. Due to purpose of formula is to estimate the theoretical cost of generating electricity without emission, given the prevailing conditions at a certain time *t*.

Second alternative would have been more appropriate if comparing construction of new power plants, but this situation is not the case of this paper, this criterion is called *Retrofit Plant* (Global CCS Institute 2013).

3.3.5.Social discount rate

Social discount rate considered here is an unique rate for every time, as for example a Ramsey´s rate (Ramsey 1928), which is utilized also by the Stern Review (Stern 2007). However, it could be used, instead of it, a statistical distribution rate (Wagner and Weitzman 2018, Weitzman 2011 and 1998).

4. Examples of use

A power plant which captures all emissions, must have included in its LCOE the CCS cost, a power plant which might capture but doesn't it, must consider cost of theoretical CCS, a power plant which emits, but technically or economically might not capture, must consider either forest capture cost or reference cost, and at last, a plant which doesn't emits, it has already in its LCOE the full cost of production without GHG emission.

5. Conclusions

Using traditional way for LCOE measuring, generation alternatives are measured according to their private costs, thus the emission of CO2-E is without consideration.

By using this paper proposed formula, electricity generation LCOE would be increased due to CO2-E emissions (for those sources of generation that are emitters).

This increasing corresponds to expenditures (discounted at the social rate).

Since social rate is smaller than the rate used to discount all LCOE's values, it is concluded that discounted amount (cost) related to GHG emissions will be bigger than whether expenditures had been made and pollution avoided or at least reduced (see appendix).

Social cost for not reducing emissions by having a private saving is bigger than private cost of investing to avoid (or diminish) such emissions.

By using proposed formula, it is possible to compare costs from different generation alternatives with different emission levels related, which otherwise would not have been comparable.

Notwithstanding this article purpose is only the proposal for estimating LCOEvar.Amb, and not policies that should be followed by a company or a Country, it can be concluded that obtaining data by using LCOEvar.Amb should provide data for being able to set carbon emissions taxes which are neither low enough to not fit its purpose, nor too high to harm society consumption. And secondly, since new costs will be calculated, priorities for generation and investment incentives would change, for example, Carbon generation will not be as cheaper as it is now, and wind generation will remain the same (supposing no change in technology and costs) so, the difference between both of them will not be the same.

Appendix

Discounted values for the same nominal values using a social discount rate smaller than discount rate used for calculating LCOE are bigger than if the same nominal values would be discounted at LCOE discount rate.

$$\sum_{n=1}^{t} \frac{AE_n}{(1+i)^n} < \sum_{n=1}^{t} \frac{AE_n}{(1+s)^n} \quad , \forall i > s, \forall n, t > 0 \quad (4)$$

With n: period, t: life cycled (time), AEn: Avoiding CO2-E emissions expenditures at time n, i: discount rate used for LCOE calculation, s: social rate.

Summatory could be re-written as:

$$\frac{AE_1}{(1+i)^1} + \cdots + \frac{AE_t}{(1+i)^t} < \frac{AE_1}{(1+s)^1} + \cdots + \frac{AE_t}{(1+s)^t} \quad (5)$$

As i<s, so:

$\frac{AE_n}{(1+i)^n} < \frac{AE_n}{(1+s)^n}$ (6) as all values are positives values, so:

$(1+s)^n < (1+i)^n$ (7)

$s < i$ (8)

So, if AEdin = AEn discounted to i rate and AEdsn = AEn discounted to s rate:

$\mathrm{AEdi}_n < \mathrm{AEds}_n$ (9)

And, for any period there will be the same, so:

$AEdi_1 + \cdots + AEdi_t < AEds_1 + \cdots + AEds_t$ (10)

$\sum_{n=1}^{t} AEdi_n < \sum_{n=1}^{t} AEds_n$ (11)

$\sum_{n=1}^{t} \frac{AE_n}{(1+i)^n} < \sum_{n=1}^{t} \frac{AE_n}{(1+s)^n}$ (12)

Reference

Bruckner T., I., et al. "Energy Systems." In *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, by IPCC, 511-597. 2014.

Garðarsdóttir, Stefanía Ósk, Fredrik Normann, Ragnhild Skagestad, and Filip Johnsson. "Investment costs and CO2 reduction potential of carbon capture from industrial plants – A Swedish case study." *International Journal of Greenhouse Gas Control* (Elsevier) 76 (2018): 111-124.

Ghobadi, Jalal, David Ramírez, Shooka Khoramfar, Robert Jerman, Michele Crane, and Kenneth Hobbs. "Simultaneous absorption of carbon dioxide and nitrogen dioxide from simulated flue gas stream using gas-liquid membrane contacting system." *International Journal of Greenhouse Gas Control* (Elsevier) 77 (2018): 37-45.

Global CCS Institude. "Global Costs of Carbon and Storage 2017 update." 2017.

Global CCS Institute. "The costs of CCS and other low-carbon technologies in the united states." 2015.

Global CCS Institute. "Toward a Common Method of Cost Estimation for CO2 Capture and Storage at Fossil fuel Power Plants." Canberra, 2013.

Godard, Olivier. "La pensée économique face à la question de l'environnement." *CECO* (Ecole Polytechnique Centre National de la Recherche Scientifique), 2004.

Greaker, Mads, and Kristoffer Midttømme. "Network effects and environmental externalities: Do clean technologies suffer from excess inertia?" *Journal of Public Economics* (Elsevier) 143 (2016): 27-38.

Hardin, Garrett. "The tragedy of the Commons." *Science* 162 (1968): 1243-1248.

Hotelling, Harold. "The Economics of Exhaustible Resources." *Journal of Political Economy* (The University of Chicago Press) 39, no. 2 (1931): 137-175.

Hu, Bingyin, and Haibo Zhai. "The cost of carbon capture and storage for coal-fired power plants in China." *International Journal of Greenhouse Gas Control* (Elsevier), 2017: 23-13.

Hueting, Roefie. "The use of the discount rate in a cost-benefit analysis for different uses of a humid tropical." *Ecological Economics* (Elsevier), 1991: 43-57.

IPCC. "Cambio climático 2014: Informe de síntesis. Contribución de los Grupos de trabajo I, II y III al Quinto Informe de Evaluación del Grupo." Ginebra, 2014a.

IPCC. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. .* Cambridge University Press, 2014.

IPCC. *Global Warmin of 1.5° An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.* [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, MTignor, T. Waterfield (eds.)], 2018.

IPCC. *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)].* Cambridge University, 2005.

Kapp, William. *The social costs of business enterprise.* Nottingham: Russell House, 2000 [1968].

Krutilla, John V. "Conservation Reconsidered." *The American Economic Review* 57, no. 4 (Sept. 1967): 777-786.

Martínez Alier, Joan. *L´Ecologisme des pauvres.* Primera. Paris: Institut Veblen, 2014 [2011].

Miklós-Thal, Jeanine, and Greg Shaffer. "Private contracting with externalities: Divide and conquer?" *International Journal of Industrial Organization* 50 (2017): 460-472.

Naciones Unidas. "Protocolo de Kyoto sobrela convención marco de las Naciones Unidas sobre el cambio climático." 1998.

Nwaoha, Chikezie, David Smith, Raphael Idem, and Paitoon Tontiwachwuthikul. "Process simulation and parametric sensitivity study of CO2 capture from 115MW coal–fired power plant using MEA–DEA blend." *International Journal of Greenhouse Gas Control* (Elsevier) 76 (2018): 1-11.

Porter, Richard, Michael Fairweather, Clea Kolster, Niall Mac Dowell, Nilay Shah, and Robert Woolley. "Cost and performance of some carbon capture technology options for forproducing different quality CO2product streams." *International Journal of Greenhouse Gas Control* 57 (2017): 185-195.

Ramsey, F. "A Mathematical Theory of Saving." *The Economic Journal* 38, no. 152 (1928): 543-559.

Richard, Jacques. *La Comptabilté environemmental.* 2012.

Rubin, E, John Davison, and Howard Herzog. "The cost of CO2 capture and storage." *International Journal of Greenhouse Gas Control* (Elsevier) 40 (2015): 378-400.

Rubin, Edward, et al. "A proposed methodology for CO2 capture and storage cost estimates." *International Journal of Greenhouse Gas Control* (Elsevier) 17 (2013): 488-503.

Samuelson, Paul A. "The Pure Theory of public expenditure." *The review of Economics and Statistics* 36, no. 4 (1954): 387-389.

Stavins, Robin, and Kenneth Richards. "The Cost of U.S. forest-based carbon sequestration." Pew Center on global climate change, Arlington, 2005.

Stern, Nicholas. *The Economics of Climate Change: The Stern Review.* Cambridge: Cambridge University Press, 2007.

Wagner, Gernot, and Martin Weitzman. "Potentially large equilibrium climate sensitivity tail uncertainty." (Elsevier) 168 (2018): 144-146.

Weitzman, Martin. "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5, no. 2 (2011): 275-292.

Weitzman, Martin. "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate." *Journal of Environmental Economics and Management* , 1998: 201-208.