Abating CO2 emissions in the Greek energy and industry sectors

Halkos, George and Tzeremes, Nickolaos and Kourtzidis, Stavros

Department of Economics, University of Thessaly

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Abating CO_2 emissions in the Greek energy and industry sectors*

George E. Halkos, Nickolaos G. Tzeremes & Stavros A. Kourtzidis
Laboratory of Operations Research, Department of Economics,
University of Thessaly, Korai 43, 38333, Volos, Greece

Abstract
The purpose of this paper is to construct the abatement cost curve for the Greek Energy and Industry sectors. To achieve our goal we present and analyze the abatement options available in the sector of energy and in the industrial subsectors of petroleum and gas refinery, cement and iron and steel. Next, we estimate and present the costs and abatement potentials for each abatement option in each sector. We also present the cost-effective options for individual energy and industrial sources. Finally, the marginal abatement cost curve is constructed and the policy implications are discussed. Our analysis reveals a promising potential for pollution reduction and a wide range of cost-effective abatement options.

Keywords: Abatement cost curve; air pollution; energy and industry sectors.

JEL codes: Q42; Q52; Q53.

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ΕΥΔΕ-ΕΤΑΚ

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1. Introduction

Greenhouse gases[1] (hereafter GHG) emissions from human activities are the primary source of anthropogenic air pollution (pollution due to human activities) and their mitigation is at the center of environmental policies both at national and international level. Air pollution from GHG is of extreme importance due to the negative effects on the environment (the problem of climate change among others) and the high global warming potential[2]. The most important greenhouse gas is carbon dioxide which accounts for the 57% of the total greenhouse gases (IPCC 2007). Policy makers around the world wish to achieve the reduction of GHG in a cost-effective way.

The Kyoto protocol is the most important international attempt towards the reduction of GHG. It was adopted in 1997 and came into force in 2005 and currently has 192 signing parties. The target of the first commitment period (2008-2012) was a 5% reduction of GHG emissions compared to 1990 level and the target of the second commitment period (2013-2020) is to reduce GHG by 18% compared to 1990 levels which however have not yet been ratified by all countries[3]. Another important cross-national attempt towards the reduction of GHG emissions is the European climate and energy package known as "20-20-20" targets[4]. According to these targets countries are committed to reduce the total EU GHG emission by 20% in 2020 compared to 1990 levels[5]. The parties are also obliged to raise the share of renewable energy sources to 20% of the total EU energy consumption and to improve EU's energy

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[1] The term *greenhouse gases* refers to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and F-gases (HFCs, PFCs and SF_6) emissions.
[2] Global warming potential is an index measuring different GHGs emissions with different atmospheric lifetimes and different radiative properties (for more information see Halkos, 2014).
[3] More information can be found at: http://unfccc.int/kyoto_protocol/items/2830.php
[4] For more details see Halkos et al. (2014).
[5] More information can be found at: http://ec.europa.eu/clima/policies/package/index_en.htm

efficiency by 20%. The European Commission has also adopted a proposal which will be further discussed in 2015 about a 40% reduction of GHG emissions by 2030[6].

Policy makers require a number of environmental tools in order to plan effectively[7] their environmental strategies towards the aforementioned reductions. Marginal abatement cost (hereafter MAC) curves are important tools which illustrate the cost associated with carbon mitigation and contribute to the optimal pollution control levels (Beaumont and Tinch, 2004; McKintrick, 1999). Recently, MACs have been applied to estimate the impacts of environmental policies on the reduction of GHG emissions (Klepper and Petterson, 2006; Vijay et al., 2010). Therefore a marginal mitigation curve is an empirical tool which shed light to control policies and classify various abatement options based on their cost-effectiveness and their pollution abatement potential, in order to maximize the net social cost. The construction of MACs promotes environmental awareness and offers insights into the most cost-efficient measures to abate emissions (Beaumont and Tinch, 2004). Furthermore, MACs might provide valuable knowledge regarding the environmental abatement options and regulations in energy, industry and transport sectors (Kesicki, 2010).

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[6] More information can be found at: http://www.bloomberg.com/news/2014-01-22/eu-said-to-propose-40-greenhouse-gas-reduction-target-by-2030.html

[7] Economic interdependence and structure of the economy are important determinants in the effectiveness of adopted policies. Halkos and Tzeremes (2009a) investigated the effect of electricity generation on 42 World and East Asian countries' economic efficiency. Their findings reveal an inverted U-shape relationship between electricity generation and countries' economic efficiency with a much smaller turning point for the European countries compared to the East Asian countries due to the shift in energy use from electricity to other sources of energy. At the same time, Halkos and Tzeremes (2009b) examining the effects of the European Union enlargement estimated the economic efficiency of growth policies of the 25 member countries. Their findings show that the old 15 EU members have confronted with problems in reforming their economic policies to face EU’s enlargement which in turn had an impact on their economic efficiencies.

The purpose of this paper is to construct the abatement cost curve for the Energy and Industry sectors in Greece. In order to achieve our goal we present and analyze the abatement options under consideration in the energy sector as well as in the industrial subsectors of petroleum and gas refineries, cement and iron and steel. The structure of the paper is the following. Section 2 presents a brief review of the abatement costs curves literature and a presentation of the types of control cost curves. Section 3 analyzes the abatement options available for each sector. Section 4 presents the costs and potentials for every abatement option both at sector and at plant levels. In section 5 the abatement cost curve for the Greek energy and industry sectors is extracted and the policy implications are discussed. The last section concludes the paper.

2. Literature review

2.1 The concept of marginal abatement cost curves

Marginal abatement cost (hereafter MAC) curves are a popular tool for assessing abatement options because they approach the complex issue of cost-effective options in a simple and straightforward manner. MAC curves demonstrate graphically the cost-effective way to reduce pollutant's emissions (in our case carbon dioxide). Specifically, they contrast the marginal abatement cost (€/tCO_2 equivalent) on the y axis for varying amounts of emission reductions (thousand tCO_2 equivalent). These emission reductions are compared relative to the business as usual economic activity where no CO_2 reduction policies are implemented. A negative abatement cost may be due to market imperfections and proposed control methods have to be confronted with the existing ones in the business as usual economic activity.

The popularity of MAC curves concept is based on its simplicity as it can yield the marginal abatement cost for any given amount of pollution reduction. In addition, we can set a desired amount of emissions to be abated and calculate the total abatement cost required for this reduction. A MAC curve can also yield the average abatement costs. However, the concept of a MAC curve has a number of drawbacks (Elkins et al., 2011). At first, the curve is a snapshot and it is limited only at a point of time. Furthermore, the curve offers no path dependency or technological structure for the abatement options as the decision maker can apply any option in order to achieve a desired emission reduction. In addition, uncertainty is an important issue for MAC curves which becomes more significant as the time horizon widens e.g. 2050. Finally, the reduction of emissions might probably yield a number of additional benefits which are not included in the curve such as health benefits. Various alternative models have been proposed across the literature, which aim to solve some of the aforementioned drawbacks, such as the model proposed by Ward (2014).

MAC curves have been widely used across the literature. Halkos (1993) investigated the transboundary problem of acid rain and sulphur dioxide emissions and relied on MAC curves in order to evaluate and classify the abatement options for sulphur dioxide reductions in all European countries. In addition, the author examined whether economic instruments work better than regulations. The results indicated significant differences in favor of economic instruments. The author has marked the significance of international cooperation towards the joint reduction of emissions. Halkos (1994) examined the abatement technologies for sulphur emissions regarding the minimization of abatement cost under different policy scenarios. The results indicated significant emissions reductions if countries cooperate instead of acting independently.

Halsnaes et al. (1994) constructed MAC curves for ten countries for short and long term targets for the needs of the UNEP Greenhouse Gas Abatement Costing Project. The objective of the Project was to perform studies at a country level and to provide a unified framework for countries which have signed the United Nation's Framework Convention on Climate Change in 1994. Soloveitchik et al. (2002) studied the electricity sector of Israel for the time period 2003-2013. The authors presented MAC curves in order to address emissions mitigation problems and to assist the decision maker to set the optimal taxation.

Baker et al. (2008) investigated how technical change via innovation affects the marginal abatement cost and emissions mitigation and they employed MAC curves in their analysis. Kuik et al. (2009) conducted a meta-analysis of GHG mitigation studies and found abatement costs are sensitive to many factors such as business as usual emissions, a number of model assumptions and control variables. They constructed long-run MAC curves and found that strict long term targets set by the European Commission appear to be highly uncertain. Park and Lim (2009) presented a MAC curve for the electricity sector in Korea in order to evaluate alternative mitigation options. They have provided insights which are able to assist power plants to harmonize with the imposed regulations. Recent studies by Garg et al. (2014) and Vogt-Schilb et al. (2014) constructed MAC curves for India and Brazil respectively.

2.2 Types of MAC curves

Marginal abatement cost curves might adopt various shapes and forms as a result of differences among countries/regions, sectors, time, etc (Kesicki, 2010). Kesicki (2011) classify MAC curves into two general types, expert-based and model-derived MAC curves. Expert-based MAC curves are developed based on assumptions made by experts and they present detailed technological options. Each bar of this stepwise curve represents solely one technological option (Halkos, 1992, 1995a, 2010). The width of the bar represents the abatement potential of this abatement option and the height of the bar represents the cost for each year, relative to the business as usual economic activity. The width of all bars together reveals the total abatement potential. Furthermore, the left side of the curve demonstrates the cheapest abatement options and as we move to the right side the costs increase rapidly (Halkos, 1995b).

Among the advantages of this type of MAC curve is the easy understanding, the simple representation of technological options and the ability to account for marker distortions. On the other hand, the principal disadvantage is the simplification of the assumptions. Furthermore, other drawbacks of expert-based MAC curves are the inability to account for any possible interactions among the abatement options or for any other interactions, time uncertainty and inconsistency of business as usual emissions (Kesicki 2011).

Recently McKinsey & Company brought expert-based MAC curves back into the attention of policy makers by publishing MAC curves for a number of countries[8] and also published a global MAC curve regarding energy, industry, transport, residential, agricultural, wastes and forestry sectors (Naucler and Enkvist, 2009). McKinsey & Company (2012) published a MAC curve for Greece regarding three sectors in detail (energy, residential and transport) and two more sectors (industry and agriculture). The report indicated that the energy sector is the primary source of possible emissions reductions accounting for 40% of possible emissions reduction while industry accounts only for 10%. In 2020, the average abatement cost for energy

[8] Marginal abatement cost curves and the corresponding reports can be found at: http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves

sector will be 31€/ t CO_2 equivalent and the contribution of the sector into the overall abatement potential will be 55%. On the other hand industry's average abatement cost will be -38€/ t CO_2 equivalent and the contribution of the sector into the overall abatement potential will be 13%.

The government and scientific communities in the United Kingdom have also adopted the concept of expert-based MAC curve. Atomic Energy Authority (2008) published a report for Ecofys and Committee on Climate Change with MAC curves for industrial, domestic and non-domestic sectors. The Stationery Office (2008) has issued a report regarding UK's emission targets towards 2050, the mitigation choices between CO_2 and other GHG emissions and other guidelines regarding the optimal abatement strategy. They include expert-based MAC curves in their analysis for energy, residential, non-domestic buildings, industrial and transport sectors.

The UK's Department of Energy & Climate Change (2009a, b) constructed MAC curves for the entire UK economy including domestic, non-domestic, transport, industry, agriculture and wastes sectors. The target of the reports is to assess the mitigation policies under the EU Emissions Trading System (ETS) and those which are not included in the ETS and to propose the optimal mitigation strategy for the United Kingdom. Johnson et al. (2009) constructed expert-based MAC curves for Mexico including agriculture and forestry, oil and gas, energy end-use, transport and electricity sectors. O'Brien et al. (2014) also used an expert-based MAC curve in order to evaluate abatement options for GHG emissions in Irish agricultural sector.

The second type of MAC curve, the model-derived MAC curve, relies on calculating the abatement costs and potentials via energy models. Model-derived MAC curves avoid a number of drawbacks of expert-based curves, such as the interactions between abatement options, model uncertainty and the incorporation of additional benefits (Kesicki, 2011). On the other hand, this type of MAC curve does not offer any insights on technological abatement options and cannot handle negative costs. Kesicki and Strachan (2011) present two types of model-derived MAC curves, those which are based on partial equilibrium bottom-up models which consider one sector, and top-down models such as the computable general equilibrium (CGE) models accounting for the entire economy. Regarding the strengths and drawbacks of each model, bottom-up models offer the ability for a detailed presentation and in-depth analysis of the energy sector; however all other sectors are not included in the analysis. Furthermore, bottom-up models are susceptible to small changes in costs and they tend to underestimate abatement costs (Edenhofer et al., 2006). Top-down models offer no technological details and no in-depth sectoral analysis; however they incorporate macroeconomic effects from the whole economy.

Beaumont and Tinch (2004) investigated whether environmental regulation on industrial wastes can result in improvement for both industrial activity and the environment. The authors used a bottom-up approach and constructed MAC curves for copper pollution in Humber Estuary, UK. Criqui et al. (2006) used the bottom-up AGRIPOL model to evaluate the mitigation options for GHG emissions and created MAC curves for the agricultural sector. Simoes et al. (2008) used TIMES_PT which is a bottom-up model to create MAC curves and study the CO_2 emissions in Portuguese energy sector. Delarue et al. (2010) used a simulation bottom-up model in order to study the electricity sector in Europe. In addition the authors constructed a 3D abatement curve where they included gas to coal price ratio in order to capture more complex interactions. Kiuila and Rutherford (2013a) proposed a methodology about a piecewise smoothing approximation for bottom-up MAC curves. The methodology could be introduced to any sector with decreasing returns to scale technologies.

Rasmussen (2001) constructed a multi-sector MAC curve for Denmark using a top-down general equilibrium model in order to study the effects of learning-by-doing in renewable energy. Sands (2004) applied the Second Generation Model which is a top-down collection of CGE models and constructed MAC curves over time for GHG emissions abatement. Klepper and Peterson (2006) used the top-down CGE model DART and studied how the MAC curves in a country level are affected by global abatement efforts and energy prices. The findings indicate that global actions affect national MAC curves.

Bernard et al. (2006) investigated the global economy using a top-down CGE model for different regions in multiple countries. The authors found that the incorporation of more GHGs than just CO_2 in the analysis results in a cost reduction in long term. Bohringer et al. (2009) applied the CGE PACE model to examine the impact of EU climate policies on international trade and the use of energy. Dellink et al. (2004) integrated a bottom-up and a top-down approach in a dynamic CGE framework. Kiuila and Rutherford (2013b) also deal with the incorporation of bottom-up approach inside the top-down framework. The above approaches aim to tackle the entire economy (top-down model) and to benefit from the detailed information for the sector (bottom-up).

3. Abatement options for energy and industry sectors

3.1. Energy sector

The last decades the Greek national energy policy target is the relevant independence of the country from petroleum. In that manner, other energy sources have been exploited such as lignite and hydro energy and others have been imported such as natural gas. Petroleum remains the largest source regarding the total primary energy supply, followed by other fossil fuels like lignite and natural gas. Lignite (with the associated environmental problems) is the primary energy source for electricity in Greece.

Next we present five abatement options for the Greek energy sector followed by a number of abatement options available in the industrial sector and in the subsectors of petroleum and gas – downstream refining, cement and iron and steel.

3.1.1. Wind Power

Wind power refers to the power which comes from the wind. Wind turbines, windmills and wind pumps are used to convert wind into energy such as electrical or mechanical power. In order to produce a considerable amount of energy, large wind farms are needed which consist of hundreds of wind turbines. When these constructions are onshore, the cost is very low and in most cases it is considerable cheaper than fossil fuels. On the other hand, when the farms are offshore, the cost of construction and maintenance is significantly higher; however the construction is better and more efficient. Wind is plenty in Greece and wind power is a good alternative option. Furthermore, it is a clean energy and produces no greenhouse gases. The average efficiency wind power is 35% (EURELECTRIC, 2003).

In this abatement option we assume that ten wind parks which have already been announced or are in the process of planning, will be constructed. These parks are located in Karditsa, Lefkada, Rethymno, Andros, Tinos, Kefallonia, Samos, Mykonos, Pella and Sifnos. The total installed capacity of these ten wind parks is 94.4 MW[9]. The capital cost of these plants in average is 2500 €/kWe and the fixed operating and

[9] http://www.ppcr.gr/Home.aspx?C=2

maintenance cost is 90 €/kWe (IPA, 2010). Two years[10] are needed for the parks to be constructed while the amortization period is five years (Karagiorgas et al., 2010).

3.1.2. Solar Photovoltaic

A Photovoltaic system uses the sun as a source of power in order to produce electric power. Photovoltaic cells are made usually from silicon. When the sun is shining the light hits on the cells and an electric field is created. On hotter and more shinny days more electricity is produced, however electricity is still produced on cloudy days. The efficiency of a photovoltaic panel is at 27%[11]. A photovoltaic module is a connected assembly of about 40 solar cells ad a solar panel or solar array is consists of multiple photovoltaic modules. The use of photovoltaic systems offers multiple advantages. Sunlight is free and as a result, after the initial capital cost, the operational cost for electricity will be significantly reduced. In addition, solar energy is a renewable energy source and does not release any greenhouse gases.

Solar energy is another abundant energy source in Greece. This abatement option assumes that five photovoltaic parks which have already been announced or are in the process of planning will be constructed. The locations of these parks are in Agrinio, Megalopoli, Ptolemaida, Athina and Thessaloniki with total installed capacity at 260.84 MWh[12]. The capital cost of a photovoltaic park is at 4500 €/kWe and the fixed operating and maintenance cost is at 30 €/kWe (IPA, 2010). Two years are needed for the parks to be constructed (PPC, 2012) while the amortization period is seven years (Karagiorgas et al., 2010).

[10] http://www.ppcr.gr/Home.aspx?C=2
[11] http://www.cres.gr/kape/index.htm
[12] http://www.ppcr.gr/Home.aspx?C=2

3.1.3. Geothermal energy

Geothermal energy is produced and stored inside the earth. The sources of thermal energy are primarily the decay of uranium and potassium (80%) and also the formation of the earth (20%). Beneath the surface of the earth there is the magma layer which is a very hot mixture of molten and semi-molten rocks, volatiles and solids. Most of the decay of radioactive materials takes place here. When the crust of the earth is very thin, the heat can come up to the surface. These places are seismically active and as a result earthquakes can break the rocks on the surface, letting hot water out. These areas are called hot springs. This is the natural expression of geothermal energy.

However, geothermal energy can be found everywhere. Geothermal power plants can exploit the geothermal energy almost anywhere in the world using hydrothermal convection. The geothermal plant sends cool water into the earth where it is heated and then rises up to the surface. The heated water produces steam which powers the electrical generators. The average efficiency of a geothermal power plant is 55% (Karagiorgas et al., 2010).

Greece meets the geological standards in order to produce geothermal energy in large scale. Geothermal energy is currently used in Greece for residential, industrial and agricultural use. This abatement option assumes that four geothermal plants which have already been announced or are in the process of planning will be constructed. The locations of these power plants are in Kimolos, Lesvos, Nisyros and Methana with total installed capacity at 23 MWh[13]. The capital cost of a geothermal power plant is at 2600 €/kWe and the fixed operating and maintenance cost is at 110

[13] http://www.ppcr.gr/Home.aspx?C=2

€/kWe (IPA, 2010). Three years are needed for the plants to be constructed (PPC, 2012) while the amortization period is five years (Karagiorgas et al., 2010).

3.1.4. Biomass

Biomass is a carbon neutral source of energy and it is created from organic waste which comes from living or recently living organisms which can be either plants or animals. Biomass can be directly used for energy purposes or it can be used to produce biofuels. The biomass coming from plants is called lignocellulosic biomass and currently its largest source is wood such as forest debris. The biomass power plants burn the organic waste in order to produce steam which drives a turbine to produce electricity and heat. The average efficiency of a geothermal power plant is 34% (Karagiorgas et al., 2010).

There are various types of biomass plants which use alternative sources to produce biomass such as wood (bark, brash, logs, sawdust, wood chips, wood pellets and briquettes), energy crops (miscanthus, switchgrass, reed canary grass, rye, giant reed, hemp, poplar, willow, eucalyptus, nothofagus, sycamore, ash, sugar crops, starch crops, oil crops, microalgae, macroalgae, pond and lake weeds, etc), agricultural residues (straw, corn stover, poultry litter, animal slurry, grass silage, dying biomass material), food waste and industrial waste and co-products (untreated wood, treated wood and residues, wood composites and laminates, paper pulp and wastes, textiles and sewage sludge)[14].

Greece has abundance of raw materials for the production of biomass and an agricultural sector which accounts for 5.2% of GDP which is significantly above the average of the European Union (1.8%). Furthermore, the country is obliged to replace 10% of the conventional fuels with biofuels by 2020. This abatement option assumes

[14] http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17304&_dad=portal&_schema=PORTAL

that a biomass power plant in Kozani which has already been announced will be constructed with total installed capacity at 25 MWh[15]. The capital cost of a biomass power plant is at 2000 €/kWe and the fixed operating and maintenance cost is at 50 €/kWe (IPA, 2010). Four years are needed for the plants to be constructed (PPC, 2012) while the amortization period is three years (Karagiorgas et al., 2010).

3.1.5. Small-hydro

Small hydro refers to plants which generate hydroelectric power in order to power an industrial plant or a small community. By definition, a small hydro plant has a generation capacity up to 10 MW. Hydroelectric power uses the movement of water (falling or flowing) in order to produce electricity. The power plant needs a reasonable flow and a height in order the water to fall. Then the water flows or falls inside a pipe and drives a turbine which generates the electrical power. A common place for a small hydro is an existing or a newly developed dam. The most challenging aspect of small hydro power plants is their high average efficiency (90%) (Karagiorgas et al., 2010). Small hydro offers a number of advantages such as it does not pollute the environment and does not rise the water temperature. Also, their construction usually benefits other activities such as pumping, fishing and leisure.

The geographical and geological shape of Greece fosters the development of small hydro power plants under certain circumstances and planning. This abatement option assumes that eight small hydro power plants which have already been announced or are in the process of planning will be constructed. The locations of these power plants are in Alatopetra Grevena, Ilariona Kozani, Kalamata, Ladona, Makrohori, Mesohora Trikala, Pournari and Smokovo with total installed capacity at

[15] http://www.ppcr.gr/Home.aspx?C=2

24.62 MWh[16]. The capital cost of a small hydro power plant is at 3000 €/kWe and the fixed operating and maintenance cost is at 50 €/kWe (IPA, 2010). Three years are needed for the plants to be constructed (PPC, 2009) while the amortization period is five years (Karagiorgas et al., 2010).

3.2. Industry sector

Here we consider three of the most polluting industrial subsectors: petroleum and gas – downstream refining, cement and iron and steel.

3.2.1. Petroleum and Gas – Downstream Refining

The downstream sector commonly refers to the refining of petroleum crude oil and the processing and purifying of raw natural gas, as well as the marketing and distribution of products derived from crude oil and natural gas. The Greek market consists of two companies, namely Hellenic Petroleum and Motor Oil Hellas. Hellenic Petroleum operates three refineries in Aspopyrgos, Thessaloniki and Elefsina and Motor Oil Hellas operates one refinery in Agioi Theodoroi. The total installed capacity of these four refineries is 726.96 MW and the annual load factor is 79.4% (Ministry of Development, 2008).

The available abatement methods in this subsector follow.

3.2.1.1. Energy efficiency from behavioral changes

This option assumes the implementation of energy conservation awareness programs such as energy and GHG awareness of personnel, a management system which includes monitoring and an energy management which focuses on all processes. The average efficiency of behavioural changes is assumed at 100% and we assume that there are no losses due to human factor. The capital cost and the fixed

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[16] http://www.ppcr.gr/Home.aspx?C=2

operating and maintenance cost is 0 €/kW (McKinsey& Company , 2009). We assume that behavioral changes are applied immediately.

3.2.1.2. Energy efficiency from improved maintenance and process control

This option assumes additional and/or improved maintenance which ensures optimal condition for the equipment. In addition, improved process control is assumed which reduces suboptimal performance. The average efficiency of improved maintenance and process control is assumed at 100% and we assume that there are no losses due to human factor. The capital cost is at 1.65 €/kW and the fixed operating and maintenance cost is at 0.25 €/kW (McKinsey & Company, 2009). We assume that improved maintenance and process control is applied immediately while the amortization period is assumed to be one year.

3.2.1.3. Energy efficiency requiring capital expenses at process unit level

This abatement option assumes replacements, upgrades and additions which do not alter the process flow of a refinery. Also, it assumes replacement of boilers, heaters, turbines and motors and waste heat recovery through heat integration. The average efficiency of energy efficiency changes which require capital expenses at process unit level is assumed at 100% and we assume that there are no losses due to human factor. The capital cost is at 82.51 €/kW and the fixed operating and maintenance cost is at 4.13 €/kW (McKinsey & Company, 2009). We assume that changes are applied immediately while the amortization period is assumed to be one year.

3.2.1.4. Carbon capture and storage

It is applied to the exhaust emissions coming from the direct energy use in the downstream refineries and at the emissions which are coming from the hydrogen generation unit. Carbon capture and storage (CCS) captures CO_2 which otherwise would have been emitted to the environment. The captured CO_2 is then transported to a storage site and is disposed back to the environment but in a way which it cannot enter the atmosphere (e.g. underground). It is a method to decrease carbon dioxide emissions, global warming and ocean acidification. The average efficiency of carbon capture and storage is at 72% (McKinsey & Company, 2009). The capital cost is at 3.16 €/kW and the fixed operating and maintenance cost is at 0.137 €/kW[17]. Nine years are needed for the plants to be constructed[18] while the amortization period is assumed to be one year.

3.2.2. Cement

Cement sector is one of the leaders in Greek industry. Three companies operate in this sector. Namely, Heracles GCC of Lafarge Group with cement plants in Volos and Milaki[19] and a total installed capacity of 6.7 million tons[20], TITAN with cement plants at Thessaloniki, Drepano, Kamari and Elefsina and a total installed capacity of 7,04 million tons[21] and Halyps Cement of Italcementi Group with a total installed capacity of 1 millions tons[22]. The total installed capacity of the sector is 14.74 million tons of cement. The annual load factor is estimated at 39.8% with an annual production of 5.86 million tons[23].

The available control methods in this subsector are presented next.

[17] Calculated relying on McKinsey (2009) data.
[18] http://www.iea.org/publications/freepublications/publication/CCS_roadmap_foldout.pdf
[19] The company has a third plant in Halkida with installed capacity at 2.9 million tons which was recently closed.
[20] http://www.lava.gr/en/whoweare/
[21] http://www.cemnet.com/GCR/country/Greece
[22] http://www.sepan.gr/index.php/el/xalyps
[23] http://www.kathimerini.gr/30873/article/oikonomia/epixeirhseis/hellastat-ypoxwrhsh-ths-paragwghs-skyrodematos

3.2.2.1. Clinker replacement with fly ash and slag

This option assumes the reduction of clinker component in cement by substitution with fly ash or slag. Clinkers are formed by heating cement elements in a kiln. Limestone, clay, bauxite and iron ore sand in specific proportions are heated in a rotating kiln until they begin to form clinkers. Fly ash is one of the two by-products burning coal. When coal is burned it produces coal ash which is a non-combustible byproduct. Two types of coal ash are produced: bottom ash which is collected at the bottom of coal furnaces and fly ash which is collected at the smokestacks. Slag is a byproduct of iron production. During the iron blast furnace, slag and iron both are collected at the bottom of the furnace in molten form and are separated from each other. The molten slag is drenched with water until it turns into a raw material called granules, which then are cooled and dried in order to be ready for cement use.

The substitution of clinker with other elements such as fly ash and slag helps towards the reduction of process and fuel combustion emissions and also the reduction of electric power used for clinker production. These emissions account for the 90% of total emissions in the cement industry. Max replacement of clinker with fly ash is 25% and with slag is 40% (McKinsey & Company, 2009). Based on max replacement the total installed capacity for fly ash is calculated at 3.685 million tones and for slag is calculated at 5.896 million tones. The average efficiency of clinker replacement with fly ash is at 80% (Tsakalakis, 2010) and with slag is at 95%[24]. Fuel calorific value for the abatement option of fly ash is 25.3 GJ/tonne (coal burning) and for the abatement option of slag is 29.5 GJ/tonne (coke burning). The capital cost is at 5 €/tonne for fly ash and at 145 €/tonne for slag (McKinsey & Company, 2009). The fixed operating and maintenance cost is at 17.5 €/tonne for fly ash and 21.5 €/tonne

[24] http://en.wikipedia.org/wiki/Ground_granulated_blast-furnace_slag

for slag (McKinsey & Company, 2009). We assume one year for both replacements to fully take place and an amortization period of one year.

3.2.2.2. Increased share of waste or biomass as kiln fuel

This option assumes the substitution of fossil fuels in the cement kiln with alternative fuels (municipal and industrial fossil waste or biomass). This will reduce the average fuel combustion emissions of the clinker making process. It is assumed that CO_2 from biomass is climate-neutral. The real reductions of CO_2 emissions at the alternative waste-disposal operations are attributed to the cement sector and sufficient amount of biomass and waste are available to substitute fossil fuels. The average efficiency of increased share of waste as kiln fuel is at 21%[25] and of increased share of biomass as kiln fuel is at 34% (Karagiorgas, 2010).

Fuel calorific value for the abatement option of waste as fuel is 21 GJ/tonne (Tsakalakis, 2010) and for the abatement option of biomass as fuel is 16 GJ/tonne[26]. The capital cost is at 200 €/tonne for both abatement options (McKinsey & Company, 2009). The fixed operating and maintenance cost is at 12 €/tonne for waste as fuel and 27 €/tonne for biomass as fuel (McKinsey & Company, 2009). For the increased share of waste as fuel we assume one year for the abatement option to fully take place and an amortization period of one year. For increased share of biomass as fuel four years are needed for biomass plants to be constructed (PPC, 2012) while the amortization period is three years (Karagiorgas et al., 2010).

[25] http://en.wikipedia.org/wiki/Waste-to-energy
[26] http://www.omafra.gov.on.ca/english/index.html

3.2.3. Iron and Steel

Since 1937, iron and steel sector is also one of the leaders in the Greek industry. After 2000 the sector experienced a rapid growth, however the last couple of years it has been highly affected by the global financial crisis. The three major companies of iron and steel industry are Hellenic Halyvourgia, Sidenor S.A. and Hellenic Steel[27] with total installed capacity at 4,445 million tones. Specifically, Hellenic Halyvoyrgia operates two plants in Volos and Velestino[28] with total installed capacity of 1.3 million tons[29]. Sidenor S.A. operates two plants in Thessaloniki and Almyros with total installed capacity of 2 million tons[30]. Hellenic Steel operates one plant in Thessaloniki with installed capacity of 1,145 million tons[31]. A distinctive mark of the financial crisis is the low annual load factor which is only 5.6%[32].

The available mitigation options in this subsector are discussed next.

3.2.3.1. Co-generation

The Blast furnace (BF) and Basic Oxygen furnace (BOF) in steel manufacturing process generate waste gas as a by-product. This abatement option recovers the gas and cleans it and then uses it for power generation. Co-generation is assumed to be a thermodynamically efficient use of fuel because instead of disposing the waste heat which is produced in the process, it employs it in a good use. This option is integrated into the furnaces and helps towards the reduction of the total energy demand. All energy plants which use BF and BOF can be generated internally without the need of an outside generation at all. The average efficiency of co-

[27] Halivourgiki is another major company which however it is not operating for the last year and it is not included in our analysis.
[28] Aspropyrgos plant with installed capacity of 0,4 million tons was closed.
[29] http://www.hlv.gr/company-facilities-en.html/
[30] http://www.sidenor.gr/PlainText.aspx?MenuTxtId=20&lang=GR/
[31] https://www.steelbb.com/?PageID=157&article_id=84264/
[32] http://www.greenpeace.org/greece/el/blog/blog_dimitris_ibrahim/blog/48287/

generation is at 80%[33]. Fuel calorific value for the co-generation due to burning of natural gas is 38.1 GJ/tonne[34]. The capital cost is at 70 €/tonne and the fixed operating and maintenance cost is at 0 €/tonne (McKinsey & Company, 2009). We assume that co-generation is applied after one year while the amortization period is four years[35].

3.2.3.2. Direct casting

Current techniques in steel casting favor the continuous casting into slabs, billets and blooms. After the casting and during the rolling, they need to be reheated in order to take the final shape. This abatement option integrates the casting and hot rolling into one step and reduces the heat needed. In addition, it incorporates two newly developed direct casting techniques, namely the net-shape casting and the strip casting. The only drawback is that it can only be applied to new-builds. The average efficiency of direct casting is at 90%[36]. The capital cost is at 80 €/tonne and the fixed operating and maintenance cost is at 0 €/tonne (McKinsey & Company, 2009). We assume that direct casting is applied after one year and the amortization period is three years.

3.2.3.3. Smelt reduction

As smelting reduction abatement option we can group a set of ironmaking processes which aim to surpass certain fundamental problems of the currently in-use blast furnace route. Such problems are the dependence on large scale operation, reliance on coking coal and environmental pollution. Specifically, this abatement option combines upstream hot metal production processes into one step and therefore it completely avoids the coking process. The result is less fuel used and less

[33] http://en.wikipedia.org/wiki/Cogeneration
[34] http://setis.ec.europa.eu/technologies/Cogeneration-of-heat/info
[35] http://www.cumminspower.com/www/literature/technicalpapers/PT-7018-EvaluatingCogen-en.pdf
[36] http://climatetechwiki.org/technology/direct-casting

emissions. The average efficiency of smelt reduction is at 29%[37]. The capital cost is at 100 €/tonne and the fixed operating and maintenance cost is at 0 €/tonne (McKinsey , 2009). Smelt reduction needs up to ten years[38] in order to be available in Greece (currently it is available only in developing countries) and the amortization period is four years.

4. Cost analysis

In order to find the least cost of each potential technology we use the cost function given by: [39]

$$L = \frac{\sum_{t=1}^{N} \frac{C_t + FOM_t + VOM_t + F_t}{(1+r)^{t-1}}}{\sum_{t=1}^{N} \frac{P_t}{(1+r)^{t-1}}} \quad (1)$$

Where C_t represents the annual Capital cost; FOM_t and VOM_t the annual Fixed and Variable Operating and Maintenance cost respectively; F_t stands for the annual Fuel cost; P_t represents the amount of energy produced from the candidate power technology in year t; **r** represents the discount rate; **N** represents the number of years.[40]

In these lines we present in Tables 1-4 the least cost options and the abatement potentials for each abatement technology option. We used the abatement potential from McKinsey & Company (2009). Table 1 shows the least costs for the energy sector.

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[37] http://climatetechwiki.org/technology/smelt-reduction
[38] http://climatetechwiki.org/technology/smelt-reduction/
[39] We acknowledge the help of the member of our research team Chris Tziourtzioumis for discussions and advice on the least cost calculations.
[40] A number of other cost functions are used in the calculation of the least cost of each potential technology like annual energy production, annual capital cost, annual fixed and variable operating and maintenance costs and the annual fuel cost. For simplicity these cost functions are not presented here.

Table 1: Least cost options and abatement potentials for Energy sector

Abatement options	Least cost options (million €)	Abatement potentials
Wind power	39.12	7.9%
Solar photovoltaic	49.18	10.5%
Geothermal energy	44.66	5.25%
Biomass	356.85	11.2%
Small-hydro	39.52	4.5%

Table 2 shows that energy efficiency from behavioural changes is the least cost option with abatement potential up to 2.75%. On the other hand carbon capture and storage abatement technology option has an abatement potential up to 40%.

Table 2: Least cost options and abatement potentials for petroleum downstream refining subsector

Abatement options	Least cost option (million €)	Abatement potential
Energy efficiency from behavioral changes	0	2.75%
Energy efficiency from improved maintenance and process control	319.49	4.25%
Energy efficiency requiring Capital expenses at process unit level	831.229	4.2%
Carbon capture and storage	43.451	40%

Table 3 shows that clinker replacement with slag is the least cost option with abatement potential up to 50%.

Table 3: Least cost options and abatement potentials for cement subsector

Abatement options	Least cost option (million €)	Abatement potential[41]
Clinker replacement with fly ash	241.29	50%
Clinker replacement with slag	223.02	50%
Increased share of waste as kiln fuel	765.60	27%
Increased share of biomass as kiln fuel	710.17	27%

Table 4 demonstrates that energy efficiency improvements is the least cost option with abatement potential up to 32%.

[41] The abatement potential for clinker replacement with fly ash and with slag and the abatement potential for increased share of waste and biomass as kiln fuel are all in average values.

Table 4: Least cost options and abatement potentials for iron and Steel subsector

Abatement options	Least cost option (million €)	Abatement potential
Energy efficiency improvements	1.91	32%
Co-generation	34.40	21%
Direct casting	4.49	3%
Smelt reduction	10.45	12%

Next, we will focus our analysis at a plant level. Table 5 presents a brief overview for the energy sector concerning the existing thermal plants in Greece. Specifically we present the number of units for each plant, the fuels used and the installed capacity (in MW) (YPEKA, 2013)[42]. Table 6 presents the cost-effectiveness of the conversion to RES.

Table 5: Existing thermal power plants in Greece

Power plant	Region	Number of units	Fuel used	Installed Capacity (MW)
Agios Georgios	Attica	2	NG	360
Agios Dimitrios	W. Macedonia	5	Lignite	1595
Aliveri	C. Greece	4	Mazut	380
Amynteo	W. Macedonia	2	Lignite	600
Kardia	W. Macedonia	4	Lignite	1250
Lavrio	Attica	5	NG-Mazut	1572
Liptol	W. Macedonia	2	Lignite	43
Megalopoli	Peloponnese	4	Lignite	850
Ptolemaida	W. Macedonia	4	Lignite	620
Linoperamata	Crete	12	Diesel-Mazut	192.87
Florina	W. Macedonia	1	Lignite	330
Komotini	Thrace	1	NG	485
Rhodes	Dodekanisa	10	Diesel-Mazut	206.11

Table 6: Cost effectiveness for thermal power plants

	Cost effectiveness (€/ t CO_2 equivalent)				
Power plant	**Small-hydro**	**Solar Photovoltaic**	**Geothermal**	**Biomass**	**Wind**
Agios Georgios	650.96	818.40	657.60	5938.16	743.15
Agios Dimitrios	1035.85	1302.28	1046.41	9449.14	1182.55
Aliveri	2920.30	3671.43	2950.07	26639.27	3333.87
Amynteo	1024.67	1288.22	1035.11	9347.11	1169.78
Kardia	1047.95	1317.50	1058.64	9559.55	1196.36
Lavrio	3020.21	3797.04	3050.99	27550.61	3447.92
Liptol	991.37	1246.36	1001.47	9043.33	1131.76
Megalopoli	1031.41	1296.70	1041.92	9408.61	1177.47
Ptolemaida	1021.01	1283.62	1031.41	9313.73	1165.60
Linoperamata	2964.41	3726.89	2994.63	27041.66	3384.23
Florina	1014.42	1275.34	1024.76	9253.64	1158.08
Komotini	648.21	814.94	654.82	5913.06	740.01
Rhodes	3167.91	3982.73	3200.20	28898.00	3616.54

[42] http://www.dei.gr/el/i-dei/i-etairia/tomeis-drastiriotitas/paragwgi/analutikos-xartis-stathmwn

Next, in a similar way, tables 7-12 present the information for petroleum refineries, cement and iron and steel plants.

Table 7: Installed capacity and pollutants for petroleum refineries

Company	Refinery	Region	Installed Capacity (MW)
Hellenic Petroleum	Aspropyrgos	Attica	239.38
	Thessaloniki	C. Macedonia	132.96
	Elefsina	Attica	177.31
Motor Oil Hellas	Agioi Theodoroi	Peloponnese	177.31

Table 8: Installed capacity and pollutants for cement plants

Company	Plant	Region	Installed Capacity (thousands tons of cement)
Heracles GCC (Lafarge Group)	Volos	Magnesia	4500
	Milaki (Evia)	C. Greece	2200
TITAN	Elefsina	Attica	140
	Thessaloniki	C. Macedonia	2000
	Drepano (Ahaia)	Peloponnese	2000
	Kamari	C. Greece	2900
Halyps Cement (Italcementi Group)	Aspropyrgos	Attica	1000

Table 9: Installed capacity and pollutants for iron and steel plants

Company	Plant	Region	Installed Capacity (thousands tons of cement)
Hellenic Halyvourgia	Velestinos	Magnesia	700
	Volos	Magnesia	600
Sidenor S.A.	Thessaloniki	C. Macedonia	800
	Almyros	Magnesia	1200
Hellenic Steel	Thessaloniki	C. Macedonia	1145

Table 10: Abatement costs for petroleum refineries

	Abatement cost (thousand €)			
Refinery	Energy efficiency from behavioural changes	Energy efficiency from improved maintenance and process control	Energy efficiency requiring Capital expenses at process unit level	Carbon capture and storage
Aspropyrgos	0	10521.19	273726.19	14308.82
Thessaloniki	0	5843.59	152030.72	7947.29
Elefsina	0	7792.77	202741.93	10598.17
Agioi Theodoroi	0	7792.77	202741.93	10598.17

Table 11: Abatement costs for cement plants

	Abatement cost (thousand €)			
Plant	Replacement of clinker with fly ash	Replacement of clinker with slag	Increased share of waste as fuel	Increased share of biomass as fuel
Volos	73.67	68.09	233.73	216.81
Milaki (Evia)	36.01	33.29	114.27	106.00
Elefsina	2.29	21.18	7.27	6.75
Thessaloniki	32.74	30.26	103.88	96.36
Drepano (Ahaia)	32.74	30.26	103.88	96.36
Kamari	47.47	43.88	150.63	139.72
Aspropyrgos	16.37	15.13	51.94	48.18

Table 12: Abatement costs for iron and steel plants

	Abatement cost (thousand €)			
Plant	Improvements in energy efficiency	Co-generation	Direct casting	Smelt reduction
Velestinos	0.30	5.42	0.71	1.65
Volos	0.26	4.64	0.61	1.41
Thessaloniki	0.34	6.19	0.81	1.88
Almyros	0.52	9.29	1.21	2.82
Thessaloniki	0.49	8.86	1.16	2.69

5. Marginal Abatement cost curves and policy implications

Following Kesicki (2011) mitigation policies can be divided into two categories: incentive and non-incentive based instruments. On the one hand, incentive based instruments create motives for the emitters to reduce their emissions. They are preferred relative to non-incentive instruments because they do not enforce a solution; on the contrary they motivate towards a lower level of emissions and let the market choose the optimal solution. Incentive based instruments might take two forms: price-based instruments such as taxes and quantity-based instruments such as tradable permits. Both of these instruments set a limit for the emissions and it is assumed that up to this point all the available abatement options will take place.

Specifically, taxation on emissions incentivizes an emitting firm to internalize the cost of its emissions. The firm who wishes to maximize its profits will control the emissions through mitigation policy up to the point which it costs less than the imposed tax. A cap and trade system creates a market for emission permits which are tradable. These permits define the amount of emissions which any source is able to emit. Emissions above this point or without any permit are charged with large fines. The total amount of permits inside a market defines the optimal level of emissions.

Non-incentive based instruments are considered less efficient than incentive based instruments because they are less flexible and they do not let the market to choose the optimal solution. However, they are considered as necessary in the presence of market imperfections. Non-incentive based instruments can be divided into two categories: command and control policies and research and development and deployment policies (Keisicki 2011). Command and control policies are enforced through regulation and they cannot be ignored by any party. They are useful in case of market failures such as imperfect information and they can be enforced at the first part of the MAC curve, the negative part.

As mentioned previously, negative costs for abatement options imply that these options have to be confronted with the existing methods in the business as usual economic activities. This market failure can be easily tackled with command and control policies. Command and control policies among others might take the form of standards, voluntary agreements and subsides. Conversely research and development policies are useful for the last (steep) part of the MAC curve where the marginal abatement cost is very high. The target is to promote innovation through academic and non-academic research and projects. Deployment policies are also useful for the last part of the MAC curve and they may be formed by fiscal or non-fiscal policies.

Following Kesicki (2011) the first part of MAC curve, where negative marginal abatement costs are present due to market imperfections, command and control policies are the best available option. The second part of the MAC curve where the marginal abatement cost is positive the optimal policies are price or quantity market-based instruments such as taxes and tradable permits. The last part of the MAC curve where marginal abatement costs are very high demands research and development or deployment policies.

Next in Figure 1 we present the MAC curve for the energy and industry sectors. The business as usual economic activity is the standard activity which is presently in action, for example the energy sector to continue with its present form which is based primarily to lignite. At the first part of the MAC curve, the negative part, there are five abatement options, namely small-hydro, behavioral changes in petroleum refineries, direct casting, smelt reduction and co-generation for iron and steel. Specifically, small-hydro offers the ability to abate 1494 thousand t CO_2 equivalent for a marginal abatement cost of -19.93 euro/tCO_2 equivalent.

Furthermore, behavioral changes abatement option in petroleum refineries offers the opportunity to abate up to 1498.76 thousand t CO_2 equivalent for a marginal abatement cost of -0.51 €/ t CO_2 equivalent. Direct casting abatement options for iron and steel can abate up to 1503.21 thousand t CO_2 equivalent for a marginal abatement cost of -0.48 €/ t CO_2 equivalent. Smelt reduction abatement option for iron and steel can abate up to 1520.99 thousand t CO_2 equivalent for a marginal abatement cost of -0.41 €/ t CO_2 equivalent. Co-generation abatement option for iron and steel offers the opportunity to abate up to 1552.12 thousand t CO_2 equivalent for a marginal abatement cost of -0.18 €/ t CO_2 equivalent.

Regarding the above analysis this might be a result of market imperfection such as split incentives, imperfect information or other barriers. The optimal strategy for this abatement option is to impose command and control policies in order to build more small-hydro plants. Innes and Bial (2002) found evidence that support setting environmental standards as a better option than market-based instruments such as taxes. In addition, Requate and Unold (2003) compared a number of alternative climate change policies and found that in some cases command and control policies, and specifically imposing standards, appear to perform better than other instruments. Bauman et al. (2008) found evidence that command and control policies work better than market-based instruments for the case of Korean energy sector.

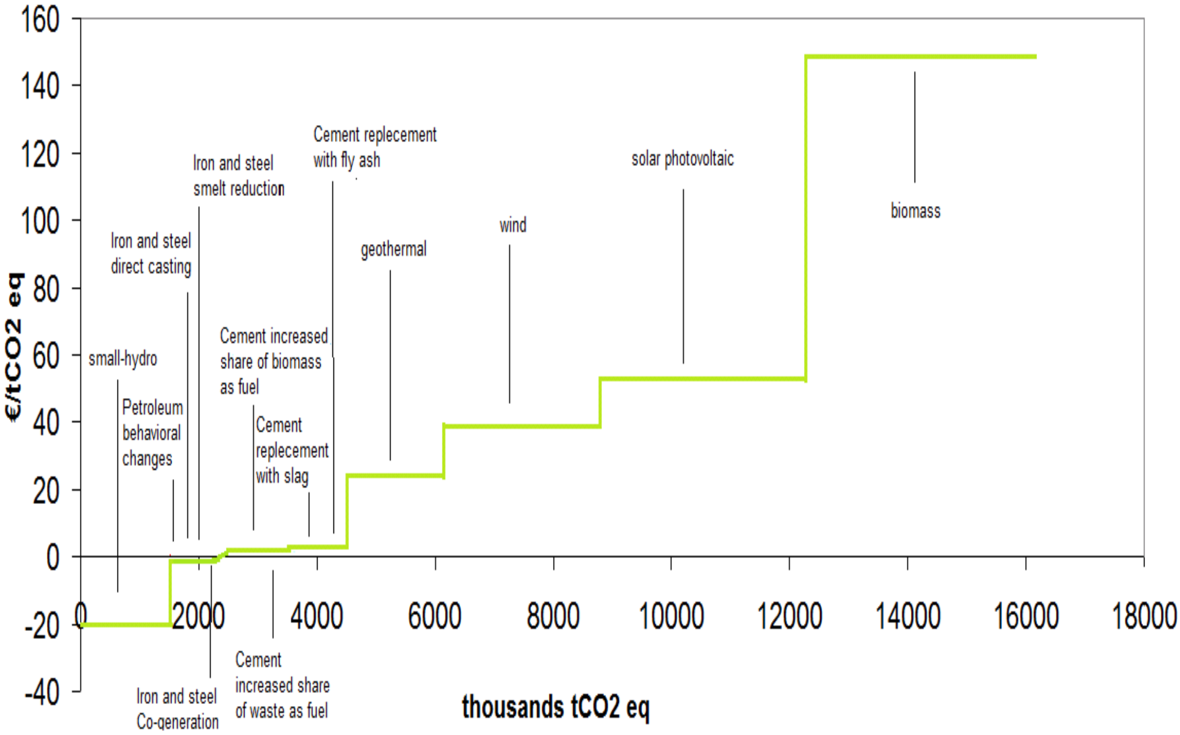
Furthermore, seven abatement options which appear to be at the second part of the MAC curve where market-based policies are the optimal strategy. Specifically, increased share of biomass as a fuel at cement plants offers the opportunity to abate up to 2035.96 thousand t CO_2 equivalent for a marginal abatement cost of 0.22 €/ t CO_2 equivalent. Increased share of wastes as a fuel at cement plants can abate up to 2519.80 thousand t CO_2 equivalent for a marginal abatement cost of 0.65 €/ t CO_2 equivalent. Clinker replacement with slag at cement plants can abate up to 3415.80 thousand tCO_2 equivalent for a marginal abatement cost of 0.77 €/ t CO_2 equivalent. Clinker replacement with fly-ash at cement plants can abate up to 4311.80 thousand t CO_2 equivalent for a marginal abatement cost of 0.91 €/ t CO_2 equivalent.

Moreover, the abatement option of geothermal energy we can abate up to 6054.80 thousand t CO_2 equivalent for a marginal abatement cost of 23.58 €/ t CO_2 equivalent. Furthermore, wind power abatement option offers the opportunity to abate up to 8677.60 thousand t CO_2 equivalent. for a marginal abatement cost of 38.49 €/ t CO_2 equivalent, and solar photovoltaic abatement option can abate up to 12163.60 thousand t CO_2 equivalent for a marginal abatement cost of 52.60 €/ t CO_2 equivalent. Price-based instruments such as taxes or quantity-based instruments such as tradable permits are among others the optimal options towards the realization of these abatement options.

There are mixed results across the literature about taxes and permits. Jung et al. (1996) examined auctioned and tradable permits, emission taxes and subsidies and standards. The authors found that permits provide the best results followed by taxes. Kennedy and Laplante (1999) examined taxes and permit and found that taxes perform slightly better although the differences are not large. Carlson et al. (2000) examine the market for SO_2 tradable permits. They found that tradable permits have lowered the marginal abatement costs. Montero (2002) compared four climate change policies, namely emission and performance standards and tradable and auctioned permits. The author found in perfect competition permits perform equally or better than standards. Requate and Unold (2003) support that taxes is a better instrument than permits in terms of providing incentives to lower emissions. Since all the abatement options in industrial subsectors have low marginal abatement costs we did not propose any abatement options which require R&D or deployment policies without implying that innovative and more cost-effective control methods are not always encouraged.

Biomass abatement option is on the far right corner of our energy MAC curve with an extremely high marginal abatement cost at 148.57 €/ t CO_2 equivalent, and also very high abatement potential up to 15882 thousand t CO_2 equivalent. The very high marginal abatement cost should be addressed with R&D or deployment policies. There are controversial findings regarding these policies across the literature. According to Parry (1998) welfare gains from these policies (e.g. R&D subsidies) are insignificant. Innes and Bial (2002) argue that innovating firms among others benefit from the high cost of their rivals after their successful innovation. Bauman et al. (2008) found no support than innovations lower marginal abatement costs; on the contrary some innovations increased the marginal abatement costs for Korean energy sector. Loschel (2002) found evidence that technical change through innovation and R&D leads to lower marginal abatement costs, more efficient environmental policy both in terms of mitigation potential and time, positive spillovers and negative leakage.

Figure 1: Marginal abatement cost curve for energy and industry sectors



6. Conclusions

In this study we have presented and analyzed the available abatement options for the energy sector and the industrial subsectors of petroleum and gas – downstream refining, cement and iron and steel considered among the most important and bigger pollution sources. We have constructed the abatement cost curve aiming to assist the decision maker to determine the optimal strategy for environmental regulation and we have discussed the policy implications.

Our analysis reveals significant potentials in pollution abatement even at negative costs. Specifically we found four abatement technologies in industry sector and one in energy sector with negative costs. The interpretation of negative cost is that society benefits from these abatement technologies both in cost and pollution abatement terms. Furthermore, we found that abatement technologies in the industry sector cost considerably less than abatement technologies in the energy sector, however there are significantly larger abatement potentials in the energy sector. In addition, the energy sector emits 33.2 million tons of CO_2 equivalent while the industry sector emits 2.11 million tons of CO_2 equivalent (YPEKA, 2013). To sum up, the energy sector is by far the larger emitter but it presents significant opportunities for pollution abatement.

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