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Abstract

In order to combat global warming, Italy has committed to clear environmental goals by reducing its CO_2 emissions. To this purpose, it has notably encouraged renewable energy development through a variety of support schemes, ranging from green certificates to feed-in and premium tariffs. As a result, during the last years, the production of electricity from renewable energy sources, especially from wind and solar energy, has experienced a considerable surge. In this paper we estimate the cost of reducing CO_2 emissions in the power sector by deploying wind and solar energy in Italy from 2008 to 2011. The results show that, for the period analyzed, the average costs for wind are in the order of 150 €/tCO_2, while for solar are much higher, above 1000 €/tCO_2. This is because solar energy generators receive much higher remunerations per MWh of generated electricity than wind energy generators. These costs are about twice as high as in Germany. This is due to the difference between the incentive schemes and the power system in the two countries.

Keywords

Abatement Cost, Renewable Energy, Wind Energy, Solar Energy, Italy

1 Introduction

To combat global warming the European Union (EU) has notably committed to two binding targets by 2020 deadline. The first target is to cut greenhouse gas (GHG) emissions by 20% below 1990 levels. The main instrument to reduce the GHG emission is the EU emission trading scheme (ETS) which imposes a single carbon price on CO2 emissions from large installations in all Europe. The second target is to increase the share of EU energy consumption produced from renewable energy sources (RES) to 20%. Also the promotion of renewable energy (RE) aims at mitigating CO2 emissions as they offer clean alternatives to fossil fuels by producing almost zero emissions to the atmosphere (Directive 2009/28/EC). Unlike the GHG target, there is not an EU-wide instrument to reach the RE target. In fact the RE target was divided among the EU member states and each country has developed national policies to meet its share of the target.

Italy put in place a variety of support schemes to develop RE. They go from green certificates to feed-in tariffs and premium tariffs. The Italian RE incentives (REI) created a huge surge in installed capacity, especially in wind and solar photovoltaic (PV) in these last years. From 2008 to 2011, the installed power capacity for wind almost doubled: from 3538 MW to 6936 MW. The growth of solar PV capacity in the same period was also more striking, the installed PV capacity increased by 2 856% (from 432 MW in 2008 to 12 773 MW in 2011).

The aim of this paper is to evaluate the cost of reducing CO2 emissions through the deployment of wind and solar PV energy due to the REI from 2008 to 2011 in Italy. We conduct an ex-post analysis of the Italian renewable policy in these last years in order to estimate how much it costed to consumers to abate carbon emissions through the use of RE generation. In fact the cost of the RE policy is supported by electricity consumers through increased electricity prices and surcharges in the electricity bills. We also compare these costs with those for Germany calculated by Marcantonini and Ellerman (2015). We want to analyse whether there are major differences between the cost in the two countries and if so to deduct which factors determine them. The focus of this work is only on RE as tool to reduce CO2 emission. Certainly, there are other important reasons to promote RE in addition to reducing CO2 emissions -as acknowledged in the Renewable Directive 2009/28/EC- such as the reduction of the EU's dependence on foreign energy imports or to steer the EU towards economic growth and higher employment. However the analysis of these reasons to develop RE are beyond the scope of this paper.

A number of studies have analysed the costs and benefits of renewable generation in different European countries (e.g. Denny and O'Malley (2007) for Ireland, Dale et al. (2004) for UK, Holttinen (2004) for Nordic countries, DEWI et al. (2005)). Marcantonini and Ellerman (2015) calculated the CO2 abatement cost due to RE for Germany; this was the first work to analyse the cost from an ex-ante point of view. Regarding Italy, the literature on the analysis of the cost of RE in international peer-reviewed journals is scarce. Cucchiella and D'Adamo (2012) and Aste et al. (2007) analysed the net present value of investing in photovoltaics taking into account the REI. Regarding the consumers point of view, Bollino (2009) studied the willingness to pay in order to use renewable energy in the electricity production in Italy. To the best of our knowledge, this study is the first work that estimates the costs and benefits due to the deployment of RE in the power generation sector in Italy and the related the CO2 abatement cost.

We calculate the carbon surcharge and implicit carbon price for wind and solar energy for the years 2008-2011 using the methodology of Marcantonini and Ellerman (2015). The carbon surcharge measures the extra cost paid to reduce the CO2 emissions in addition to the carbon price resulting from the EU ETS. It is given by the ratio of the net cost of the renewable energy over the CO2 emission reductions resulting from the injection of renewable energy in the power sector.[1] The implicit carbon price is the sum of the carbon surcharge and the average EU ETS carbon price paid by conventional generators. It gives an estimation of the CO2 abatement cost associated with the REI. The net cost is the sum of the costs and cost savings due to the injection of renewable energy into the electric power system. The costs include the remunerations given to wind and solar energy producers and the additional balancing cost. The remunerations account for the direct cost of the RE incentives, while the balancing cost represents the increase of costs in the managing of power system due to the intermittency of wind and solar energy. The benefits include the fossil fuel cost saving, the carbon cost saving and the capacity savings, all related to the reduction of energy generated from conventional capacity due to the injection of renewable energy. We estimate the fossil fuel, the carbon cost savings as well as the CO2 emissions reduction due to wind and solar using a unit commitment model of the Italian power system: the ELFO++. These are calculated by comparing the cost and the emissions in scenarios with different level of renewable energy in the power sector.

The results of our analysis show that the carbon surcharge for wind energy on average equals 150 euro per tonne of CO2 (tCO2) between 2008 and 2011. The carbon surcharge for solar energy is higher than for wind energy, at 1005 €/tCO2 on average. This is due to the difference between the incentive schemes for wind and solar: solar energy generators receive much higher remunerations per MWh of generated electricity than wind energy generators. The implicit carbon prices for wind and for solar are close to the carbon surcharge as a result of the low values of the carbon cost saving due to the low EU ETS carbon price in the analysed period (the average EU ETS carbon price in the period 2008-2011 was 13.4 €/tCO2).

The results reveal that the cost of reducing CO2 emissions in the power sector through the deployment of wind and solar energy in Italy were much higher than in Germany. This is due to the higher net cost and lower CO2 emission reduction of RE in Italy. The higher net cost is explained by the higher level of remuneration given to the RE producer in Italy with respect to Germany. The lower CO2 emission reduction is linked to the differences in power generation between the two countries. The Italian electricity production is dominated by gas while in Germany by coal. Hence in Italy RE displaces mostly gas while in Germany both gas and coal. Given that coal emits more CO2 than gas per MWh of electricity produced, the CO2 emission reduction per MWh of RE energy generated is much lower in Italy with respect to Germany.

This paper is organised as follows. Section 2 describes the Italian incentives for RE. Sections 3 and 4 are the technical part of the study. Section 3 explains the computation of the net cost and of the CO2 emission reduction, while Section 4 describes the ELFO++ model. Section 5 presents and comments the results for Italy and Section 6 compares them with those calculated for Germany. The last Section concludes.

[1] In this paper, CO2 emissions reduction only refers to emission abatement in the power generation system, not with respect to the total aggregated CO2 emissions. As CO2 emissions are capped by the EU ETS, the total CO2 emissions are not reduced and the net effect of the injection of RE energy is to displace CO2 emissions from the electricity sector to other ETS sectors.

2 Renewable Energy Incentives in Italy

Italy experienced an impressive growth of wind and PV capacity and energy production in these last years. Table 1 shows the annual wind and PV capacity installed and energy produced from 2000 to 2011. Wind capacity grew from 363 MW in 2000 to 6.9 GW in 2011, and wind energy generation went from 563 GWh in 2007 to 9.9 TWh in 2011. Solar PV capacity was negligible until 2006 and it has increased from 87 MW in 2007 to 12.8 GW in 2017. The electricity generated by PV reached 10.7 TWh in 2011, 3% of the national total energy produced. This growth was supported by several REI which are the result of different regulation frameworks introduced over the years. The first support scheme for renewable energy was a feed-in tariff system, called CIP6, which started in 1992. CIP6 was substituted by a green certificate market in 2001: the *certificati verdi* (CV). Since 2005, the support scheme for PV has been changed to a feed-in premium called *conto energia* (CE). Since 2009 small wind power plants can receive a feed-in tariff as an alternative to the CV: the *tariffa onmicomprensiva*. All these support schemes grant remuneration to RE producers per quantity of electricity generated. In the period 2008-2011 by far the main support scheme for wind energy was the CV, while the main support scheme for PV was CE. In the rest of the section we describe these four support schemes for RE.[2]

Wind		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Capacity	[MW]	363	664	780	874	1131	1639	1908	2714	3538	4898	5814	6936
Energy	[GWh]	563	1179	1404	1458	1847	2343	2971	4034	4861	6543	9126	9856

Solar PV		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Capacity	[MW]	6	7	6	7	7	7	7	87	432	1142	3470	12 773
Energy	[GWh]	6	5	4	5	4	4	2	39	193	676	1874	10 668

Table 1: annual capacity and final energy produced from wind and solar PV power plants. Source: Terna (see www.terna.it/default/home_en/electric_system/statistical_data.aspx).

2.1 *CIP 6.*

The CIP6 system was the first Italian incentive scheme for RE, which was introduced in 1992. This is a feed-in tariff system where RE is remunerated with a guaranteed price. The GSE purchases the RE at the CIP6 guaranteed price and sells it to the market at the market price. The difference is paid by consumers as a surcharge in the retail electricity price.[3] The incentivised tariff has two components: the *costo evitato*, and the *componente di incentivazione*. The *costo evitato* corresponds to the avoided cost of producing energy through conventional generators, while the componente di incentivazione is an additional component which depends on the type of RES. RE producers are guaranteed the *costo evitato* for 15 years and the *componente di incentivazione* only for 8 years. The level of the *costo evitato* is updated on an annual basis for

[2]The main sources used for the data and the policies regarding RE are the annual reports of the Gestore Servizi Energetici (GSE), which is the state-owned company responsible for implementing the policy aimed at promoting RE in Italy (GSE, 2006, 2007, 2008, 2009, 2010*a*,*b*, 2011*a*,*b*), and the data on energy production and capacity reported by the Italian Transmission system operator, Terna, and available at www.terna.it/default/home_en/electric_system/statistical_data.aspx. Additional information was found in Farinelli (2004), Spitaleri (2012) and for the CIP6 incentives in Poletti et al. (2009).

[3]Before the liberalisation of the electricity market, the utility company ENEL (at that time the state-owned company responsible for electricity production, transmission and distribution) was obliged to purchase energy from RES at the CIP6 guaranteed price.

all RE produced. The level of the *componente di incentivazione* is updated on a regular basis only for new contracts and it is constant for the entire duration of the contract. In 2001, CIP6 was substituted by the CV system. However, power plants that had already stipulated CIP6 contracts at that time could benefit from the CIP6 tariff until the end of the contract. Table 2 shows data for wind energy as from 2002 (no solar energy was supported by CIP6 (GSE, 2007)). Data for the capacity supported by CIP6 are available only from 2008, for the total annual cost from 2007, and for the energy supported by CIP6 starting from 2002. Both the energy and the capacity supported by CIP6 have sharply decreased during the last years, indicating that an increasing number of CIP6 contracts has expired. However, in 2011 there was still 346 MW of wind capacity under CIP6 contracts, which produced 465 GWh of energy. This corresponds to 10% of wind capacity and 4% of wind annual energy.

CIP6		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Capacity	[MW]								847	622	346
Energy	[GWh]	1271	1274	1407	1201	1117	1281	1153	880	816	465
Cost	[M€]						323	174	111	85	51

Table 2: data on CIP6 for wind power plants. *Capacity*: wind capacity supported by CIP6. *Energy*: wind energy paid with CIP6. *Cost*: annual cost of CIP6 for wind energy. Source: GSE (2008, 2009, 2010*a*, 2011*a*).

2.2 *Certificati verdi*

The *certificati verdi* (CV) is a green certificate system in place since 2001 which substituted the CIP6 support scheme. The CV is a tradable asset granted by the GSE in proportion to the energy produced by RES power plants. Since 2004, the CVs have been traded in the Gestore dei Mercati Energetici (GME), the Italian power market operator. For on-shore wind energy, one CV corresponds to one MWh of electricity produced.[4] Each entity producing or importing more than 100 GWh of electricity from conventional sources must satisfy a REN obligation. It must produce or introduce in year $n+1$ a quantity of REN energy equal to a quota of the energy produced or imported in year n. The power producers can meet the quota either by producing RE energy on their own or by purchasing CVs. Each CV is valid to satisfy the RE obligation for three years. CVs are granted for a period of 12 years to RE power plants built (or refurbished) from April 1999 to the end of 2007, and for a period of 15 years since 2008.[5]

Table 3 shows data for the CVs for wind energy since 2002: the supported capacity, the annual number of CVs issued by GSE and their average annual prices. In our analysis, we do not take into account CVs for solar PV since only a small fraction of solar photovoltaic capacity is supported by CVs. In 2011 only 3.4 MW of solar PV uses the CV system. This corresponds to less than 0.003% of all solar capacity. Almost all solar capacity is remunerated through CE which is by far a more convenient remuneration scheme for solar PV; CE is not compatible with CVs. On the other hand, for wind energy we observe that the capacity supported by CVs has constantly increased. In 2011, almost 90% of wind capacity received CVs.

The trade of CVs was greatly influenced by the GSE. The GSE does not only issue CVs but it can also sell CVs to the market at a price called *prezzo of riferimento* (reference price). The GSE can sell CVs for a quantity which corresponds to the production of electricity from

[4]For the period analysed, all wind energy was produced by on-shore installation (EWEA, 2013).

[5]The RE producer can be granted in year n CVs for the energy produced in year $n-1$ (called CV *a consultivo*) and, for the installations that have been in activity for at least 2 years, for the energy they expect to produce in year n and $n+1$ (called CV *a preventivo*).

RE power plants supported by CIP6 incentives.[6] In the early years of the system, the offer of CVs by the GSE was much higher than by RE producers, and the price of CV was practically defined by the prezzo di riferimento. Moreover, since 2008, RE energy producers that have not sold CVs in the market, can sell them back to the GSE during the following year, at a price called *buy-back price*. The cost of buying-back these CVs is paid by consumers as a surcharge in the retail electricity price. The *buy-back price* has resulted higher than the price offered in the market, therefore RE producers found more convenient to sell back their CVs to the GSE. Pursuant to a law passed in 2012, the CV has been substituted by an auction system for the capacity built as from January 2013. However, for all capacity built until the end of 2012, CVs will continue until the end of 2015 and starting from 2016 they will be replaced by a feed-in premium system, whose tariff will be equal to the *buy-back price*. Since 2012 the *buy-back price* has been equal to 78% of the difference between 180 €/MWh and the average electricity price of the previous year. The sum of the *buy-back price* and the electricity price is quite stable with respect to the electricity price (it varies between 151 €/MWh and 162 €/MWh with the electricity price fluctuating between 50 €/MWh and 100 €/MWh). Therefore the system has effectively become similar to a feed-in tariff system.

Certificati verdi		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Capacity	[MW]					1003	1886	2795	4251	4963	6213
Number	[GWh]	148	181	464	1282	2002	2653	3625	5463	8148	9179
Price	[€/MWh]	84.18	82.40	97.70	106.90	110.40	120.19	77.87	88.46	84.41	82.25

Table 3: data on certificati verdi (CV) for wind power plants. *Capacity*: wind capacity supported by CV. Source: GSE (2006, 2007, 2008, 2009, 2010*a*, 2011*a*). *Number*: number CV issued by GSE for the energy produced in the same year, one CV equals one MWh. Source GSE (2010*a*, 2011*a*). *Price*: average annual price of CV. For year 2002 and 2003 the price refers to the GSE prezzo di riferimento, from year 2004 the price refers to the GME price. Source: GSE (2008) and GME (http://www.mercatoelettrico.org/It/Statistiche/CV/StatCV.aspx).

2.3 Conto Energia

Conto Energia (CE) is a feed-in premium only for solar power plants. Power plants that use CE cannot obtain or sell CVs. The feed-in premium is a tariff paid to solar energy on top of the market electricity price. The cost of the CE is paid by consumers as a surcharge on the retail electricity price. The CE was introduced in 2005 and initially it was only for the electricity produced and consumed on-site. In 2007, the CE was extended to all electricity produced by solar technology.[7] The tariff level depends on the capacity and type of installation and is guaranteed for 20 years at a fixed nominal term. The level has been updated periodically for new installed capacity and it has decreased along the years.[8] Table 4 shows data for the CE for solar PV in 2007-2011, in particular: the supported capacity, the quantity of energy that received the CE tariff (only data for 2010 and 2011 was published), the minimum tariff and maximum tariff for new capacity installed, and the total annual cost. The remuneration received with the CE was much higher than the remuneration from selling electricity to the market. The average real electricity price in the periods 2007-2011 was 7 ¢/MWh. In 2011 almost all solar

[6]The *prezzo of riferimento* is equal to the difference between the annual level of the CIP6 incentive per KWh and the average price of electricity.

[7]The GSE website has a page dedicated to the history of CE: www.gse.it/it/Conto%20Energia/Fotovoltaico/Evoluzione%20del%20Conto%20Energia/Pages/default.aspx

[8]In the period 2007-2010 the tariff has been decreased on an annual basis Since 2011 it has been decreased approximately every three months.

energy received the feed-in premium from CE: more than 96% of all photovoltaic capacity and more than 97% of all energy from PV technology was supported by CE. The CE has sustained a fast deployment of PV (solar capacity increased by a factor 150 in only five years) with an increasing high cost for consumers. As a result of the last amendment in 2012, there has been a restructuring of the entire CE system and the legislator decided that the scheme will cease to provide incentives to new capacity once the cumulative cost of incentives reaches the level of 6.7 billion euro per year.[9] This happened in July 2013.

Conto energia		2007	2008	2009	2010	2011
Capacity	[MW]	80	418	1138	3459	12305
Energy	[GWh]				1899	10411
Minimum tariff	[¢/kWh]	46.2	36.0	35.3	34.6	25.1
Maximum tariff	[¢/kWh]	53.9	49.0	48.0	47.0	40.2
Annual cost	[M€]	19	91	304	773	3855

Table 4: data on conto energia (CE) for solar PV. *Capacity*: photovoltaic capacity supported by CE. *Energy*: energy paid by CE tariff (only data for year 2010 and 2011 was published); the tariff for new capacity installed could ranges between the *Minimum tariff* and *Maximum tariff*. *Annual cost*: total annual expenditure the CE. Sources: International Solar Energy Society (www.isesitalia.it/atc_03_01.asp), GSE (2013), GSE (2011*b*) and GSE (2010*b*).

2.4 *Tariffa Onmicomprensiva*

The *Tariffa Onmicomprensiva* (TO) is an all-inclusive a feed-in tariff support scheme only for small RES, excluding PV. TO is an alternative to the CV scheme. The tariff includes both the incentive and the value of electricity fed into the power grid. It is granted to plants commissioned as from 2008 and, for wind farms, with a capacity not exceeding 200 kW. The support period is guaranteed for 15 years and the level of the tariff is constant in nominal terms over the entire period. Table 5 shows data for the TO for wind energy in the period 2009-2011 (data for 2008 could not be found): the capacity supported, the quantity of energy paid with TO and the total annual expenditure. The difference between the cost of the TO and the electricity price is paid by consumers as a surcharge on the retail electricity price. For the period 2009-2011 the tariff was 30 ¢/kWh, much higher than the electricity price. Only a small amount of wind energy is remunerated with TO: in 2011 this was less than 1%.

Tariffa Omnicomprensiva		2009	2010	2011
Capacity	[MW]	0.87	3.00	7.20
Energy	[GWh]	0.21	1.67	4.37
Annual cost	[M€]	0.06	0.49	1.31

Table 5: data on tariffa omnicomprensiva (TO) for wind power plants. *Capacity*: wind capacity supported by TO. *Energy*: wind energy paid by TO. *Annual cost*: total annual expenditure for TO to wind energy. Sources: GSE (2009, 2010*a*, 2011*a*).

[9] Another important change is that for producers who inject electricity to the power system the new CE tariffs include both the incentive and the value of electricity fed into the power grid. This changes the system from a feed-in premium to a feed-in tariff.

3 Methodology

The carbon surcharge and implicit carbon price are calculated using the methodology of Marcantonini and Ellerman (2015). The carbon surcharge is given by the ratio of the net cost of the renewable energy over the CO2 emission reductions resulting from the injection of renewable energy in the power sector. The net cost is the sum of the costs and cost savings due to the injections of renewable energy into the electric power system. The cost of RE includes the *equalized remuneration* and the *additional balancing cost*.[10] The equalized remuneration takes into account the remuneration to power generators for producing electricity from RE. They are related to the REI. The balancing cost represents the increase of costs in the managing of power system due to the intermittency of RE. The savings include the *fuel cost saving*, *carbon cost saving* and *capacity saving*. They are related to the reduction of energy generated from conventional capacity due to the injection of renewable energy. The fuel cost saving is the saving coming from consuming less fossil fuel for thermal generation. The carbon cost saving is the saving coming from purchasing less allowances in the EU ETS market because of the reduction of CO2 emissions. The capacity saving is the saving of the fixed cost of building or maintaining conventional capacity which is no longer needed because of the increase of the capacity from renewable energy. The implicit carbon price is calculated as the carbon surcharge but without considering the carbon cost saving in the net cost of RE; it is equivalent to the carbon surcharge plus the average EU ETS carbon price paid by conventional generators.

In the rest of this Section we describe how we determine the CO2 emission reduction and the costs and savings of deploying wind and solar energy in Italy for the years 2008-2011. The additional balancing cost and carbon cost saving are calculated only for wind due to little data available about these costs for solar. However in the Section 5.2 we show that the impact of these two elements on the carbon surcharge of solar is secondary.

3.1 Equalized Remuneration

The equalised remuneration is given by equalising in annual terms the sum of all the remunerations made along the lifetime of the power plants (Marcantonini and Ellerman, 2015). The estimation of the equalized remuneration can be summarized in the following steps. We first estimate the annual remunerations for each vintage of capacity and for the entire lifetime of the power plants, which is assumed to be 25 years (IEA/NEA, 2010). Secondly, we discount the remunerations at a fixed rate of 7% to the first year of activity and we sum them up to obtein the initial net present value (NPV).[11] Thirdly, we redistribute the NPV in a 25-year mortgage using the same interest rate. The equalised remuneration in a given year is given by the sum of the mortgage rates of the capacity in service in that year. We calculate the remunerations for solar and wind energy in €(2011). We convert all the prices in real value.[12] We calculate the annual remuneration making use of information collected in the tables of Session 2. In the following paragraphs we provide additional details on how we estimate the annual remunerations for wind

[10]The use of RE may also increase the cycling cost for conventional generators, such as ramping costs and start-up cost. These are not taken into account in this analysis because of the limit of the model used and of lack of information about these costs for the Italian system. Van den Bergh et al. (2013) shows that these costs are much lower with respect to the fuel cost

[11]The existing literature on cost of generation electricity generally uses a cost of capital between 5% and 10% (IEA/NEA, 2010).

[12]From 2012, the inflation rate is considered equal to 2%; the average annual inflation in Italy in the years 1997-2013 was 2.17%.

and solar PV.

3.1.1 Wind

Annual remunerations are estimated for each vintage of capacity from 2002 to 2011.[13] Wind energy can be remunerated with the CV, CIP6, TO support schemes and from selling electricity to the market. Regarding CV, we have data on the annual capacity supported by CVs (which we call CV capacity) from year 2006; on the annual issued CVs and the CV price we have data only from year 2002 (Table 3). For the years 2002-2005, we simply assume that all new installed capacity since 2002 has been CV capacity as CIP6 was substituted by the CV in 2001 and the TO system only started in 2009. In order to estimate the annual remuneration for each vintage of capacity coming from selling CVs for the years 2002-2011, we first distribute the CVs issued by GSE to the CV capacity built in different years in proportion to the value of annual CV capacity. We then suppose that all CVs are sold during the year of their issuing, at the annual average market price of Table 3. To estimate the annual remunerations since 2012, we suppose that all CV capacity will produce energy at a constant annual capacity factor of 17% (the average annual capacity factor of power plants in 2011 was 16.1%), that CVs are issued for all energy produced, and that they are sold to GSE at the *buy-back price* assuming for future years a real price of 75 €/MWh (the average real electricity price in the periods 2008-2011 was 71.7 €/MWh). We consider that the CVs are issued for 12 years for the capacity built until 2007 and for 15 years for the capacity built since 2008, as the current law provides.

Regarding CIP6, we have data on the capacity supported by this instrument from year 2006, on the energy paid with the CIP6 tariff from year 2002, and for the total annual cost only from year 2008 (Table 2). The quantity of energy which received the CIP6 tariff was quite constant up to year 2007, and it has remarkably declined from 2006 onwards. This is not surprising given that the *componente di incentivazione* of the CIP6 tariff only lasts for eight years and that as from 2002 new wind capacity could not receive the CIP6 tariff any longer. This resulted, year by year, in a reduction of the capacity receiving the CIP6 tariff as CIP6 contracts were expiring. For our analysis we assume that all CIP6 energy comes from the capacity built before 2002 (which is about 1.6GW) as CIP6 was substituted by CV in 2001. We estimate the electricity supported by CIP for future years by extrapolating the linear decreasing trend of CIP6 energy in the period 2007-2011. In this way, we estimate that there will be no use of the CIP6 supported scheme for wind as of 2014. Regarding the CIP6 tariff level for wind energy, we have data on the average tariff level only for the years 2007-2011 (Table 2). For the period 2002-2006 we use the average CIP6 tariff for all RE, which was published by the GSE (2008). For the years 2012 and 2013 we use the same value as for 2011.

Regarding the TO, we have information on the annual supported capacity (which we call TO capacity), annual energy supported and annual cost for the years 2009-2011 (Table 5). The average annual tariff in these years was 30 ¢/kWh. We assume that all new annual TO capacity was capacity built in that year. To estimate the annual remuneration of the years 2009-2011 for each vintage of capacity, we distribute the annual cost to the capacity supported by TO built in different years in proportion to the value of the capacity. For future annual remunerations, we first assume that all capacity supported by TO (Table 5) as from 2012 produces electricity at constant capacity factor of 6% (the capacity factor of power plant using TO in year 2011

[13] We assume that all the installations built before 2002 were commissioned in 2002. This assumption is reasonable because the capacity built before 2002 was very low compared to the capacity constructed between 2002 and 2011.

was 5.3%).[14] We then assume that all this energy is remunerated by the TO feed-in tariff at 30 ¢/kWh for 15 years, as provided by the current law.

All power plants except the ones which are supported by CIP6 and TO can sell electricity to the market. We estimate the capacity that sells electricity to the market by subtracting from the total capacity, the capacity supported by CIP6 and TO. For the years 2002-2012 we assume that all electricity produced minus the electricity supported by CIP6 and TO was sold to the market at the annual average market price. To estimate the annual generation of electricity for the years 2002-2011 for each vintage of capacity, we allocate the estimated historical annual wind electricity sold to the market to the capacity installed in different years by assuming a constant annual capacity factor. From 2012 until the end of the lifetime of the power plants we consider that all power plants that can sell electricity to the market generate electricity at 17% constant capacity factor and that the electricity is sold at a real price of 75 €/MWh.

3.1.2 Solar Photovoltaic

The annual remuneration is estimated for each vintage of capacity from 2007 to 2011.[15] Solar energy is remunerated through two separate components. The first component comes from the sale of electricity, the second from CV. To estimate the remuneration coming from the sale of electricity, we assume that all solar electricity produced is sold to the market. Table 1 shows data on solar electricity produced and solar capacity. From 2007 to 2011, we allocate the historical annual electricity generated by solar PV to power plants installed in different years by assuming a constant annual capacity factor which depends on the year of installation. In fact the average solar capacity factor has drastically increased during the last past years. Using the annual historical levels of energy and capacity of Table 1 and supposing that all solar capacity was built on the 1st of January,[16] the capacity factor of new installed capacity would grow from 6% in 2007 to 11% in 2011.[17] Given that the capacity is installed throughout the year, these values underestimate the real capacity factors. In our analysis we assume 7% capacity factor for plants installed in 2007 and 2008, 9% for 2009 and 2010 and 13% for 2011. From 2012 until the end of the lifetime of the power plants we assume that the power plants produce energy at the same capacity factors. The average electricity price paid to solar energy is higher than the average total electricity price because solar energy is produced during daytime. Based on the data of Terna on the solar energy hourly production, we estimate that the annual average electricity price paid to solar energy was on average 10% higher than the average electricity price for the years 2010 and 2011. From the year 2012 we assume that the average electricity price paid to solar energy is 79 €/MWh in real terms, 10% more than the average price for the period 2007-2011.

Regarding CE, not all solar capacity is supported by this scheme, although if the large majority is (Table 4). We have data on the annual capacity that uses CV for all years since 2007, but on the energy remunerated only for years 2010 and 2011. For the period 2007-2009, and since 2012, we simply assume that all capacity supported by CE produced energy at the constant capacity factors defined above. We also assume that all the energy produced by the

[14]TO is given only to small power plants are less efficient than bigger plants and thus have a lower capacity factor than an average power plant.

[15]We assume that all the installations built before 2007 were commissioned in 2007. This assumption is reasonable because the capacity built before 2007 was very low compared to the capacity constructed between 2007 and 2011.

[16]The capacity value of Table 1 refers to the level of all solar capacity at the end of the year.

[17]We assume that the capacity factor does not change along the lifetime of the power plants.

capacity supported by CEs receives the CEs for 20 years, as the current law provides. Regarding the level of the feed-in premium, we suppose that the average feed-in premium given to all new installed solar capacity in its first year of activity would be the same for 20 years.

3.2 CO2 emission reductions, fuel cost saving and carbon cost saving

The CO2 emission reductions the fuel cost savings and the carbon cost savings are estimated by calculating the fuel cost, the carbon cost and the CO2 emissions of the Italian power sector in two different scenarios. The observable (*OBS*) scenario which corresponds to the historical scenario, and the counterfactual scenario $NoWind$ (resp. $NoSolar$) in which no energy would have been produced by wind (resp. solar) technologies. The CO2 emission reductions, the fuel cost savings and the carbon cost savings of wind (resp. solar) energy are the difference between the total CO2 emissions, the total fuel cost and the total carbon in the scenarios $NoWind$ (resp. $NoSolar$) and in the OBS scenario. The total fuel cost is the total annual cost to buy the fossil fuel needed to produce electricity by convention generation. The total carbon cost is the total cost to purchase the EU ETS allowances for the CO2 emitted in the power sector. In the $NoWind$ and $NoSolar$ scenarios more electricity is produced by conventional generators than in the OBS scenario and this results in higher CO2 emissions, higher fuel and carbon costs.

All the exogenous variables in the *No Wind* and *No Solar* scenarios are assumed to be the same as in the *OBS* scenario except for the renewable energy production. In particular the demand, net export, fossil fuel prices and the EU ETS carbon price are the same in all scenarios and equal to the historical values. This signifies that several assumptions are made. First we assume that the demand is completely inelastic. Secondly we do not take into account the impact of transnational transmission in the CO2 emission abatement and we only focus on abating CO2 at national level. Thirdly we assume that the development of RE in Italy did not have any impact on the fossil fuel prices which are the same in all scenarios. This assumption is justified because we only look at the Italian power sector while the fossil fuel price is determined by the international market. The forth assumption is that we do not consider the interaction between the RE deployment on the EU ETS price which is considered the same in all scenarios as if it was a carbon tax. We acknowledge that the RE deployment had an impact on the carbon price because it decreased the demand for allowances. Nevertheless, in absence of a reliable estimation of the effect of RE injections on the carbon price, we prefer to use the historical carbon price in all scenarios. However it is not obvious that the relaxation of this assumption would significantly change the results (Marcantonini and Ellerman, 2015).

For the years 2010, 2011 we use the ELFO++ model to simulate the *No Wind*, *No Solar* and *OBS* scenarios. ELFO++ is a deterministic unit commitment model of the Italian electricity market. Given the hourly power demand, it simulates the optimal dispatching of electricity from thermal and hydro power plants on hourly time by minimizing the total generation costs. Section 4 describes the model and the data used.

Due to data unavailability, we can make hourly simulations with the ELFO++ model only for the years 2010 and 2011. There are no data available for an entire year on the hourly injection for wind and solar energy for previous years. However for the years 2008 and 2009 we could make estimations on the CO2 abatement, fossil fuel savings and carbon cost savings using data for the annual production from Terna and the results of simulations for the years 2010-2011. The results for these latter years 2010-2011 show that wind energy has displaced on average 90% of gas, 4% of coal and 4% of oil, and solar 97% of gas, 2% of coal and 2% of oil. That is because the Italian electricity production comes for about 50% from gas which tends to be always on margin. For the years 2008-2009 we assume that wind and solar energy has displaced in percentage the same amount of gas, coal and oil. Terna published annual data on the aggregated efficient factor for all fossil fuels. We use these data to estimate the quantity of coal, gas and oil displaced by wind and solar. We calculate the CO2 emissions reduction by using the value of CO2 emission factors provided by REF-E. The carbon cost savings are calculated by multiplying CO2 emission reduction by the average annual carbon price.[18] The fuel savings are calculated by multiplying the fossil fuel reduction by the average annual fossil fuel price. For the fuel price and the carbon price we use the estimation by REF-E and the data from Point Carbon respectively.

3.3 Additional balancing cost for wind

Unpredicted short-term fluctuations of intermittent generation increases the balancing cost with respect to conventional generations. Regarding wind energy, there are several studies on the additional balancing cost which show estimations of the order of 1-4 €/MWh also for high wind penetrations (Holttinen, 2008). In this study we estimate the additional balancing cost for wind by assuming a cost of 2 €/MWh.

3.4 Wind capacity saving

The capacity saving is the saving of the fixed cost of building or maintaining conventional capacity which is no longer needed because of the increase of the capacity from renewable energy. The time when conventional capacity is displaced because of the additional renewable generation and the type of power generation depends on how the Italian power system will develop in the next years. A study of the development of the Italian system is beyond the scope of this work. We calculate the capacity benefit for wind based on simple and transparent assumptions as in Marcantonini and Ellerman (2015). The goal is to estimate the order of magnitude of the capacity saving and to compare with other costs and cost savings. A key element in the capacity saving is the capacity credit, which corresponds to the amount of conventional capacity that can be replaced by wind capacity (in general it is defined as a % of the installed capacity). The capacity credit depends on many factors -such as the quantity and geographic distribution of wind, the penetration of wind energy in the power system, the transmission sector- and it varies considerably from country to country (Gross et al. (2006), Giebel (2005), IEA (2011)). Estimations show that the capacity credit may be as low as 5%, and up to 25% such as in UK where there are many windy areas (IEA, 2011). To the best of our knowledge, there are not specific studies on the capacity credit for wind energy in Italy. For our analysis we assume a 7% capacity credit in the base case scenario, as used for the for German case. In the sensitivity analysis, we give results with assumed capacity credit of 5% and 20%.

We assume that the wind capacity saving is realized in 2015 and that the wind capacity credit will be used to substitute 70% of coal and 30% of gas. In other words we suppose that in 2015 less conventional capacity will be constructed because of the wind capacity already installed. We assume that more coal than gas is displaced because wind power needs flexible generation to cope with wind fluctuations. The capacity saving are calculated by estimating the economic benefit of savings the capital cost and the fixed O&M cost of the coal and gas capacity displaced by the wind capacity credit. For the fixed O&M cost, we take into account the cost for the period when wind generators are active. As is done for the equalized remuneration to

[18]For solar, given that the production profile changes over the solar year while it is quite stable from year to year, we weighted the monthly fossil fuel prices over the monthly solar production of year 2010.

generators, we redistribute the saving along the lifetime of the wind power plants using a 7% cost of capital. The costs are estimated using data from NEA (2011) for the overnight costs, from EIA (2010) for the fixed O&M costs, and from (IEA/NEA, 2010) for the capacity factors.

4 ELFO ++

This section describes the ELFO++ model which is used to estimate the CO2 abatements, the fuel savings and the carbon savings due to the injection of wind and solar energy into the Italian power system for the years 2010 and 2011.

4.1 Model description

ELFO++ is a cost-based deterministic model of the Italian market that has been developed and maintained by the energy consulting company REF-E. The model simulates the optimal dispatching of electricity generation on hourly time by minimising the total generation costs on a yearly basis. The transmission sector is simulated as a zonal model. The zone is defined as a geographical area where generation and demand can be considered interconnected through a single node. The grid is represented as interconnections among zones, without losses and with hourly details on transmission limits. The model considers the dispatching of conventional generators: fossil fuels and hydro power plants (Italy does not have nuclear power plants). The inputs of the model are the technical details of the power plants, the fossil fuel prices, the carbon price and the residual demand for conventional generation. All the inputs are specified at a zone level. The thermal power plants are modeled individually by distinguishing the different units existing in the same plant. Each unit is defined by: zone, technology, company, fuel, minimum and maximum capacity, availability configuration, average availability rate, coefficients for the hourly consumption curve. The hourly consumption curve of the thermal unit is a quadratic function of the power generated defined by three coefficients. The hydro plants are modeled without distinguishing amongst the units existing in the same plant. Each hydro plant is defined by: type, zone, company, minimum and maximum possible power, minimum and maximum possible volume of the reservoir, energy coefficient for generation and for pumping, average availability.[19] The model is fully deterministic and the optimisation problem is a mixed variable quadratic programme. The time-step of the simulation is the single hour, defined as the maximum time duration during which all parameters of the electricity system are assumed to be constant. For the solution ELFO++ uses dynamic programming and Kuhn-Tucker optimisation conditions.[20]

4.2 Data and calibration

Due limited data availability we made simulations using the ELFO++ only for the years 2010 and 2011. The dataset used for the simulations comes from GSE, GME, Terna (the Italian Transmission System Operator) and from utility company reports.[21] Similarity, because of lack of data and model limitation we could only model the dispatching of thermal and large hydro

[19]There are three types of hydro power plants: *reservoir* (with weekly to seasonal storage capacity), *pumped storage* (with storage capacity lower than a week), and *run of river* (without storage capacity).

[20]For more technical details see the *ELFO++ Technical Guide* (REF-E, 2012) available on request to info@ref-e.com.

[21]Data on energy production from Terna are downloadable from the website http://www.terna.it. GSE data are published in the GSE annual reports (GSE, 2010*a*, 2011*a*). GME data are downloadable from the website http://www.mercatoelettrico.org.

power plants which are not auto-production generators and are not CIP-6 power plants.[22] We do not model the dispatching of run-of-river and non-hydro renewable (geothermal, biomass, wind and solar). Data for conventional power plants comes from company reports collected by REF-E. For hydro plants, the natural inflow has been modeled on an historical profile, and calibrated to match the annual historical production as reported by Terna. We calculate the residual hourly demand for thermal and large hydro power plants by subtracting to the total demand of electricity of the network (which excludes auto-production) the hourly production of electricity from non-hydro renewable power plants, run-of-river power plants, non-renewable CIP6 power plants and the hourly net import-export. Data for demand of electricity from the network are from the GME (hourly day-ahead market) and from Terna (total annual demand). We scale the hourly data of GME to match the total annual production from Terna. Data for RE production comes from Terna. For wind energy, Terna published data for hourly production and for annual aggregated production for the years 2010 and 2011. We scale the hourly data to match total annual production.[23] For solar and geothermal production, we have data for annual production for the years 2010 and 2011, but data for hourly production only for the year 2011. For the year 2011 we scale the hourly data to match the total annual production.[24] For the year 2010, we distribute the annual production on an hourly basis by using the profile production of the year 2011. For run-of-river energy we use data on hourly production from Terna. For biomass and non-renewable CIP6 we use data on total annual production, coming from Terna and GSE respectively, and we assume a constant hourly production profile. Data on the transmission zones and the minimum and maximum exchange limits between zones comes from Terna. For the net import-export demand we use hourly data of the day-ahead market of the GME and data on total annual demand from Terna. We scale the hourly data of GME to match the total annual demand.

For the cost of producing electricity from fossil fuel-fired power plants, we take into account only the fuel cost. Regarding fossil fuel prices, prices paid for coal, gas and oil by fossil-fuel generation producers are not publicly available. Using only spot price is not realistic as the prices paid by generators are often fixed in long term contracts which are not disclosed. For our analysis we use monthly estimations made by REF-E based on the analysis of the European historical spot prices of oil and gas and on information that REF-E regularly collects about the Italian gas market and electricity market.[25] The calorific value and CO2 emission factor are provided by REF-E based on average values for each kind of fuel.[26] For carbon price we use monthly average EUA spot prices from Point Carbon.

The model is calibrated to replicate historical conditions so that it reproduces the observed yearly generation by fuel. Without doing any calibrations, the model tends to overestimate the historical use of coal with respect to gas. This is not surprising as analogous models simulating

[22]CIP6 incentives were granted not only to facilities using RES but also to *assimilated* power plants, including a few thermal power plants (Poletti et al., 2009).

[23]The data on hourly production are only for relevant installations. The difference between the sum of hourly data for relevant installation and the annual production from all installations is small (about 2%).

[24]The data on hourly production are only for relevant installations. The difference between the sum of hourly data for relevant installation and the annual production from all installations is small for geothermal (about 6%), while for solar is around 15%. However the profile of solar production tends to be independent from the size of the power plant.

[25]For more technical details on the estimation of the fossil fuel prices see *Italian Electricity Market Study: Price Forecast* available on request to info@ref-e.com.

[26]The calorific values for coal, gas and oil are 6300 kcal/kg, 8250 kcal/sm^3 and 9600 kcal/kg. The CO2 emission factors for coal, gas and oil are 2.482 kg(emission)/kg, 1.928 kg(emission)/sm^3 and 3.078 kg(emission)/kg. Coal is hard coal. The values of CO2 emission per net calorific basis are in the ranges defined in Eggleston et al. (2006).

European electricity systems found similar results (Weigt et al., 2012; Delarue et al., 2010). In order to reproduce an historically realistic outcome, we calibrate the model by reducing coal plant availability. The calibration, however, changes only marginally the results on the CO2 abatement emissions as well as the fuel cost saving and carbon cost saving. This happens because, the Italian electricity production comes mostly from gas. As a consequence, both with and without calibration in the model's simulations, gas tends always to be on margin and wind and solar energy in both cases displays almost only electricity generated by gas-fired power plants.

5 Results

This Section presents the results of our analysis. Section 5.1 shows the carbon surcharge and implicit carbon price of the REI for wind and solar PV technologies. In Section 5.2 we discuss the robustness of these results with respect to some key assumptions made to calculate the different costs and benefits.

5.1 Carbon surcharge and implicit carbon price

We determine the carbon surcharge and implicit carbon price in Italy for the years 2008-2011. Tables 6 and 7 show the annual carbon surcharges and the annual implicit carbon prices of wind and solar PV. The net cost is given by the sum of the costs minus the cost savings. The carbon surcharge is the net cost divided by CO2 emission reduction. The implicit carbon price is the sum of the carbon surcharge and the average EU ETS carbon price paid by conventional generators. It is equal to the net cost without carbon cost savings, divided by CO2 emission reduction. The column *Average* is the average annual CO2 abatement costs weighted over CO2 emission reductions. Fig. 1 shows the costs and cost savings per tonne of CO2 (tCO2). These are calculated by dividing the cost and cost savings over the CO2 emission reduction. Fig. 2 shows the costs and cost savings per tonne per MWh of wind and solar energy, they are calculated by dividing the cost and cost savings over the total annual electricity produced by wind and solar (Table 1). Costs are above zero, cost savings are below zero and the black bars indicate the carbon surcharges in Fig. 1 and the net costs per MWh of wind and solar energy in Fig. 2. All data are in €(2011).

Wind

		2008	2009	2010	2011	Average
Costs						
Equalized remuneration	[M€]	681	937	1143	1400	
Additional balancing Cost	[M€]	10	14	18	20	
Cost Savings						
Fuel cost saving	[M€]	419	378	490	674	
Carbon cost saving	[M€]	28	42	54	51	
Capacity saving	[M€]	23	34	42	52	
Net Cost	[M€]	220	498	576	642	
CO2 emission reduction	[MtCO2]	2.1	3.0	3.7	4.1	
Carbon surcharge	**[€/tCO2]**	**103**	**166**	**157**	**157**	**150**
Implicit carbon price	**[€/tCO2]**	**116**	**180**	**172**	**170**	**164**

Table 6: annual carbon surcharge and annual implicit carbon price for wind energy. Data are in €(2011)/tCO2.

Solar Photovoltaic

		2008	2009	2010	2011	Average
Costs						
Equalized remuneration	[M€]	123	370	1068	4686	
Cost Savings						
Fuel cost saving	[M€]	16	35	104	736	
Carbon cost saving	[M€]	1	4	11	53	
Net Cost	[M€]	106	334	962	3949	
CO2 emission reduction	[MtCO2]	0.1	0.3	0.7	4.2	
Carbon surcharge	**[€/tCO2]**	**1399**	**1263**	**1303**	**930**	**1005**
Implicit carbon price	**[€/tCO2]**	**1412**	**1277**	**1318**	**943**	**1018**

Table 7: annual carbon surcharge and annual implicit carbon price for solar PV energy. Data are in €(2011)/tCO2.

The annual carbon surcharge for wind was between one to two hundred euro per tCO2. The average value for the period 2008-2011 was 150 €/tCO2. The carbon surcharge for solar PV for the period analyzed was much higher: in average 1005 €/tCO2. Looking at the entries of the net cost, we observe that this is mostly determined by the equalised remuneration, and the fuel saving. The other costs and savings are small, if not irrelevant, with respect to these two. The large difference between the results of wind and solar energy is due to the net cost. Fig. 2 shows that fuel cost savings over energy production per MWh of wind and solar are comparable as both technologies displace energy produced by gas-fired power plants. Instead the equalized remunerations per MWh of solar are much higher than those of wind making the net costs of solar greater than the net costs of wind. This happens because the incentive schemes for PV grant higher remunerations than incentive schemes for wind.

We also observe that the carbon surcharge has changed considerably from year to year. This reflects the changes in the annual net cost. One of the causes is the variation in annual fuel cost savings and carbon cost savings, which are linked to the fluctuations of fossil the fuel prices and the carbon prices. Wind energy has its minimum carbon surcharge in year 2008 because of the high fuel cost saving, due to the high prices for coal and gas in that specific year. Solar has also the highest fossil fuel price in 2008, but its impact on the total net cost is less than for wind because of its higher equalised remuneration. The decrease in the solar carbon surcharge from 2008 to 2011 is due to the decrease in the equalized remunerations per tCO2. This decrease is due to two factors. First, the general decrease of the tariffs levels for new installed capacity (see Table 4). Second, the fact that, in the most recent years a greater number of large solar power plants were installed, which received a lower tariff with respect to smaller installations. In fact, the CE tariff level depends also on the capacity of the power plant: the larger the capacity, the lower the tariff.

The implicit carbon price, both for wind and for solar, is very close to the carbon surcharge. The average for the period analysed is 162 €/MWh for wind and 1018 €/MWh for solar. The difference between the implicit carbon price and the carbon surcharge is only in the carbon cost savings which is not taken into account in the implicit carbon price. The carbon cost savings is quite small with respect to the main entries of the table: the equalized remuneration and the fossil fuel saving. This occurs because the level of the EU ETS carbon price in the period analysed was quite low (the average value in the year 2008-2011 was 13.4 €/tCO2). Therefore, if we compare the implicit carbon price with the historical annual average EU ETS

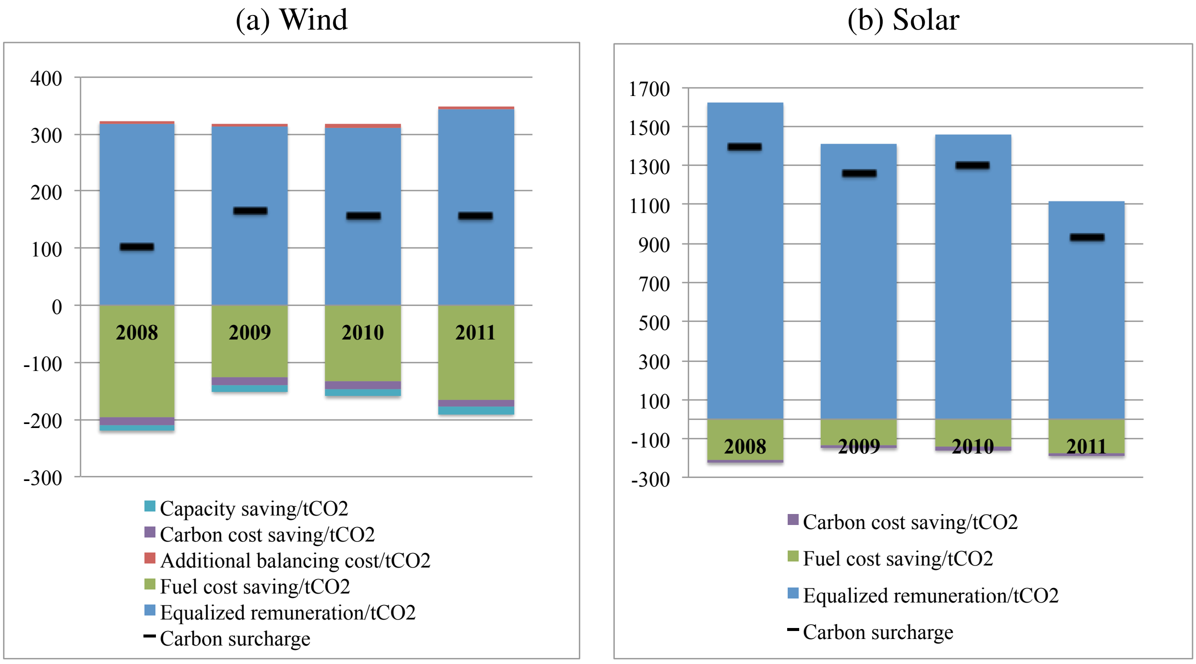

Figure 1: (a) costs and cost savings of wind energy per tCO2 abated. (b) costs and cost savings of solar energy per tCO2 abated. Costs are positive numbers, cost savings are negative numbers. Data are in €(2011)/tCO2. Note the difference in scale between the two figures.

carbon price, the implicit carbon price is both much higher than the historical EUA prices, especially for solar energy. Moreover, it is also much higher than any realistic prediction on EUA prices in the next years.

Due to data availability, our research only covers the years 2008-2011. In this period, remunerations for RE have been reduced in these last years, especially for solar energy, and it is foreseen that they will keep decreasing in the future. For solar, the CE for new installed capacity has come to an end in 2013. For wind, as of 2013, the CV system has been substituted by an auctioning system for new capacity which is expected to remunerate wind energy with lower tariff. The decrease in the support scheme was done due to higher-than-expected reduction of the capital cost for wind and solar installations, as well as because the cost of these support schemes have become very expensive for consumers (Verde and Pazienza, 2013). Thus we expect that the annual carbon surcharges in the next years would be lower than those calculated until 2011. However, also with lower REI, the annual carbon surcharge may still remain high. In fact the annual carbon surcharge is not directly proportional to the most recent level of remuneration. Firstly, this depends also on the fossil fuel prices. Secondly, the annual carbon surcharge takes into account all the capacity in service in the year analyzed and not only the capacity built in the last year.

For example, if we calculate the carbon surcharge only for the new capacity built in year 2013, the level would be lower than those in Table 6 because of the lower remuneration. Nevertheless, to estimate the annual carbon surcharge in 2013, we have to consider not only the costs and the benefits of the capacity built in year 2013, but also of all the capacity built in previous years that is still active in 2013. Therefore, we have to take into account also the capacity built before 2012, which will continues to receive higher remuneration for many years. This implies that the reduction of carbon surcharge depends not only on the level of reduction of remuneration but also on how much capacity is built with the lower remuneration. There is a

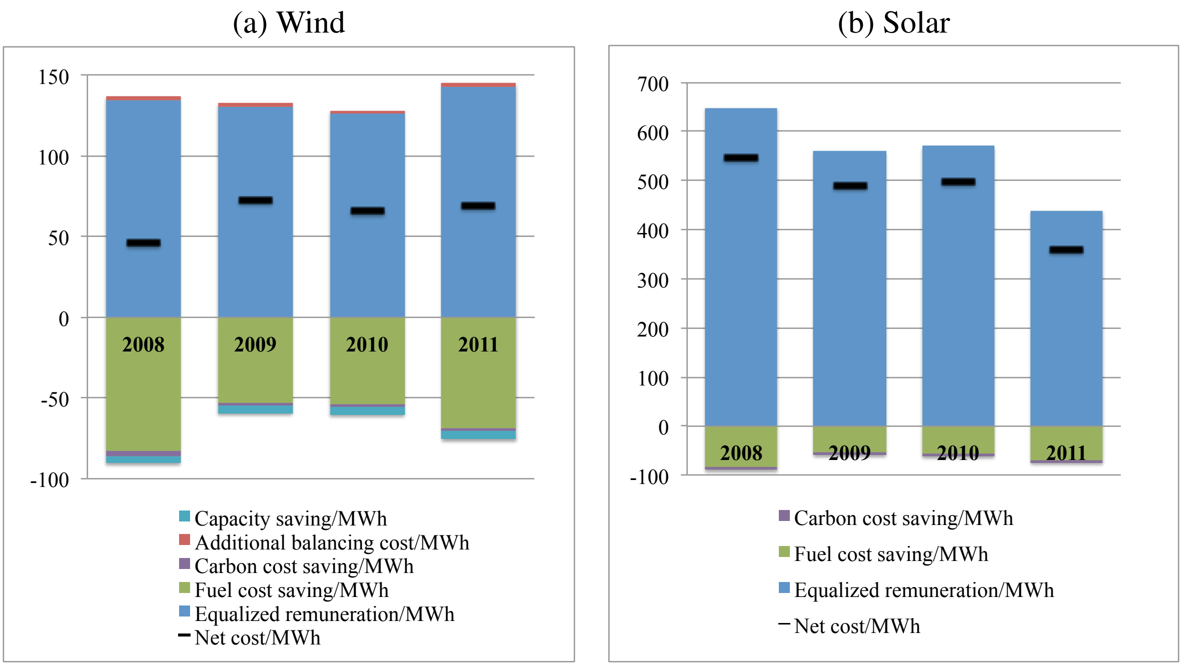

Figure 2: (a) costs and cost savings of wind energy per MWh of wind energy generated. (b) costs and cost savings of solar energy per MWh of solar energy generated. Costs are positive numbers, cost savings are negative numbers. Data are in €(2011)/MWh. Note the difference in scale between the two figures.

lot of uncertainty regarding how much solar and wind capacity will be built in Italy in the next years with lower remuneration. Data for solar suggest that with the decrease of the RE support scheme the level of capacity build decreases. In 2012 and 2013 when the CE level of tariff has been sharply reduced with respect of the previous year, the new solar capacity built was 3.6 GW in 2013 and 2 GW in 2013 against the 9.3 GW installed in 2011. Thus even with large reduction of the remuneration, the annual carbon surcharge might still remain high in the next years.

5.2 Sensitivity analysis

Tables 8 and 9 show the carbon surcharge under alternative assumptions about the future electricity price, the cost of capital and, in the case of wind, the capacity credit used to estimate the capacity saving. They show that the results of our analysis are quire robust. The average carbon surcharge of wind energy ranges between 129 €/tCO2 and 183 €/tCO2, while for solar between 923 €/tCO2 and 1043 €/tCO2.

We did not calculate the capacity saving and the additional balancing cost for solar in the base case scenario due to little available data. In order to make an estimation of the impact of these costs on solar, we calculated the carbon surcharge for solar considering that it has the same additional balancing cost and capacity saving of wind. If we include an additional balancing cost of 2 €/MWh, the average carbon surcharge in the period 2008-2011 increases only to 1007 €/tCO2, while if we consider a capacity saving calculated as described in Session 3.4 with a 10% capacity credit, it decreases only to 956 €/tCO2. This shows how these two costs have a minor impact on the carbon surcharge of solar.

Wind	2008	2009	2010	2011	Average
Base case	**103**	**166**	**157**	**157**	**146**
€50/MWh electricity price	84	148	137	133	129
€100/MWh electricity price	122	184	177	182	171
5% cost of capital	88	153	145	145	138
10% cost of capital	122	183	172	172	183
5% capacity credit	152	106	169	160	153
15% capacity credit	138	91	153	144	142

Table 8: carbon surcharge of wind under different assumptions regarding future electricity price, cost of capital and capacity credit. Data are in €(2011)/tCO2.

Solar	2008	2009	2010	2011	Average
Base case	**1399**	**1263**	**1303**	**930**	**1005**
€50/MWh electricity price	1328	1195	1217	847	923
€100/MWh electricity price	1450	1312	1366	990	1065
5% cost of capital	1353	1223	1265	900	974
10% cost of capital	1456	1311	1347	965	1043

Table 9: carbon surcharge of solar under different assumptions regarding future electricity price and cost of capital. Data are in €(2011)/tCO2.

6 Comparison with the German case

In this Section we compare the results for Italy with the results that Marcantonini and Ellerman (2015) calculated for Germany. We can do a meaningful comparison because the methodology and the main assumptions used to calculate the carbon surcharge and implicit carbon prices are the same in both studies, and because the models used to simulate the power sectors are similar. The results for Germany were calculated by using a model developed by Weigt et al. (2012), while we run the ELFO++ model. Both models are deterministic unit commitment models that simulate the optimal dispatching of electricity generation on hourly time by minimising the total generation costs. Moreover both models are calibrated to replicate historical observed yearly generation by fuel. Weigt et al. (2012) also calculate the startup costs that we do not take into account for lack of information about these costs in Italy. However, startup costs are much lower with respect to fuel costs, at least on order of magnitude smaller, and their impact on the total cost of generating electricity is marginal (Van den Bergh et al., 2013).

The periods analyzed for Italy and Germany are close but not the same. We have data for Germany for the years 2006-2010 while for Italy for the years 2008-2011. The different inputs used for the model reflects the difference between the Italian and German power sectors. In particular we use different estimations for the fossil fuels price. The prices paid for coal, gas and oil by fossil-fuel generation producers are not published. They are often fixed in long term contracts which are not disclosed. Weigt et al. (2012) use the prices published by the German Federal Office of Economics and Export Control. These prices refer to German market and cannot be applied to Italy. For our analysis we use monthly estimations made by REF-E based on the analysis of the European historical spot prices of oil and gas and on information that REF-E regularly collects about the Italian gas market and electricity market. For the years 2008-2010 for which we have data both for Italy and Germany, the prices estimated for coal used in our simulations are close to those used by Weigt (about 3% higher in Italy). In contrast, the prices for gas we use for Italy are about 40% higher than those used for Germany. This difference reflects partialy the differences between the Italian and German gas markets. It is also explained because the prices used by Weigt are cross-border prices which do not include additional costs paid by generators such as transmission and distribution, while the prices we use for the simulations reflect the entire cost for the gas to be delivered to the plants.

Wind

Italy		2006	2007	2008	2009	2010	2011
Net cost per MWh	[€/MWh]			46	72	66	69
CO2 emission reduction per MWh	[tCO2/MWh]			0.4	0.4	0.4	0.4
Carbon surcharge	**[€/tCO2]**			**103**	**166**	**157**	**157**
Germany							
Net cost per MWh	[€/MWh]	34	31	16	39	44	
CO2 emission reduction per MWh	[tCO2/MWh]	0.7	0.7	0.8	0.8	0.7	
Carbon surcharge	**[€/tCO2]**	**47**	**47**	**21**	**51**	**62**	

Table 10: *Net cost per MWh* for Italy, see Table 6. *CO2 emission reduction per MWh* for Italy is given by the *Net cost per MWh* over the annual electricity produced by wind, see Table 1. Source for Germany: Marcantonini and Ellerman (2015). Data are in €(2011).

Solar

Italy		2006	2007	2008	2009	2010	2011
Net cost per MWh	[€/MWh]			559	501	508	365
CO2 emission reduction per MWh	[tCO2/MWh]			0.4	0.4	0.4	0.4
Carbon surcharge	**[€/tCO2]**			**1399**	**1263**	**1303**	**930**
Germany							
Net cost per MWh	[€/MWh]	373	398	362	391	340	
CO2 emission reduction per MWh	[tCO2/MWh]	0.7	0.6	0.8	0.7	0.6	
Carbon surcharge	**[€/tCO2]**	**552**	**627**	**439**	**557**	**547**	

Table 11: *Net cost per MWh* for Italy, see Table 7. *CO2 emission reduction per MWh* for Italy is given by the *Net cost per MWh* over the annual electricity produced by solar, see Table 1. Source for Germany: Marcantonini and Ellerman (2015). Data are in €(2011).

For the comparison, we will only focus on the carbon surcharge. Tables 11 and 10 compare the results of Italy and Germany for wind and solar energy. They show the carbon surcharge for wind and solar as well as the net cost and CO2 abatement reduction per MWh of wind and solar energy. Fig. 3 shows the costs and cost savings per MWh of wind and solar energy for Germany. As for Fig. 2, costs are above zero, cost savings are below and the black bars indicate the net cost per MWh of wind and solar energy. We observe that the Italian carbon surcharge both for wind and solar ,is about twice as high as in Germany. As shown in Tables 10 and 11, this is because Italy has a higher net cost per MWh and lower CO2 reduction per MWh than in Germany both for wind and for solar. Given that the carbon surcharge is the net cost divided by the CO2 emission reduction, the higher cost and lower emission reduction make the Italian carbon surcharge much higher than in Germany. Regarding the CO2 emission reduction, the different level of abatement is due to the different sources used to generate electricity. In Italy the most important source of electricity is gas, while in Germany is coal. In Italy gas tends to be always at margin and renewable energy displays almost only gas, while in Germany wind and solar energy displays both gas and coal. Given that coal-fired power plants emit much more than gas-fired power plants per each MWh of energy produced (about twice as much), in Italy wind and solar energy reduced much less CO2 emissions per MWh of energy produced than in Germany. For example in 2010, in Italy 51% of energy came from gas-fired power plants and only 13% from coal. In Germany, on the contrary, in 2010 coal accounted for 42% of energy production, while gas for 13%. Wind(resp. solar) energy in 2010 has displays 95%(98%) of gas and 5%(3%) of coal in Italy while in Germany 41%(47%) of gas and 59%(51%) of coal. This explains why in 2010 one MWh of wind(resp. solar) energy displaced 0.7(0.6) tCO2 in Germany and only 0.4(0.4) tCO2 in Italy.

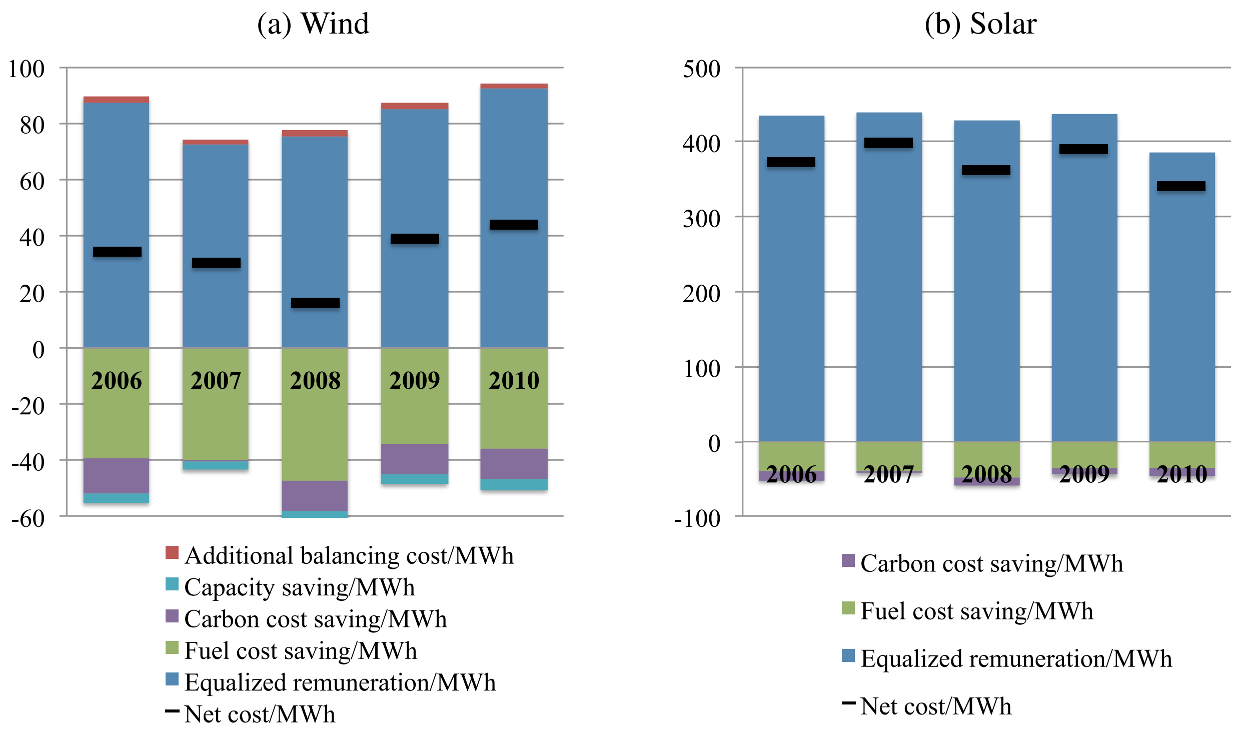

Figure 3: net cost of renewable in Germany: (a) costs and cost savings of wind energy per MWh of wind energy generated; (b) costs and cost savings of solar energy per MWh of solar energy generated. Costs are positive numbers, cost savings are negative numbers. Data are in €(2011)/MWh. Note the difference in scale between the two figures. Source: Marcantonini and Ellerman (2015).

Regarding the net costs, if we compare the data in Figs. 2 and 3, we see that what makes the Italian net cost higher are the equalized remuneration which for the years 2008-2010 are on average 131 €/MWh for wind and 593 €/MWh for solar, about 70% and 30% higher than for Germany whose levels are 77 €/MWh for wind and 450 €/MWh for solar. We may ask if this difference in remunerations is justified. If we look at the capacity factors, from the analysis of historical data, for Germany it was assumed an average capacity factor of 18% for wind and 8% for solar, while we assume for Italy 17% for wind and 12% for solar. The capacity factor for wind is comparable, while for solar is 50% higher in Italy. This is not surprising given that Italy is notably much sunnier than Germany. Assuming that the capital cost for wind and solar in the two countries are similar, from the comparison of the capacity factor we would expect similar levels of remuneration for wind in the two countries, and higher levels for solar in Germany. What we have instead is that the remunerations for both technologies are much higher in Italy, suggesting that the Italian RE policies might be unnecessarily more generous than the German one.

Regarding the cost savings we notice that the carbon cost savings are higher in Germany while the fossil fuel saving is higher in Italy. Germany has higher carbon cost savings because RE reduces more CO2 emissions than in Italy. Italy has higher fuel saving because, unlike Germany, it saves mostly gas whose price is higher than the price of coal per MWh of energy generated. Even if the price of gas we use for Italy is higher than the price of gas used by Weigt for Germany, the higher fossil fuel saving in Italy does not compensate for the increase in the equalized remuneration.

7 Conclusion

In this paper, we evaluated the cost of reducing CO2 emissions in the power sector through the deployment of wind and solar PV energy in Italy from 2008 to 2011. We thus determined the carbon surcharge and the implicit carbon price. The results indicate that the carbon surcharge for wind energy is 164 €/tCO2 in average from 2008 to 2011, while the implicit carbon price 150 €/tCO2. For solar energy, the carbon surcharge and implicit carbon price are higher than for wind energy, respectively 1005 €/tCO2 and 1018 €/tCO2 in average. The difference between wind and solar is due to the different level of remunerations. The incentive scheme for solar allows higher remunerations per MWh of generated electricity than those for wind.

The carbon surcharges calculated for Italy are much higher than those calculated for Germany in the period 2006-2010. We showed that the difference in the carbon surcharge between the two countries is due to two main factors. The first is the higher level of remuneration for solar and wind energy in Italy with respect to Germany. This determines higher net cost for the Italian RE. The difference in remuneration between the two countries comes from the different national RE support schemes. The second factor is linked to the difference of the national power sectors: in Italy it is dominated by gas, and in Germany by coal. This means higher CO2 abatements in Germany because RE displaces coal power generation, which is more carbon intense than gas.

As for any other similar research, our work is based on simplifying assumptions. In particular, we did not consider the interaction between the RE support scheme and the EU ETS, neither the interaction between the impact of RE on the demand of electricity. Addressing these issues in a rigorous way is left for future research. Moreover this work only focuses on the RE as an instrument to reduce CO2 emissions in the power sectors. We do not take into account other important benefits of RE such as energy security or economic development. Quantifying these other benefits is an important future area of research which is necessary for a comprehensive cost-benefit analysis of the RE policies.

To conclude, this research shows that the cost of abating CO2 emissions by deploying RE may be substantially different depending on whether it refers to wind or solar energy. In Italy, in the period analyzed, Solar was more costly than wind. Our research also shows that the cost may largely differ from country to country in Europe. If the EU and the Member States want to reduce emissions at the lowest cost, policy makers should consider these differences when devising RE policy.

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