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Wind and solar energy: a comparison of costs and environmental impacts

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Abstract. This study is concerned with the analysis of two renewable technologies for electric energy production: wind energy and photovoltaic energy. The two technologies were assessed and compared by economic point of view, by using selected indicators characterized by a clear calculation approach, requirement of information easy to be collected, clear, but even complete, interpretation of results. The used economic indicators are Levelized Cost of Energy, CO_2 abatement cost and fossil fuel saving specific cost; these last two specifically aimed at evaluating the different capabilities that renewable technologies have to cut down direct CO_2 emissions and to avoid fossil fuel extraction. The two technologies were compared also from the environmental point of view by applying Life Cycle Assessment approach and using the environmental impact categories from the Eco-indicator'95 method. The economic analysis was developed by taking into account different energy system sizes and different geographic areas in order to compare different European conditions (Italy, Germany and Denmark) in term of renewable resource availability and market trend. The environmental analysis was developed comparing two particular types of PV and wind plants, respectively residential and micro-wind turbine, located in Italy. According to the three calculated economic indicators, the wind energy emerged as more favorable than PV energy. From the environmental point of view, both the technologies are able to provide savings for almost all the considered environmental impact categories. The proposed approach, based on the use of economic and environmental indicators may be useful in supporting the policies and the decision making procedures concerned with the promotion and use of renewables, in reference to the specific geographic, economic and temporal conditions.

Keywords: renewables; wind energy; photovoltaic; economics; Life Cycle Assessment

1. Introduction

The renewable energies quota in the countries' energy mix is overall expanding and a continuous increase is expected to be beneficial since could guarantee a more safe, reliable and accessible energy supply (IRENA 2012a). In Europe, the renewable energies exploitation is seen as the key factor for reaching the 2020 climate and energy package targets. The "20-20-20" package is a set of directives (2009/28/EC, 2009/29/EC, 2009/30/EC, 2009/31/EC, 2009/406/EC, 2009/443/EC, 2012/27/EU) involving the European Union the climate and energy targets for 2020:

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a 20% reduction in EU greenhouse gas emissions from 1990 levels; increasing the share of EU energy consumption produced from renewable resources up to 20%; a 20% improvement in the EU's energy efficiency. Moreover, the renewable energy is considered a promising sector in term of occupation; around five millions of people are currently involved, directly and indirectly, in this industrial sector, one million and half in Europe (REN21 2012).

Electric energy, thermal energy, transports and off-grid systems are the four areas where the renewable energies are awaited to be competitive (REN21 2012).

According to Eurobserv'ER, in the EU 27 Countries the renewable contribution to the gross energy demand (electricity, thermal and transport) is increased from 12.9% (2011) to 14.3% (2012) or 15% (2013), against the target of 20% (EurObserv'ER 2014).

As for the electricity, the renewable energies cover 23.4% of the European consumption in 2012 and increase to 25.4% in 2013 (EurObserv'ER 2014). Meanwhile a different distribution between the different sources and technologies is registered, moving from a predominance of hydroelectric (84%) in the previous years to a variegated mix made up of 43.3% of hydroelectric, 27.5% wind, 18.4% bioenergy, 10% solar energy, 0.7% geothermal and 0.05% ocean energies in 2013 (EurObserv'ER 2014).

For the time being the main elements affecting their diffusion are: resource availability, technology reliability, economic competitiveness and support schemes (i.e., subsidies) (REN21 2012). A significant worldwide increase in term of technology reliability has been registered in the renewable energy industrial sector. A virtuous circle has been generated by the combination of technological advancement, the growing interest for renewables and the numbers of subsidies, leading to a general price decrease of technology. This is particularly true for solar energy and biomass, whereas hydroelectric and wind were already considered solid and competitive technologies (IRENA 2012c).

Nevertheless, it is evident that aside from the technological and economic feasibility, the effective applicability and sustainability depend on the available resource.

As a consequence it is not possible to identify a single best technology but a set of technologies needs to be selected according to trade-off between economic and environmental issues, for a given Country. This is the reason why a comprehensive analysis and comparison of the different renewable technologies relies on the integration of local specific environmental and economic analysis.

There are many available indicators which can be used to quantify and compare the advantages/disadvantages of renewables technologies. Many of them seek to evaluate the potential benefits deriving from the substitution of traditional systems; in particular the possibility of carbon dioxide emissions abatement and the reduction of fossil fuels use, by taking into account the current and future energy demand.

Being the absence of emissions during the use phase one of the main features of renewable technologies, a life cycle-based approach has been considered one of the most promising and interesting in order to evaluate the energetic and environmental performances of such technologies as a whole. This approach allows avoiding burden shifting since production, installation, operating, dismantling and disposal phases are all included in the analysis.

A review of the available indicators has been developed in order to have an overview of the mostly used for comparing renewable energies. They can be ranked into three main classes: i) energy efficiency/intensity; ii) environmental sustainability; iii) economic sustainability.

The first group includes indicators like *Embodied Energy*, the energy used for producing and assembling materials, and *Cumulative Energy Demand (CED)*, the primary energy involved along the life cycle steps of the technology (Nawaz and Tiwari 2006, Gürzenich *et al*. 1999). The *Energy Yield Ratio (EYR)* is another indicator representing the ratio between the produced energy (net, gross or primary energy) and the CED value. Both CED and EYR are life cycle-based indicators which are usually used to quantify the energy intensity of a system (Giirzenich 1999). The *Energy Pay Back Time (EPBT)* is another widely-used indicator defined as the time (years) necessary for an energy system to produce a certain quantity of energy for counterbalance the energy consumption over its life cycle (Lu and Yang 2013).

The Life Cycle Assessment (LCA) is a well-known method already used by several actors (e.g., companies, authorities, research) in the energy sector (Vargas *et al*. 2015, Behadili and El-Osta 2015, Xue *et al*. 2015, McManus and Harajli 2015, Fthenakis and Kim 2011a, Qu and Zhao 2012, Koroneos and Nanaki 2012).

Life Cycle Assessment (LCA) offers a systematic approach to evaluate the main inputs and outputs in terms of materials, energy and emissions, while identifying and quantifying the material used and the associated energy and emissions; then it allows estimate the potential environmental impacts throughout products' lifetime span (cradle-to-grave) including the materials extraction, its processing, manufacturing, transport, use, re-use, maintenance, and finally its end-of life (ISO 14040 2006). In this sense there are many indicators which mainly differ in the involved environmental compartment, geographic scale and method of analysis. The most important and recognized methods are CML, Eco-Indicator, EDIP e ReCiPe (European Commission, Joint Research Centre, and Institute for Environment and Sustainability 2011); all of them offer a different set of impact categories (e.g., acidification, eutrophication, ozone layer depletion).

As a consequence, many of the environmental indicators of the second group stemmed from the LCA family. The *Carbon Footprint (CF)* is one of the most popular among the single-indicators and measures the global warming potential of greenhouse gasses emissions (expressed as kg $CO_{2\text{-equivalent}}$) (Agrawal and Pandey 2010, ISO/TS 14067 2013). The *Carbon Pay Back Time (o CO_2 pay back time* - $CO_{2eq\ PBT}$) is similar to the EPBT principle and it is particularly used for the renewable energies to calculate the time required to avoid a certain amount of CO_2 emissions for compensating the CO_2 emissions produced during the energy system life cycle (Marimuthu and Kirubakaran 2013).

The economic feasibility and sustainability of a given renewable technology is overall evaluated by means of different indicators and models. They usually include the cost associated to the whole system life cycle and are evaluated by means of static or dynamic approach, depending on the expected outcomes. Net present value, Total Life Cycle Costing, Discounted or Simple payback period are some examples of indicators which take into account even the legislative context, the level of risk, the subsidies scheme, the cash flow and the cost-benefit (IRENA 2012a).

The *Levelized Cost of Energy (LCOE)* is one of the most used economic indicator and represents the ratio between the total cost of producing, installing and operating a technology and the electricity generated by the system during its life span (National Renewable Energy Laboratory 2015). However, the *Total Life Cycle Costing (TLCC)* or *Life Cycle Costing analysis (LCC*) is another significant indicator generally used in the energy sector, among others (Short *et al*. 1995). Moreover, it has been suggested as a consistent framework for combining with LCA analysis (Hunkeler *et al*. 2008). LCC is defined as "An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or EoL actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future" (Hunkeler *et al*. 2008). Unlike the LCA ISO standards, there are currently no standards available which are valid for LCC of products or services; therefore different approaches exist even depending on the sector of origin (Schau *et al*. 2011).

In the recent years new indicators have been proposed to evaluate the cost due to CO_2 and GHGs abatement; as a matter of fact different abatement actions in several sectors (e.g., energy, agriculture, building, transports) have different investment cost. In the energy sector, a simple but effective indicator is the *CO_2 abatement cost* that correlates the costs and the avoided CO_2 emissions of a given technology; nevertheless a unique evaluation method does not exist (Wesselink and Deng 2009, Lang 2011).

Overall, the review stresses that several energetic, environmental and economic indicators are available in literature; this high quantity, along with heterogeneity of names and calculation approaches make the indicator selection not easy. For the present work the indicators selection have been done according to the following features: a clear calculation approach, use of information easy to be collected, clear, but even complete, interpretation of results.

Therefore the selected indicators are LCOE and environmental impact categories from the Eco-indicator'95 method, along with two more indicators, called CO_2 abatement cost and fossil fuel saving specific cost, which has been specifically defined in the present study with the aim of evaluating, in a simplified way, the different capabilities that renewable technologies have to cut down direct CO_2 emissions and to avoid fossil fuel extraction.

The present paper is aimed at addressing a comparison of two different technologies - photovoltaic and wind- as the most diffused in many European countries and the ones demonstrating the highest industrial potential advancement (REN21 2012), by taking into account the over mentioned indicators.

The analysis has been developed by taking into account different energy system sizes and different geographic areas in order to compare different European conditions in term of renewable resource availability and market trend. In particular, for the economic analysis, the following solutions have been compared:

- photovoltaic technology: two geographic areas - Italy and Germany - and two power plant sizes - residential and industrial;
- wind energy: three different geographic areas - Italy, Germany and Denmark - and two system solutions - on-shore and off-shore.

Whereas the environmental analysis concerns the comparison of four PV technologies (residential scale) and one wind technology (micro-wind turbine 5kW) installed in central Italy (latitude 43° N, longitude 11° E, south direction) (ENEA 2015, Cartografia di base DEAGOSTINI 2015).

2. Economic evaluation

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development.

2.1 Economic indicators

Three economic indicators are used in this work: Levelized Cost of Energy (LCOE), CO_2 abatement cost and fossil fuel saving specific cost. They are described in the following paragraphs.

2.1.1 LCOE

The LCOE is a widely used measure for evaluating the economic efficiency of different energy technologies within a policy development perspective.

The LCOE is the total cost of installing and operating a technology expressed in euro per kilowatt hour of electricity generated by the system during its life span.

There are many potential trade-offs to be considered when developing an LCOE modelling approach; many data about costs and performance of renewable energy technologies are necessary but not always available, accurate or updated; therefore many assumptions are needed in order to complete the model. According to what is expressed in literature (IRENA 2012a), when the model is applied to a wide variety of power technologies in different countries, a simplified calculation needs to be used in order to reduce assumptions and uncertainties, improve transparency and enhancing interpretation of results and identification of the main drivers of LCOE variations. The approach used in this study is relatively simplified allowing the development a pure cost analysis, based on a discounted cash flow analysis, meaning a discounting financial flows to a common basis taking into consideration the time value of money, rather than a financial analysis. As a consequence, outcomes could be considered an estimate referred to the reference surrounding conditions and sensitive to assumptions especially regarding predictive parameters of performances.

The formula used for calculating the LCOE of wind and photovoltaic energy technologies is (1) (IRENA 2012a)

$$LCOE = \frac{C_{inv} + \sum_{i=1}^{N} \frac{O\&M_i}{(1+r)^i}}{\sum_{i=1}^{N} \frac{E_i}{(1+r)^i}} \tag{1}$$

where:

- C_{inv} investment expenditures in the first year;
- $O\&M_i$ operations and maintenance expenditures in the year i;
- E_i electricity generation in the year i;
- r discount rate;
- N life span of the system.

End-of-life costs, grid connection costs, incentives and costs due to externalities (carbon dioxide emissions reduction and other pollutants) are excluded. The same system boundaries were used for each technology/condition analysed in this study in order to reach robust and comparable results.

The data used in this work come from a variety of sources, mainly international agencies reports and scientific papers, and many efforts were made to select those data referred to the same temporal, technological and geographic scope of this study. Overall, a huge heterogeneity was found in the data and their system boundaries, therefore the assumptions necessary will be highlighted and explained in the following paragraphs on a case-by-case basis.

2.1.2 CO_2 abatement cost

The second economic indicator proposed in this study is the CO_2 abatement cost by which the two technologies - wind and photovoltaic - could be compared in term of their capability of CO_2 emissions avoidance during their use phase. Such indicator is expressed in euro per tonnes of avoided CO_2 emissions (Euro/t $CO_{2\ \text{avoided}}$). Several approaches can be found in literature about how to calculate it (Wesselink and Deng 2009, Lang 2011); the common intent is to correlate the costs and the avoided CO_2 emissions during the operating phase of a given technology due to the substitution of energy produced by traditional fuels or the mix of fuel of the national grid. A once-over allows detecting many differences and non-homogeneous system boundaries regarding costs and parameters considered for such analysis; as a consequence the outcomes can be unlikely compared.

Given these considerations, a simplified calculation of the CO_2 abatement cost is retrieved from (Wesselink and Deng 2009) and proposed in this work as in the following formula (2)

$$\mathrm{CO_2\ abatement\ cost} = \frac{\mathrm{annual\ amortization} + \mathrm{O\&M}}{\mathrm{CO}_{2\ \mathrm{avoided}} emissions} \tag{2}$$

where:

- Annual amortization and O&M are expressed in Euro/year;
- $CO_{2\ \mathrm{avoided}}$ emissions is expressed in tCO_2/year.

The annual amortization of the loan was calculated with the following formula (3)

$$\mathrm{annual\ amortization} = \frac{\left(\mathrm{C_{inv}} \times \left(1 + \frac{\mathrm{IR}}{\mathrm{TY}}\right)^{(\mathrm{TY} \times \mathrm{YR})}\right) \times \left(\frac{\mathrm{IR}}{\mathrm{TY}}\right)}{\left(\left(1 + \frac{\mathrm{IR}}{\mathrm{TY}}\right)^{\mathrm{TY} \times \mathrm{YR}}\right) - 1} \tag{3}$$

where:

- C_{inv} capital cost;
- IR interest rate;
- TY number of tranches of the loan per year;
- YR number of the years provided to pay back the loan.

The reference conditions are: interest rate equal to 6%, the tranche of the loan once per year and 10 years to pay back the loan. Since the assumed technologies life span is longer that the loan payback time, the annual amortization is present only during the first ten years and it is calculated according to investment and O&M costs listed in the following paragraphs, specific for each technology.

Contrasting conditions about avoided CO_2 emissions can be found in literature. In fact if some works consider only direct avoided emissions, that are emissions directly emitted during energy production by the energy country mix, other works consider the whole avoided life cycle emissions of the technologies present on the energy mix. In this study only the direct CO_2 emissions are considered as avoided burdens.

The CO_2 emissions factors of the electricity country mix - kg CO_2/kWh_{el} - are taken from (European Environment Agency 2015) and are presented in Table 1 for each geographic area analysed in this work.

Table 1 Summary of CO_2 emissions factors of the electricity country mix and average energy efficiencies for fossil-fired power generation of electricity for the geographic area analysed in this work

	IT	DE	DK
CO_2 emissions factor of the electricity country mix [$kgCO_2$/kWhel]	0.405	0.503	0.329
Average energy efficiency [$kWh_{electricity}/kWh_{Primary\ Energy}$]	0.46	0.40	0.43

2.1.3 Fossil fuel saving specific cost

The third economic indicator expresses the cost related to fossil fuel saving. In fact, according to the 2020 climate and energy package, the benefits expected from the renewable energy rely on both the reduction of CO_2 emissions and the reduction of the fossil fuel dependency, with consequent environmental, economic and strategic advantages for all the European member States (European Commission 2010).

The indicator fossil fuel saving specific cost would correlate the cost associated to the electricity production by means a given renewable technology (LCOE) with the amount of avoided/substituted fossil fuel. The fossil fuel saving specific cost is expressed in euro per tonne of oil equivalent - Euro/toe - is calculated by means of the following formula (4)

$$1\text{ toe saving specific cost } = \text{LCOE } \times \text{CF } \times \eta \tag{4}$$

where:

- LCOE expressed in Euro/kWh;
- CF conversion factor equal to 11630 $\text{kWh}_{\text{Primary Energy}}$/tep;
- η energy efficiency for average fossil-fired power generation of electricity country mix ($\text{kWh}_{\text{electricity}}/\text{kWh}_{\text{Primary Energy}}$).

The energy efficiency for average fossil-fired power generation expresses the ratio between the produced electricity and the primary energy; Table 1 reports the values for the three countries analysed in this study. The LCOE figures are the ones calculated in the following paragraph.

2.2 Economic data input

The economic data used in this work derived from a significant review and selection of information from different sources. Since the costs depend on technology, power plant size, country and time, the desk research was developed according to these features in order to collect a considerable number of information and gather representative and reliable economic data.

2.2.1 Photovoltaic

For what concerns the photovoltaic technology, three main contributes can be seen for the investment: module cost, BOS - balance of system (inverter, cabling and supporting structure) cost and installation cost. During the last 30 years, the research and the industrial processes advancement allowed to reduce the investment cost, especially regarding the module, whose contribute to the total investment was reduced from 60-75% to 50-60% (European Photovoltaic Industry Association 2011). On the other side the contributions of the inverter, the design phase and of the other elements (cables, supporting structure and installation) remain around 10%, 7% and 20.30% respectively (European Photovoltaic Industry Association 2011).

The module type and the system installation (roof-top, ground based) could contribute to a cost variation. Overall, the silicon based modules have a higher cost, between 0.8-1.5 €/Wp, while the cost of thin film module range between 0.6 and 0.7 €/Wp (European average value calculated from (IRENA 2012a)). The BOS cost is generally higher in the case of rooftop installation (IRENA 2012a).

A large variability can be seen depending on markets and size; Germany was found to be the best market for photovoltaic with an investment cost lower than the European average cost both for residential and industrial sizes (Carnevale *et al*. 2014). The effect of economies of scale is visible and reduces the difference between the different markets regarding industrial scale (IRENA

2012a).

If several sources and information can be found about investment costs, this is not true for the operating and maintenance (O&M) costs. A huge disagreement was found between the different sources (Nuclear energy agency 2005, IRENA 2012a, Pathak and Pearce 2011) thus a detailed analysis cannot be conducted. According to Branker *et al*. (2011) the O&M costs are the sum of operating costs and the maintenance costs, equal to 1.5% and 9% of the investment expenditure respectively.

For the photovoltaic technology, the present work focused on two geographic areas - Italy and Germany[1] - and two power plant sizes - residential and industrial - in order to compare two different European conditions in term of energy source availability and market trend. The economic inputs for these cases are reported in Table 2. The investment costs are average values for the given country elaborated from (IRENA 2012a), while O&M costs were calculated according to the percentage declared by Branker *et al*. (2011). The electricity production was calculated for the two different geographic areas with two different climatic conditions. The first case, representative of central Italy (latitude 43° N, longitude 11° E, south direction), has a solar radiation of 1561 $kWh/m^2 \cdot year$ (ENEA 2015), while the second case, representative of the central/north area of Europe has a solar radiation of 1091 $kWh/m^2 \cdot year$ (RHC 2012). The energy output was calculated assuming an efficiency of 14.9% with an annual reduction of performances up to 90% and 80% of the nominal power during the first 10 years and successive 10 years, respectively, according to data sheet of silicon-based modules available on the market (Lombardi and Zanchi 2014). The system performance ratio was set at 85% (European Photovoltaic Industry Association 2011) and the life span was assumed 20 years.

2.2.2 Wind energy

For the wind energy, the economic analysis involved three different geographic areas - Italy, Germany and Denmark - and two system solutions - on-shore and off-shore.

The investment expenditure could depend on reference market, size and site of installation. China and Denmark are the best market in term of prices, followed by Spain, Germany and Italy (IRENA 2012b). Even if the large scale plants (> 1MW) could be considered reliable technologies, their cost are still generally high. The 64% of the investment cost is due to turbine, followed by civil works (i.e., preparation of the area, basement construction) (16%) and grid connection (11%). It is important to consider that the source availability is often linked to sites difficult to be reached; this means that costs for civil works and grid connection could increase considerably (ENEA 2011). Overall, the off-shore plants have investment costs higher than on-shore due to higher expenditure for civil works (around 30%). Moreover, a cost that should not be neglected is related to transports of turbine elements, whose big dimensions need for specific oversize loads.

Mini ($0.5 < P < 100$ kW) and micro (0.5 kW) wind energy still need further technology progress both in term of reliability and costs. If compared with on-shore technology their investment expenditure and energy production are more variable and it is not possible to have good estimates for them (IRENA 2012b). For this reason the economic part of this study involved only large scale plants.

As in the case of photovoltaic technology, the O&M costs extracted from several sources suffer

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[1] Photovoltaic was compared only with reference to Italy and Germany, being the first two EU Countries for installed power; Denmark was not included in this comparison because of the very low installed power (EurObserv'ER 2014).

Table 2 Summary of economic inputs for photovoltaic and wind energy technologies for the different geographic areas

			Photovoltaic		Wind	
			Residential (2-10 kW)	Industrial (> 1MW)	on-shore	off-shore
IT	Investment	Euro/kW	4294	3699	1512	2170
	O&M	Euro/kW/year	23	19	24	114
	Electricity production within 20 years	kWh/kW	24430	24430	52560	78840
DE	Investment	Euro/kW	2854	2809	1353	1461
	O&M	Euro/kW/anno	15	15	40	51
	Electricity production within 20 years	kWh/kW	16816	16816	52560	78840
DK	Investment	Euro/kW	---	---	944	1342
	O&M	Euro/kW/anno	---	---	26	43
	Electricity production within 20 years	kWh/kW	---	---	52560	78840

of a huge variability and incongruence. Overall, they can be subdivided into fixed (i.e. insurance, administration, grid access fees and service contracts for scheduled maintenance) and variable costs (i.e., scheduled and unscheduled maintenance not covered by fixed contracts, replacement parts and materials) but they are not easy to obtain.

The economic inputs of on-shore and off-shore plants are listed in Table 2. The investment costs and O&M costs are average valued for the given countries elaborated from (IRENA 2012b) and (NEA 2005). Data from (IRENA 2012b) and (Nuclear energy agency 2005) above all were elaborated in order to calculate O&M costs referred to unit of installed power (Euro/kW/year) by means of the annual energy production (Carnevale *et al*. 2014). O&M costs of the off-shore plants were found to be higher than the on-shore case, this is mainly related to larger costs for maintenance operations. The electricity production was calculated by means of average values of capacity factors[2] from IRENA (2012c) which declares a range of 25-35% for the on-shore plants and a range of 40-50% for the off-shore plants, without distinguishing between geographic areas. The life span of both types of wind power plants was assumed 20 years.

3. Environmental assessment

It is widely demonstrated that Life Cycle Assessment (LCA) is a very useful tool to evaluate the environmental performances of products and services bringing powerful insights about all the technologies life cycle steps, from cradle to grave, measuring environmental, energy and resource sustainability (European Commission 2013, Fthenakis and Kim 2011a, Carnevale *et al.* 2014, Koroneos and Nanaki 2012, Martínez *et al.* 2009). In the field of the technologies for renewable

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[2] $\text{Capacity factor} = \frac{kWh/year}{kW \times 365 \times 24}$

energy exploitation, the LCA allows appraising environmental burdens and benefits in comparison with the fossil energy sources (Boldrin and Astrup 2013). Only turning the attention from the limited analysis of the functioning phase (direct emissions) to a wider analysis including also the construction and disposal steps, it is possible to analyse and demonstrate the advantages from an environmental point of view.

The LCA analysis could capture environmental impacts that accumulate over the entire life cycle (cradle-to-grave period) and spilt them into direct burdens, produced by the core part of the system, and indirect ones, occurred during background and foreground activities. This is particularly interesting for the renewable technologies which are expected to avoid direct emissions but generate inevitably indirect ones.

In order to evaluate the photovoltaic energy and wind energy from an environmental perspective, the LCA methodology was adopted in this study. In the following paragraph the steps of the analysis are reported in detail, according to the international standard EN ISO 14040.

According to the ISO 14040 and 14044 standards, LCA is an iterative process accomplished in four stages: goal and scope definition; inventory analysis; impact assessment; interpretation of results.

The goal and scope definition consists of setting the purpose and the application of the study, who is the audience that will receive and examine findings, what are the functional unit and the system boundaries. In the Life Cycle Inventory (LCI), data required for the analysis of the system are collected and processed to identify exchanges with the ecosphere during the life cycle stages. LCI is composed by a data collection phase followed by a modelling step where all elementary flows (materials, energy, emissions, etc.) of the system are characterized. The outcomes of LCI analysis become the input for the subsequent Life Cycle Impact Assessment (LCIA) phase where elementary flows are converted into potential impacts. The results need to be construed in order to find out which flows or life cycle phases impact more, how outcomes are sensitive to input data and assumptions. This phase aims at providing outcomes as much as confident and representative of the case study.

3.1 Goal and scope definition

The goal definition is the first phase of the LCA in which the purpose of the study is described. It identifies and defines the object of the assessment.

The goal of this assessment is to compare two different types of renewable energy production technologies: photovoltaics (PV) and wind energy (WD). For the photovoltaics case, four types of PV modules - silicon monocrystalline (mono-Si), silicon polycrystalline (multi-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS) - were already studied and the results of the analysis were reported in a previous publication (Carnevale *et al*. 2014): in this work those results are reported as the average values obtained for the four PV technologies. For the wind case, only one typology of micro-wind turbine was investigated. Table 3 shows the main characteristics of the considered PV modules and micro-wind turbine.

The adopted functional unit is defined as 1 kWh of electric energy produced by the compared technologies. The functional unit only includes electricity delivered to the electricity grid, without taking into account grid loss.

The system boundaries include the entire life cycle of the energy producing technologies, considering the construction phase, the operation phase and the dismantling one. The extraction of raw materials was included in the system boundaries. As the main aim of renewable energy

Table 3 Wind turbine and PV modules characteristics

Turbine type		Horizontal axis - three blades	PV type		mono-Si	multi-Si	CdTe	CIS
Power output	kW	5	Module surface area	m^2	1.64	1.64	0.72	1.07
Rotor diameter	m	6.37	n° cells	n°	60	60	154	104
Surface covered by blades	m^2	32	Power	Wp	245	245	87.5	135
Cut-in speed	m/s	4.1	Efficiency η	%	14.9	14.9	12.2	12.6
Nominal speed	m/s	12	BOS efficiency	%	85			
Cut-off speed	m/s	24	Inverter	W	250			
Life time	year	25	Life time	year	20 (inverter 15 years)			

production is to avoid the use of fossil fuels - providing benefits both in relation to global warming issue and to conventional fuel depletion - the avoided effects of producing conventional electric energy were included within the system boundary, considering the displacement of electric energy produced according to the Italian energy mix.

Waste treatment from installing and operating phase is not included. Life span of technologies was assumed 20 years whereas life span of inverter 15 years, therefore its substitution is foreseen.

The reference geographic area (geographic scope) is central Italy where energy source accessibility is 1561 kWh/(m^2·year) of solar radiation (ENEA 2015) and 1750 MWh/MW from the wind turbine (Cartografia di base DEAGOSTINI 2015).

3.2 Inventory

In this phase, all the inputs and outputs occurring in the life cycle of the systems previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary either into or out of the system itself.

3.2.1 Components production phase

Table 4 reports the inventory for the wind turbine construction phase, showing also the Ecoinvent database record used for each process. The main components of the wind turbine plant are: turbine (made by alternator, blades, and mechanical elements for connecting the alternators to the blades), tower (9 m height), braking resistance, controller inverter and electric system. The LCI compiling is based on primary data collected from technical sheet provided by the companies' personal communications and data elaborated from (de Wild-Scholten *et al*. 2006) for what concerns inverter.

The main components of the photovoltaic system are: module and BOS - balance of system (inverter, cabling and supporting structure). The photovoltaic technology consists of many different materials (silicon, metals, plastics, etc.) which generally need a more complex production phase (i.e., silicon transformation, wafer and cells production) if compared with the wind power technology. In this case the LCI was developed after a huge literature review about the current models. The materials and processes involved in the construction phase of PV plants have been retrieved from several sources reported in details in Table 5 according to (Carnevale *et al.* 2014).

Table 4 Inventory of micro-wind power plant production phase

	Components	Material	Amount	Unit	Ecoinvent process
Turbine	Alternator	Aluminum alloy	66.7	kg/turbine	Aluminium, production mix, wrought alloy, at plant/RER U
		Plastic	66.7	kg/turbine	Polymethyl methacrylate, sheet {RER}| production | Alloc Def, S
	Blades	Glass fiber	83	kg/turbine	Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER U
	Mechanical elements for connecting the alternators to the blades	Aluminum alloy	83	kg/turbine	Aluminium, production mix, wrought alloy, at plant/RER U
Other elements	Tower	Steel	500	kg/turbine	Steel, low-alloyed, at plant/RER U
	Electric cables	Copper	80	kg/turbine	Copper, at regional storage/RER U
	Braking resistance	Aluminum alloy	20	kg/turbine	Aluminium, production mix, wrought alloy, at plant/RER U
	Controller	Aluminum alloy	8	kg/turbine	Aluminium, production mix, wrought alloy, at plant/RER U
	Inverter	Steel	19.6	kg/turbine	See others
		Aluminum	2.8	kg/turbine	
		Printed circuit	3.6	kg/turbine	
		Transformer wires	11	kg/turbine	
	Basement	Concrete	2500	kg/turbine	Concrete, sole plate and foundation, at plant/CH U 1 m^3

Table 5 Inventory of PV technologies production phase (Carnevale *et al*. 2014)

	PV elements	Process	Source
	Module mono-Si	SG-silicon production	(Fthenakis *et al*. 2011b)
		Mono-Si wafer	
		Cell production	
		Module assembly	
	Module multi-Si	SG-silicon production	
		Multi-Si wafer	
		Cell production	
		Module assembly	
	Module CdTe	Module production	
	Module CIS	Module production	(Raugei *et al*. 2007)
BOS	Inverter	Case and electronic components production and assembly	(de Wild-Scholten *et al*. 2006) (Stucki and Frischknecht 2009)
	Cabling	Copper and thermoplastic production and assembly	(Fthenakis *et al*. 2011a)
	Mounting structure	Steel and aluminium processing (module frame excluded)	(de Wild-Scholten *et al*. 2006)

Table 6 Inventory of installation and maintenance phases of micro-wind power plant and photovoltaic systems

	Unit	Amount	Source
Micro-wind			
Excavation for foundation	m^3/micro-wind	4	Calculation
Inverter substitution	n°/micro-wind	1	(de Wild-Scholten *et al*. 2006)
PV systems			
Energy consumption for installation	kWh/m^2	0.018	(Stucki and Frischknecht 2009)
Inverter substitution	n°/ PV system	1	(de Wild-Scholten *et al*. 2006)
Cleaning Tap water	$kg/(m^2*year)$	20	(Stucki and Frischknecht 2009)

3.2.2 Installation and maintenance phase

Data regarding installation and maintenance phase of micro-wind power plant are reported in Table 6. They comprise preparation of foundation, basically made of excavation process and concrete cast in situ, transports of components from the manufacture facility to the site by road truck (250 km are assumed) and inverter substitution after 15 years.

Energy consumption for the installation, substitution of inverter and tap water for periodically cleaning operation of modules make up the inventory list of installation and maintenance of photovoltaic systems (Table 6).

3.2.3 Operation phase

Both micro-wind power plant and photovoltaic systems are assumed to be installed in the same place located in central Italy, then allowing impact assessment results comparison. The energy produced by the two energy systems was calculated referring to the climatic conditions of this area. From the Atlante Eolico Interattivo italiano (Cartografia di base DEAGOSTINI 2015) a productivity ranging between 1500 and 2000 kWh per unit of installed power, with an annual average wind speed of 5 m/s at 25 meter AMSL, was found. For the present study the average value of 1750 kWh/kW was assumed as productivity of the micro-wind turbine in the reference area.

As regard to PV systems, the electricity production was calculated assuming the solar radiation equal to 1561 $kWh/(m^2 \cdot y)$ from (ENEA 2015) (tilt angle equal to 30° and sun azimuth equal to 0°). The module efficiencies are the ones listed in Table 3 and BOS efficiency was set 85% according to (European Photovoltaic Industry Association 2011).

The energy output from the energy systems are reported in Table 7. For the micro-wind power plant the production is assumed constant during its life span, whereas for the photovoltaic systems an annual reduction of performances up to 90% and 80% of the nominal power during the first 10 years and successive 10 years, respectively, was set according to data sheet of silicon-based modules available on the market (Lombardi and Zanchi 2014).

3.2.4 End-of-Life phase

When plants reach the end of their life, they are dismantled. Materials are transported to their final destination, which may be disposal or recycling. As first hypothesis (scenario basic), all materials were assumed to be landfilled. Then a second hypothesis (scenario advanced), based on intensive recycling of materials was assumed.

Table 7 Summary of energy output from photovoltaic and micro-wind power plants

Energy system	Energy output first year		Total energy output throughout life span (20 years)	
Micro-wind	8750	kWh/year	175 000	kWh
PV mono-Si	324	kWh/year	5 877	kWh
PV multi-Si	324	kWh/year	5 877	kWh
PV CdTe	117	kWh/year	2113	kWh
PV CIS	179	kWh/year	3245	kWh

End-of-life phase is overall considered delicate since, for the moment, it is not well experienced for several renewable technologies; hence its inventory is based on presumed data since experienced and reported data are still not available.

For the PV plants, after the dismantling operations (consuming 0.018 kWh/m^2 of electricity (Stucki and Frischknecht 2009)), all the materials are assumed to be landfilled in the basic scenario. In the advanced scenario (see also (Carnevale *et al.* 2014)) main materials (silicon, aluminum, glass, copper, steel and semiconductor materials) are 100% recycled. For the mechanical and physic-chemical processes for panel recycling, the following electricity consumptions were assumed: 0.575 kWh/Wp for silica modules (Wambach and Alsema 2006), 9.6 kWh/m^2 for thin film modules (Held 2009). The remaining materials were assumed to be landfilled.

Overall management of exhausted elements of wind technologies is thought to be easier than in the case of photovoltaic technologies since they are mainly mono material components. Nevertheless the dismantling phase appears to be more expensive for the wind technologies, especially for large scale power plants, where operations of excavation, landscape restoration and components disassembly could involve large amounts of energy (Zauner and Pölz 2012). Several studies upon LCA of wind energy technology agree that the main metallic components (i.e., tower, rotor) can be recycled for 90% (Garrett and Rønde 2011, Kabir *et al*. 2012, Zauner and Pölz 2012), whereas the remaining 10% is a residual part that can be disposed in landfill. According to (Garrett and Rønde 2011, Zauner and Pölz 2012) the other parts made with plastics or other materials can be disposed in landfill (i.e., concrete) or incineration (i.e., plastic, glass fibre, oils). Many studies suggest considering energy consumption for dismantling phase and transports to disposal facilities. However, the only values that can be found are referred to large plants (Zauner and Pölz 2012).

Energy consumption for dismantling phase of wind turbine was not considered because the only data available were not suitable since referred to large scale plants.

The assumptions made for the end-of-life of the micro-wind plant are reported in Table 8.

3.2.5 Transports

According to many other LCA analysis (Zauner and Pölz 2012, Kabir *et al*. 2012, Martínez *et al*. 2009, Qu and Zhao 2012, Ardente *et al*. 2008, Fthenakis and Kim 2011a, Battisti and Corrado 2005), in this study the environmental contribution of transports is included but an attempt was dedicated in order to be more precise and details about conditions. The following contributions are included: transports of raw materials according to ecoinvent 2.2 database; transports of components to installation site and transports of components/materials to treatment and disposal facilities. Their quota depends on amount and distances, and then it is necessary to take into

Table 8 Inventory of the two end-of-life phase scenarios -'basic' and 'advanced' for the micro-wind plant

Basic scenario	Unit	Amount	Source	Ecoinvent process
Micro-wind				
Excavation for foundation removal	m^3/micro-wind	4	Calculation	Excavation, hydraulic digger/RER U
Landfill disposal	-	100% all material	Assumption	Several landfill processes for given materials
Advanced scenario	Unit	Amount	Source	Ecoinvent process
Micro-wind				
Excavation for foundation removal	m^3/micro-wind	4	Calculation	Excavation, hydraulic digger/RER U
Landfill disposal	100% of glass fibre and concrete			Several landfill processes for given materials
Recycling	100% of steel, aluminium and copper			Recycling aluminium/RER U; Recycling steel and iron/RER U; Recycling copper/RER U

consideration the localization of the different life cycle phases. As the reference geographic area is Italy, the distance from the production to the installation site would depict the difference that can be found between the two technologies in term of origin. In fact if the main components of micro-wind technology can be considered produced within the Italian boundaries, this is definitely not true in the case of photovoltaic technology, whose origin is presumably outside Italian borders (i.e., Germany, China). As a consequence, transport distances from production facilities to site of operation were assumed 3000 km for modules and 250 km for micro-wind components. A distance of 250 km was presumed for inverter substitution as well as disposal/treatment of spent components both energy technologies. Means of transports are all road truck by ecoinvent 2.2.

4. Results

4.1 Economic evaluation results

Table 9 reports the main results for the calculated LCOE, CO_2 saving specific cost and fossil fuel saving specific cost for the two different technologies: PV, in residential and commercial/industrial installations, and wind, for on-shore and off-shore alternatives, considering the selected geographical locations.

The LCOE values have been calculated according to equation (1) and data from Table 2; whereas for the CO_2 abatement cost and the fossil fuel saving specific cost the equation (2) and (4) have been used respectively with data from Table 1, for the CO_2 emissions factors and the average energy efficiencies, and Table 2.

4.1.1 LCOE

Generally, both in south and central/north Europe commercial/industrial PV plants have lower

Table 9 Summary of LCOE, CO_2 saving specific cost and Fossil fuel saving specific cost value for given countries and technologies

			Photovoltaic		Wind	
Indicator	Country	Unit	Residential (2-10 kW)	Commercial and industrial (> 1MW)	on-shore	off-shore
LCOE	Italy	Euro/kWh	0.32	0.27	0.06	0.08
	Germany	Euro/kWh	0.31	0.28	0.06	0.05
	Denmark	Euro/kWh	---	---	0.04	0.04
CO_2 saving specific cost	Italy	Euro/t CO_2eq	635	547	119	107
	Germany	Euro/t CO_2eq	494	486	107	75
	Denmark	Euro/t CO_2eq	---	---	116	98
Fossil fuel saving specific cost	Italy	Euro/toe	1712	1444	316	412
	Germany	Euro/toe	1442	1303	279	211
	Denmark	Euro/toe	---	---	206	203

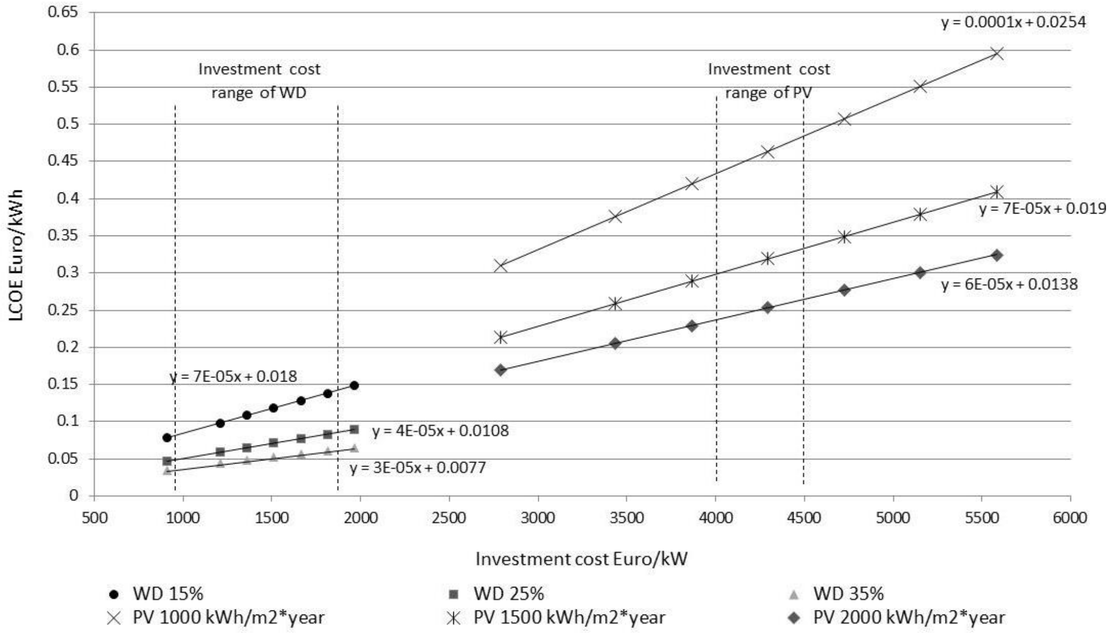

Fig. 1 LCOE variation of residential PV system and on-shore plant (reference country: Italy)

LCOE values than domestic ones, thanks to the lower specific investment prices for larger installations. There are not so much differences between the LCOE values for the PV of the two areas. Even if the investment cost in the German market is 24-30% lower than the in the Italian market, German LCOE is slightly lower than Italian LCOE, for residential plants and slightly higher for industrial/commercial plants. This is due to the solar radiation in Italy (1561 kWh/m^2*year) which is higher than in Germany (1091 kWh/m^2*year). Both investment cost and solar radiation are significant parameters for this technology. Fig. 1 shows the variation of PV LCOE for residential installations varying the investment cost and for different values of solar radiation, with reference to Italy. The range assumed for the value of the investment costs is between minimum and maximum values found in literature (IRENA 2012a) and it is in general larger than the range found for the Italian case.

LCOE calculated for wind plants is rather similar in the different cases. In central/north Europe, the off-shore option has in general similar LCOE to the on-shore case. So even if the investment cost of the off-shore plants is higher, the higher productivity makes possible to obtain lower LCOE. On the contrary, the off-shore LCOE is higher than the on-shore one in Italy. In general LCOE costs for Denmark are lower than in Italy or Germany, because of the investment costs are smaller. The LCOE variation with respect to investment cost and for different values of the capacity factor is reported in Fig. 1, with reference to an on-shore plant installed in Italy.

Observing the trends reported in Fig. 1, it clearly emerges that on-shore wind plants offer LCOE values (0.033-0.148 Euro/kWh) far below than values calculated for PV plants (0.17-0.60 Euro/kWh).

The analysis of the LCOE sensitivity to resource availability and investment cost shows that PV energy still has initial investment costs too high to be competitive with wind energy. As a matter of fact, even in the most favourable case - lowest value of investment cost in the range of figures found in the European market (about 2700-2800 Euro/kWp) and highest solar radiation, typical of Mediterranean area - LCOE is about 0,17 Euro/kWh, corresponding to the worst case LCOE of wind energy.

LCOE calculated values are comparable with other studies available in literature. Our calculated PV plant LCOE ranges from 0.31-0.32 to 0.27-0.28 Euro/kWh for residential and commercial installations, respectively. LCOE vales found in literature are in the range of 0.15-0.5 Euro/kWh for (Pathak and Pearce 2011, IRENA 2012a) for residential case and 0.08-0.46 Euro/kWh (Pathak and Pearce 2011, IRENA 2012a) for commercial case.

Literature sources generally agree on values of LCOE lower for wind than PV, in particular on-shore LCOE are in the range 0.06-0.11 Euro/kWh and off-shore LCOE are in the range 0.11-0.15 Euro/kWh (IRENA 2012b), while our values are in the range 0.04-0.06 Euro/kWh and 0.04-0.08 Euro/kWh, respectively for on-shore and off-shore installations.

4.1.2 CO_2 saving specific cost

Concerning PV plants, commercial ones present lower CO_2 abatement cost than residential ones, obviously thanks to the lower specific investment costs; CO_2 abatement cost is much lower in Germany than Italy thanks to the combined effect of lower investment and higher CO_2 emission factor per unit of conventional energy in Germany rather than in Italy.

For all the three geographical areas, off-shore wind plants have lower CO_2 abatement cost than the respective on-shore ones. Lowest costs are located in Germany for both on-shore and off-shore, because even if the investment costs are higher than in Denmark, the CO_2 emission factor per unit of conventional energy is higher in Germany than in Denmark. Denmark has actually one of the lowest CO_2 emission factors per unit of conventional energy in Europe, influencing negatively the discussed parameter. Specific CO_2 abatement cost of wind energy is higher in Italy than in the other two countries because of higher investment costs and average CO_2 emission factor per unit of conventional energy (0.405 kg CO_2/kWh).

Results suggest that this indicator is strongly influenced by the CO_2 emission factor per unit of energy which in turn depends on the percent contribution from renewables in the national energy mixes.

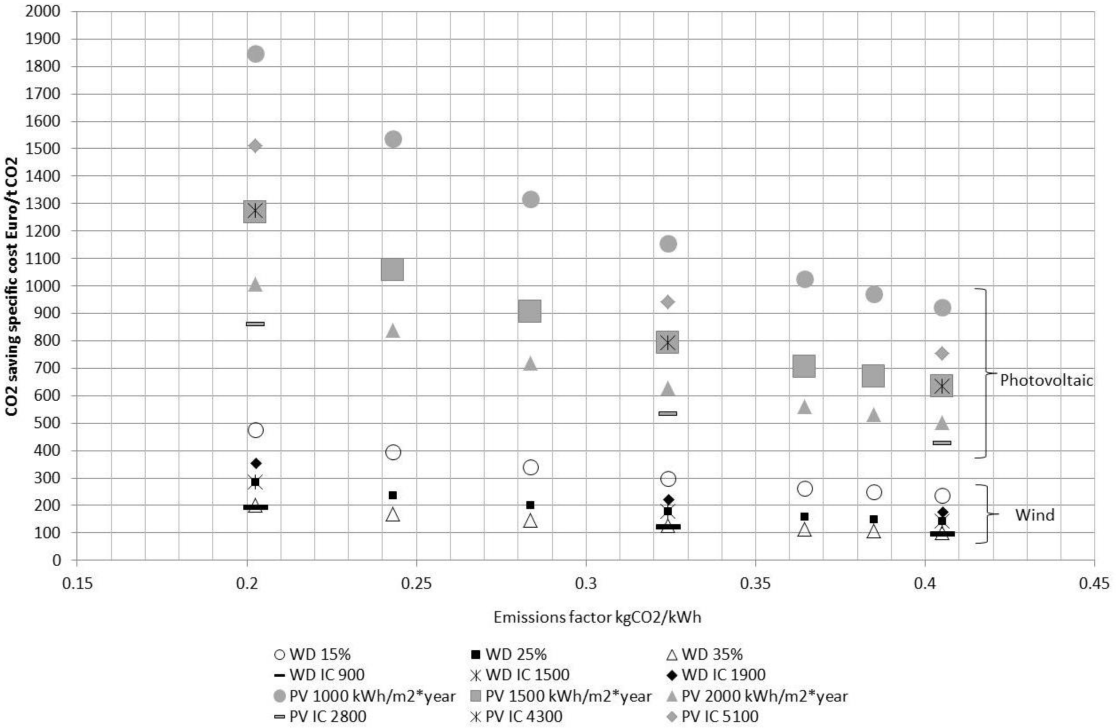

Fig. 2 CO_2 saving specific cost variation of residential PV system and on-shore plant (reference country: Italy)

Fig. 2 summarizes the trends of the specific CO_2 abatement cost for on-shore wind and residential PV vs. CO_2 emission factor per unit of energy, in the case of Italy. Values are reported for different resource availability and specific investment cost. Also in this case, the specific CO_2 abatement cost calculated according to the worst assumptions for wind energy is lower (or, in the best option, comparable) than the specific CO_2 abatement cost calculated according to the assumptions which minimize it in the case of PV energy.

4.1.3 Fossil fuel saving specific cost

Results for PV plants, show in general lower values for commercial and industrial installation than residential ones, being the LCOE of the first ones lower. The minimum of the fossil fuel saving specific cost is obtained in Germany (0.40 kWh_{el}/kWh_{EP}) because of the combined effect of low LCOE and low average energy conversion efficiency, 0.46 kWh_{el}/kWh_{EP} is found in Italy.

Concerning wind plants, the fossil fuel saving specific cost presents the same behaviour of LCOE. Off-shore plants have lower values than on-shore ones both in Germany and Denmark, while it is the opposite in Italy. For wind plants the influence of average energy conversion efficiency seems to be less important than for PV plants.

The fossil fuel saving specific cost for PV plants is in definitely higher than the cost for wind plants.

The fossil fuel saving specific cost depends strongly on the LCOE and it is influenced also by the average energy conversion efficiency of the reference country. In order to show these

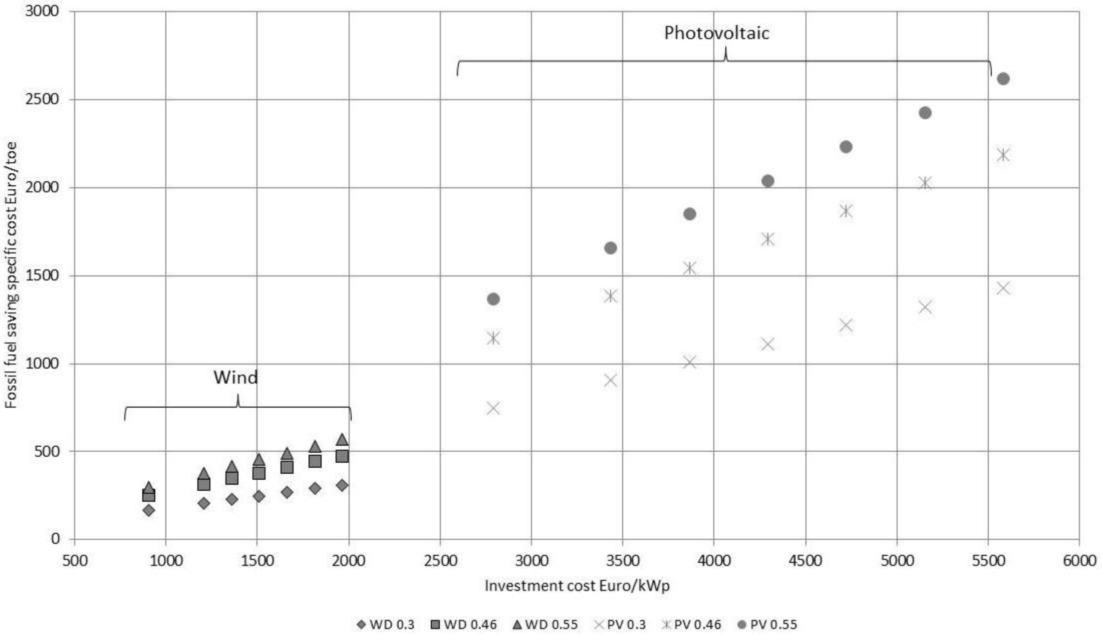

Fig. 3 Fossil fuel saving specific cost variation of residential PV system and on-shore plant (reference country: Italy)

dependencies, Fig. 3 reports the trends of the fossil fuel saving specific cost vs. the investment cost, for residential PV and on-shore wind plants installed in Italy, for different assumed values of energy conversion efficiency, in the range0.30-0.55 kWhelL/kWhEP (Graus and Worrell 2009). These results show that the fossil fuel saving specific of PV installations (747-2616 Euro/toe) is always higher than the wind one (164-569 Euro/toe), for any value of the investment cost and energy conversion efficiency in the assumed ranges.

4.2 Environmental assessment results

Impact assessment results are presented according to the Eco-indicator'95 method (Goedkoop 2012), in order to compare the results presented in this paper, related to micro-wind plants, with previous ones related to PV installations (Carnevale *et al*. 2014).

4.2.1 Impact assessment

Table 10 shows the total values of each indicator calculated according to the selected impact assessment method for both the assumed end-of-life scenarios, as described before. In general all the considered indicators have negative values, meaning beneficial effects (avoided emissions) for the specific impact categories, with the exception of carcinogens (in the basic end-of-life scenario) and solid waste. When advanced recycling assumptions are introduced, all the indicators are improved, with the carcinogens one passing from positive to negative value.

Values reported in Table 10 for each environmental indicator according to Ecoindicator’95 method for the studied micro-wind plant can be compared with the analogous results previously obtained for residential PV plants (Carnevale *et al*. 2014). In the case of basic end-of-life

Table 10 Life Cycle Impact assessment results of micro-wind technology: total score for each End-of-Life (EoL) scenario

Impact category	Units	WD - EoL: scenario ‘basic’	WD - EoL: scenario ‘advanced’
Global Warming	kg CO_2/kWh	-5.40E-01	-5.56E-01
Ozone layer depletion	kg CFC11/ kWh	-4.31E-08	-4.41E-08
Acidification	kg SO_2/ kWh	-2.51E-03	-2.59E-03
Eutrophication	kg PO_4/ kWh	-4.66E-04	-4.95E-04
Heavy metals	kg Pb/ kWh	-9.70E-07	-1.82E-06
Carcinogens	kg B(a)P/ kWh.	2.10E-08	-2.76E-08
Pesticides	kg act.subst/ kWh	0.00E+00	0.00E+00
Summer smog	kg C_2H_4/ kWh	-7.63E-05	-7.85E-05
Winter smog	kg SPM/ kWh	-1.78E-03	-1.85E-03
Energy resources	MJ LHV/ kWh	-9.28E+00	-9.58E+00
Solid waste	kg/ kWh	1.99E-02	1.48E-02

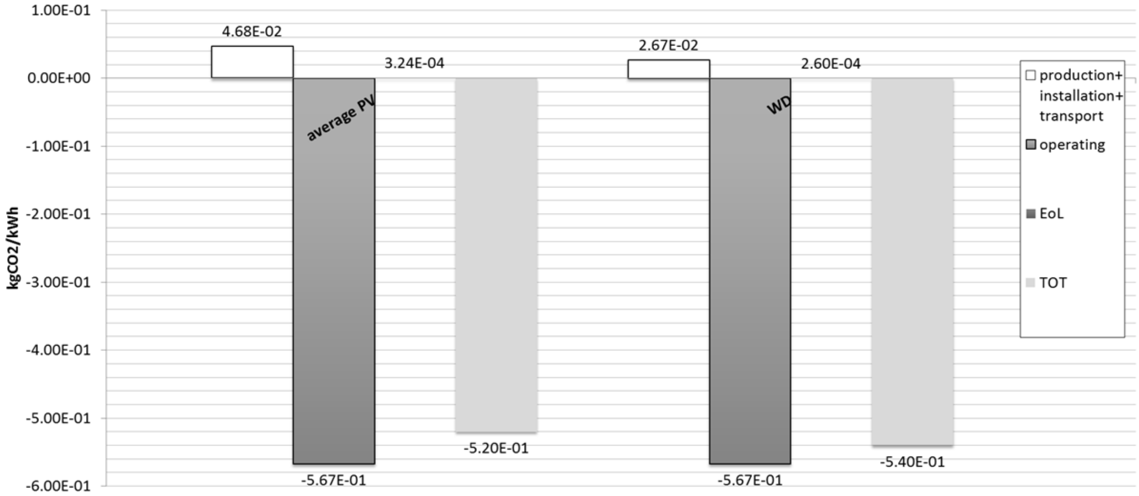

Fig. 4 Global Warming indicator results: residential PV and micro-wind comparison (reference country: Italy) (EoL: scenario ‘advanced’)

scenario, the best score is obtained by micro-wind plant for global warming, ozone layer depletion and energy resources; while residential PV plants obtain the best score for acidification, eutrophication, heavy metals, carcinogens, summer smog, winter smog and solid waste. When the advanced end-of-life scenario is considered, the micro-wind plant obtains the best score only for ozone layer depletion indicator.

More details are given in the following for global warming indicator, reporting the analysis of contributions from the different life cycle phases, in reference to the two assumed end-of-life scenarios.

Fig. 4 shows the contribution analysis to the total value of global warming indicator for residential PV and micro-wind plants from the phases: sum of production of plants, installation and transport, operation and end-of-life. For the residential PV case, results are fully reported, in

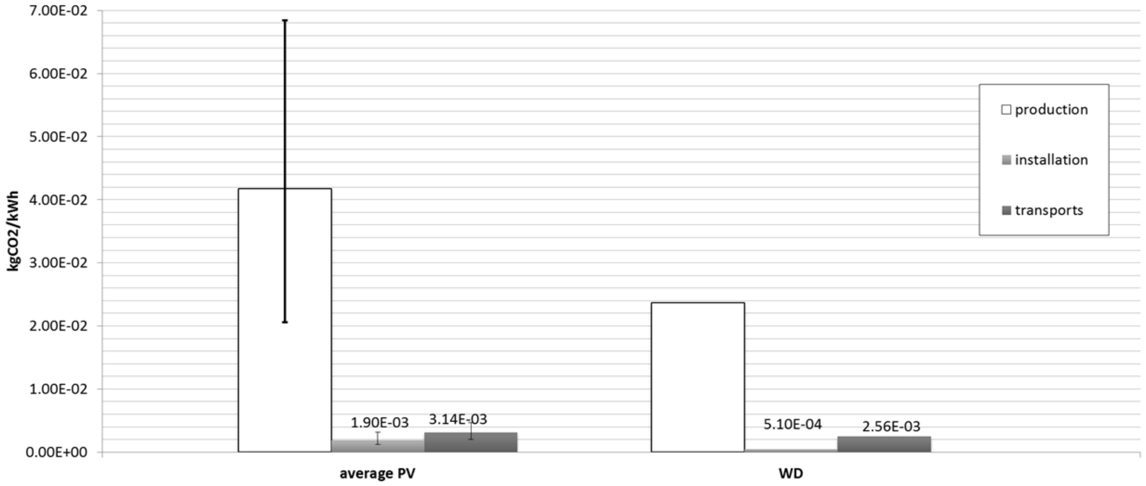

Fig. 5 Global Warming indicator results: residential PV and micro-wind comparison. Details for the production, installation and transport phases (reference country: Italy) (EoL: scenario 'basic' and 'advanced')

reference to a different functional unit, in previous publication (Lombardi and Zanchi 2014) and are here shown only as average values and minimum and maximum values of indicators obtained for four types of PV modules (silicon monocrystalline (mono-Si), silicon polycrystalline (multi-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS)).

The main contributions in term of positive impact are due to the production phase, which is one order of magnitude higher for PV than wind (Fig. 5). Concerning negative impacts - i.e. avoided effects - the main contribution comes from the operation phase, which dominates the total value of the indicator, with a smaller contribution from the end-of-life phase, which is more relevant in the PV case rather than in the wind one.

The total value of the global warming indicator is rather similar for residential PV and micro-wind. In the case of basic end-of-life scenario the total value of the micro-wind case (-5.40E-01 $kgCO_2$/f.u.) is better or equal than/to the values obtained for the residential PV (from -4.95E-01 to -5.40E-01 $kgCO_2$/f.u. (Carnevale *et al*. 2014). While the intensive recycling of PV materials in the advanced scenario allows increasing the performances of the PV systems resulting in decreased values for the global warming indicator (from -5.48E-01 to - 5.66E-01 $kgCO_2$/f.u.) which in turns scores better than the indicator values obtained for micro-wind in the advanced recycling scenario (-5.56E-01 $kgCO_2$/f.u.).

5. Discussion

The economic and environmental comparison of PV and wind energy provided some important points to be discussed.

According to the three economic indicators calculated in this work, the wind energy emerged as more favourable than PV energy. The results are mainly due to the lower investment costs which characterize the wind plants rather than the PV ones. The economic indicators are strongly affected also by the availability of the resources. A decrease in the resource availability leads to an increase in the LCOE, specific CO_2 abatement cost and fossil fuel saving specific cost, with less impact in the case of wind plants.

The CO_2 abatement cost is also influenced by the electric energy mix of the country where the plant is located. In particular if the electricity is produced with a high share of renewables, by thermal plants with high energy conversion efficiency and using low carbon content fossil fuels, the CO_2 emission factor per unit of produced electric energy will be lower, making less convenient the CO_2 abatement cost. As a matter of fact, in a future perspective with expected increase in renewable share, this type of indicator can lose its meaning for the comparative evaluation of different renewable sources.

The fossil fuel saving specific cost depends strongly on the LCOE and it is influenced also by the technological level of the thermal energy conversion plants of the country where the renewable plant is installed, through the value of the average energy conversion efficiency. In Europe the average energy conversion efficiency for the different countries varies from 0.30 kWhel/kWhPE to 0.55 kWhel/kWhPE, with an average EU-27 value of 0.41 kWhel/kWhPE (Graus *et al*. 2009). Also in this case, a progressive increase in the fossil fuel plant efficiency is expected in the future for EU, thus also this parameter is expected to change consequently.

From an environmental point of view, the comparison of two particular types of PV and wind plants, respectively residential and micro-wind turbine - showed that both the technologies are able to provide savings for almost all the considered environmental impact categories. The PV plants obtain the best values in seven out of ten of the considered indicators, while the micro-wind obtains the best values in three out of ten indicators. PV plants collect even better results if advanced recycling options are included in the end-of-life phase, obtaining better performances than the micro-wind also for the global warming indicator. However, the relative differences between average indicators for the different PV plants and indicators for the case of micro-wind are rather limited (0.2-16.2%) for the majority of the impact categories (global warming, ozone layer depletion, acidification, eutrophication, summer smog, winter smog and energy resources).

Thus, from the environmental point of view, the two technologies are almost comparable, while from the economic point of view a deep gap still exists. However, the final values of the selected economic indicators are strongly dependent on the geographical location, not only in reference to the renewable resource availability as a consequence of the climatic conditions, but also as a function of the different reference markets and of the technological boundary conditions, as availability and use of different types of fossil fuels and technological level of plants using them. Such conditions influence the values of the economic indicators when projected over a medium-long time horizon.

It is rather clear, that it is not possible to find a unique optimum solution of renewable exploitation for the different geographical locations and that the combined used of the proposed economic and environmental indicators may support the policies and the decision making procedures concerned with the promotion and use of renewables, in reference to the specific geographic, economic and temporal conditions.

6. Conclusions

The development and use of renewable energies is one of the main pillars toward the sustainability of our societies. The principal elements affecting their diffusion are: resource availability, technology reliability, economic competitiveness and support schemes. There are many available indicators which can be used to quantify and compare the advantages/disadvantages of renewables technologies. Many of them seek to evaluate the potential benefits deriving from the substitution of traditional systems; in particular the possibility of carbon dioxide emissions abatement and the reduction of fossil fuels use, by taking into account the current and future energy demand. In the present work we selected indicators according to the following features: a clear calculation approach, information easy to be collected, clear, but even complete, interpretation of results. Therefore the selected indicators are Levelized Cost of Energy and environmental impact categories from the Eco-indicator'95 method, along with two more indicators, called CO_2 abatement cost and fossil fuel saving specific cost, which have been specifically defined in the present study with the aim of evaluating, in a simplified way, the different capabilities that renewable technologies have to cut down direct CO_2 emissions and to avoid fossil fuel extraction. By these indicators the comparison of two different technologies - photovoltaic and wind - was carried out. The analysis was developed by taking into account different energy system sizes and different geographic areas in order to compare different European conditions (Italy, Germany and Denmark) in term of renewable resource availability and market trend.

According to the three calculated economic indicators, the wind energy emerged as more favourable than PV energy. The results are mainly due to the lower investment costs which characterize the wind plants rather than the PV ones. However, the economic indicators are strongly affected by the availability of the resources. The CO_2 abatement cost is influenced by the electric energy mix of the country where the plant is located. As a matter of fact, in a future perspective with expected increase in renewable share, this type of indicator can loose its meaning for the comparative evaluation of different renewable sources. The fossil fuel saving specific cost depends strongly on the Levelized Cost of Energy and it is influenced also by the technological level of the thermal energy conversion plants of the country where the renewable plant is installed, through the value of the average energy conversion efficiency.

From an environmental point of view, the comparison of two particular types of PV and wind plants, respectively residential and micro-wind turbine - showed that both the technologies are able to provide savings for almost all the considered environmental impact categories.

Thus, from the environmental point of view, the two technologies are almost comparable, while from the economic point of view a deep gap still exists.

In conclusion, a unique optimum solution of renewable exploitation for the different geographical locations does not exist. The proposed economic and environmental indicators may be useful in supporting the policies and the decision making procedures concerned with the promotion and use of renewables, in reference to the specific geographic, economic and temporal conditions.

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