Consequential Life Cycle Assessment of electricity production from biogas in Italy

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Abstract
In Italy, an increasing number of Anaerobic Digestion (AD) plants fed with agricultural feedstock has been detected to meet the European goals for Renewable Energy Sources (RES) production. AD is one of the most promising technologies for RES production, especially when wastes are used as feed instead of dedicated crops. However, the economic subsidy framework encouraged to invest in highly productive plants fed with dedicated crops. Since the economic subsidy has already been reduced, it can be expected its end in the future, thus potentially making the plants' feeding with dedicated crops uneconomic. This study aims at evaluating the consequences of the potential deletion of the subsidy framework for AD production plants. Consequential life cycle assessment (cLCA) was implemented to evaluate the environmental effects of: (i) substituting dedicated crops in the feeding mix with pig and cow slurry; (ii) closing plants fed with dedicated crops and substituting the related renewable energy production with non-renewable one from the national energy mix.
When cereal silages are substituted by animal slurry the environmental performances of agricultural AD plants are improved for two reasons. First, the avoided slurry storage at farm in traditional open tanks reduces the emissions of pollutants (e.g., methane, ammonia and dinitrogen monoxide) and, secondarily, the higher efficiency of the digestate nitrogen reduces the consumption of mineral fertilisers for crops cultivation. The outcomes of this study can be a valuable support for policy makers to drive the future towards a more sustainable energetic production.

Keywords: renewable energy, biogas, Life Cycle Assessment, agricultural biomass

1. Introduction

Over the last years, thanks to the provision of public incentives, the production of electricity from renewable sources has grown strongly throughout Europe. All Member States provide subsides for renewable energies production, among which from anaerobic digestion. Anaerobic Digestion (AD) is recognised as one of the most viable ways to produce bioenergy, also contributing to reduce GHG emissions and the amount of wastes, above all if livestock husbandry secondary products and crop residues are used. In the last decade, several studies dealt with the biogas production via AD from an environmental point of view, deepening the burdens strictly linked to life cycle of biogas production but underestimating the multi-functional role that biogas-to-electricity systems could play in the agricultural sector (Bacenetti et al., 2016).

AD can be realised using different feeding mix, primarily chosen as function of the profit maximization according to the technical and economic feasibility of the process. The grant of national incentives for increasing the share of renewable energies pushed several entrepreneurs to undertake the biogas production activity, developing partnerships with farmers to displace ordinary cultivated land management to energy crops. In Italy, above all in the Northern regions, in the last 20 years, thanks to a favourable subsidy framework, about 1800 AD plants fed with agricultural feedstock have been built. Despite the higher supply cost due to the level of subsidy (280 €/MWh of electricity fed into the national grid for plants built before 2013), several plants are fed mainly with dedicated crops, of which maize silage is the most used (Meyer et al., 2017; Negri et al., 2016). However, the trend of growth has slowed down due to the revision of the subsidy framework occurred in 2012. In fact, the exponential growth of plants entailed some problems, among which the land exploitation to produce dedicated crops. About 50-55% of European production of biomass used for AD derives from dedicated energy crops (cereals for silage above all), by withdrawing fodder from the livestock sector.

In 2012, the subsidy framework was modified to encourage the use of by-products and to improve the efficiency of plants, with a subsequent improvement in the environmental performance of the supply chain. An objective assessment of the criteria to be used in decision-making is needed to define a future subsidy framework taking into account environmental impacts. In particular, the future scenarios of bioenergy production can change considerably when the incentives cease, as can be expected. In fact, for all bioenergy plants fed with dedicated crops, revenues could not cover supply costs for feeding and the suspension of incentives could cause the end of activities.

The aim of this study is to analyse the consequences related to a change in the actual subsidy framework for renewable energies and, in particular, the deletion of the grants for biogas production. More in details, to evaluate the environmental effects related to (i) the maintenance of plants fed with dedicated crops by substituting the feeding mix with pig and cow slurry or (ii) the substitution of renewable energy with non-renewable energy, a consequential life cycle assessment (cLCA) was performed (Ekvall and Weidema, 2004). This involved assessing the future scenarios for bioenergy production from AD hypothesising the deletion of the subsidy framework for electricity production from AD plants and identifying, consequently, the useful information for decision-making about sustainable subsidy strategies.

2. Material and Methods

LCA is a methodological framework useful to determine the environmental impacts of a system, product or activity (ISO 14040, 2006). LCA features a high-developed methodology, which includes the emissions of pollutants and material and energy consumptions from raw material acquisition, through the production and use phases to waste management.

In accordance with Ekvall and Andrae (2006), cLCA aims to estimate the effects that a change of technology used within the life cycle, defined marginal technology can cause in terms of physical flows and environmental impacts. These changes are consequence of demand variation in the market caused by the substitution of marginal with new technology (Rehl et al., 2012). This represents the main difference to the attributional LCA, which considers, instead, average technologies (Marvuglia et al., 2013).

Therefore, the consequential life cycle model does not represent the real (or expected) production chain but a hypothetical future scenario resulting from market dynamics potentially influenced by different internal and external factors including, for example, political interactions and changes in consumers' behaviour (Sandén and Karlström, 2007). A key element for this modelling is the identification of marginal technology, i.e. those affected by the new technologies. A simplified approach or a general or partial equilibrium modelling could be used to assess market consequences and, in particular, to estimate the changes in the supply and demand of other goods and services caused by direct and indirect shocks (Igos et al., 2015).

2.1 Goal

This study aims to analyse how the variation in the subsidy framework for AD production could influence the renewable energy market and, secondly, the effects that such change could cause in terms of national energy mix modification, slurry management and organic and chemical fertilisation contribution. In particular, in the report by the Italian Energy Services Operator (GSE) on renewable energy trend to 2020 (GSE, 2016), it was hypothesised that the end of subsidies for bioenergy production will cause the closure of plants that buy matrixes, because economic costs would exceed revenues.

2.2 Functional unit

According to ISO standards, the functional unit (FU) is defined as the main function of the system expressed in quantitative terms (ISO 14040, 2006). The main function of the studied system is the production of electricity from a renewable energy source (the biogas). Therefore, the FU chosen was 1 kWh of electricity supplied to the national electric grid.

2.3 System boundary and system description

In this study, a "from cradle to AD plant gate" approach was applied. Therefore, with regard to the system boundary, all the processes (e.g., biomass production and transport, biomass conversion into biogas and then into electricity, digestate management) directly included in the biogas-to-energy production system were considered as well as all those directly affected by related consequential changes (e.g., crops fertilisation, slurry management, electricity production form fossil fuels). The operations related to the distribution and use of the generated electricity were excluded.

More in details, the following activities were included in the system boundary:

a) extraction of raw materials (e.g., fossil fuels, minerals, metals),
b) manufacture of the different inputs' use for feedstock production and transport as well as for AD and biogas conversion into electricity (e.g., tractors and agricultural machines, electricity, building materials, chemicals, etc.),
c) maintenance and final disposal of machines (e.g., tractors and operative machines) and other capital goods (e.g., digesters, CHP),
d) emissions into air, water and soil (e.g., diesel fuel emissions from diesel combustion in tractor engines, N and P compounds fertilisers, emissions from crops cultivation and emissions from digestate storage and from biogas combustion).

In both scenarios, no change in the soil organic carbon content was considered.

Respect to the current scenario (named BS) characterised by the granting of public subsidies to produce electricity from renewable energy sources and characterised by marginal technology producing 8.2 TWh of electricity per year (GSE, 2018), two different alternative scenarios were evaluated:

a) AS1 called "+ SLURRY", in this scenario to the grant deletion corresponds a reduction of electricity production from agricultural AD plants due to a change in the digester feeding. In particular, only animal slurry is used instead of a mix with cereal silage. More in details, the volume of digesters not filled by the cereal silage is supposed to be occupied by the animal slurry. However, considering that animal slurry shows a considerably lower biogas production respect to cereal silages, this scenario involves a reduction of biogas production and, consequently, of electricity production. Consequently, keeping constant the Italian electricity demand and the "filling rate" of the digesters, the reduced production from biogas is balanced out by an increase in electricity production from non-renewable energy sources;
b) AS2 called "NO BIOGAS", in this scenario the grant deletion is supposed to cause the stop of the AD plants involving an increase in electricity production from non-renewable energy sources.

The effects of future scenarios were evaluated with a partial equilibrium model. The different scenarios considered in the study are shown in Figure 1.

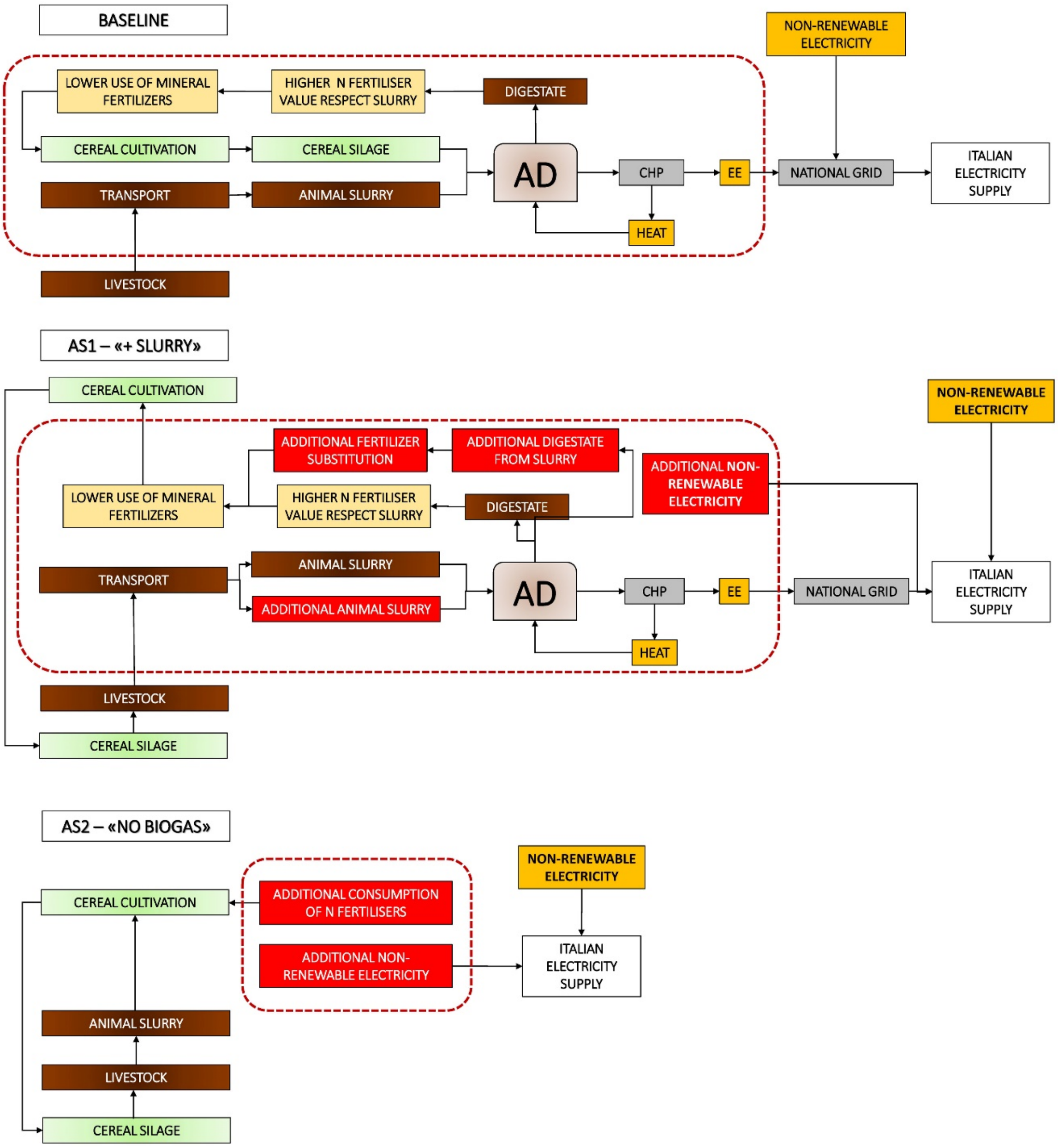

Fig 1 System boundary for the three scenarios. For AS1 and AS2 the boxes with the red pattern highlight the main differences respect to BS. (AD = anaerobic digestion plant, EE = electricity, CHP = combine heat and power).

2.5 Assumptions and Inventory data collection

The modelling of the two scenarios was carried out based on the following assumptions:

a) the anaerobic digestion of animal slurries allows:
   - to avoid their traditional storage carried out in open tanks, and, consequently, to avoid the emissions of methane, ammonia and nitrous oxides that normally/usually are released during storage. In environmental terms, this involves a benefit for all those environmental impacts that are affected by the emission of these substances;
   - to better exploit the nitrogen content of slurry. In fact, due to AD the digestate shows a higher share of ammonia nitrogen respect to slurry and, thus, a higher Mineral Fertiliser Equivalent (MFE)[1]. Anaerobic digestion allows the substitution of a larger share of mineral N fertilisers with digestate compared with the use of animal slurry "as is", thanks to the higher concentration of ammonia nitrogen in the digestate. Table 1 shows the characterisation of the two types of animal slurries considered, pig and cow, which once digested in the AD plant, increase the MFE to 65% and 75%, respectively.

b) for all scenarios the heat cogenerated by CHP units is used only for the heating of digesters (i.e. digesters' temperature regulation) while the surplus is dissipated;

c) in the two alternative scenarios, the reduction of electricity production from biogas is replaced with electricity from non-renewable sources, according to the current national electricity mix;

d) in AS1 "+ SLURRY" scenario, the animal slurries used to replace the cereal silages must be transported over a longer distance than in BS, because manure has to be delivered from more distant farms in order to meet the capacity of the plant. In detail, an average distance of 5 km was considered. The increased use of animal slurry for AD implies, according to the abovementioned point a), the replacement of an additional share of mineral nitrogen fertilisers and, therefore, an environmental benefit;

e) in AS2 "NO BIOGAS" scenario, the entire renewable electricity production from biogas must be replaced by non-renewable energy and the benefits of AD and slurry management are lost. Contrariwise to AS1 "+ SLURRY", where the increased use of slurry has a double environmental benefit (emissions avoided by traditional storage and increased use of fertiliser avoided), in this scenario no benefits are considered;

f) the environmental impact of the electricity produced by agricultural AD plants was assessed as a weighted mean value (based on the produced electricity) of 30 biogas plants previously evaluated by means of LCA and located in Italy (Bacenetti et al., 2016; Lijò et al., 2017)

For BS and AS1 "+ SLURRY" scenario, Table 1 shows the different feeding mixes as well as the share of the generated electricity in function of matrices used in the mix (GSE, 2018).

Table 1 – Feeding mix and subdivision of the produced electricity depending on the digested biomass (other matrix = agro-industrial by-products)

Feedstock	**Feeding mix**		**Produced Electricity**	
	BS	**AS1**	**BS**	**AS1**
Maize silage	30%	0%	62%	0%
Other silages	10%	0%	16%	0%
Pig slurry	25%	46%	3%	20%
Cow slurry	25%	46%	8%	47%
Other matrix	10%	9%	12%	33%

LUC modelling was performed through a "backwards looking" approach, a simplified modelling inspired by Schmidt (2008), by assessing the historical trend of cereal silage area, focusing on "status quo ante" the AD

[1] The mineral fertiliser equivalent (MFE) for nitrogen is a measure of the fertiliser ability to supply nitrogen to crops compared with mineral fertiliser. It expresses the amount of N from mineral fertiliser substituted by the same amount of N from organic fertiliser.

plants building. The trend analysis from 1961 to 2013 (FAOSTAT, 2018a and 2018b) showed that the use of cereal silage for AD did not cause relevant LUC thanks to productions intensification. With regard to the substitution of mineral fertilizers due to the increase on the MFE of digestate, the urea was considered as N mineral fertilizer.

Background data for electricity production in Italy, transport and nitrogen mineral fertiliser production were obtained from the Ecoinvent database® v.3 (Weidema et al., 2013).

2.6 Impact assessment

Using the characterisation factors reported by the midpoint ILCD method (Wolf et al., 2012), the following impact categories were considered: Climate change (CC), Ozone depletion (OD), Human toxicity, cancer effects (HTc), Human toxicity, non-cancer effects (HTnoc), Particulate matter (PM), Photochemical oxidant formation (POF), Terrestrial acidification (TA), Freshwater eutrophication (FE), Terrestrial eutrophication (TE), Marine eutrophication (ME), Freshwater ecotoxicity (FEx), Mineral fossil and renewable resource depletion (MFRD).

3. Results and Discussions

Figure 2 shows the relative comparison of the three different scenarios for the different environmental impact categories. For each impact category, the scenario with the worst performance (i.e. with the highest environmental load) is 100% while the others are proportionally scaled.

Compared to the Baseline Scenario (BS - current Italian production of EE from agricultural AD plants thanks to the current public subsidies):

a) AS1 "+ SLURRY" involves an impact reduction for all the impact categories affected by cereal silage production and, in particular, for PM (-77%), TA (-134%) and eutrophication (-191% TE, and -97% ME). Moreover, the higher content of NH_3 in the digestate and the consequently higher MFE involve a reduction of the use of mineral N fertilisers. Finally, the offsetting of the reduced EE production through non-renewable fossil sources does not affect considerably the performances of AS1 "+ SLURRY" except for CC, OD, HTc and FE, where BS shows a lower environmental impact.

b) AS2 "NO BIOGAS", due to the complete substitution of EE from biogas with non-renewable energy sources, shows the worst environmental performances for all impact categories except for HTnoc and ME. For these impact categories, BS scenario, representing the marginal technology in the current biogas production system, shows a higher impact (+25% and +50%, respectively) mainly due to the cultivation of cereals for silages and, in particular, to their fertilisation. For CC, the worsening of the impact is related to the slurry storage in open tanks that takes place instead of AD. In fact, the traditional storage involves higher emissions of CH_4, N_2O and NH_3. Furthermore, the lower availability of N (in the animal slurry respect to digestate) requires a supplemental consumption of N fertilisers respect to AS1 "+ SLURRY" and BS. Even if AS2 "NO BIOGAS" scenario shows the worst results for TA, TE and FEx, the difference with BS is small.

BS scenario shows the best performances for CC, OD, HTc and FE. For these impact categories, the impact of AS1 and AS2 is higher due to the increased production of electricity from non-renewable energy sources.

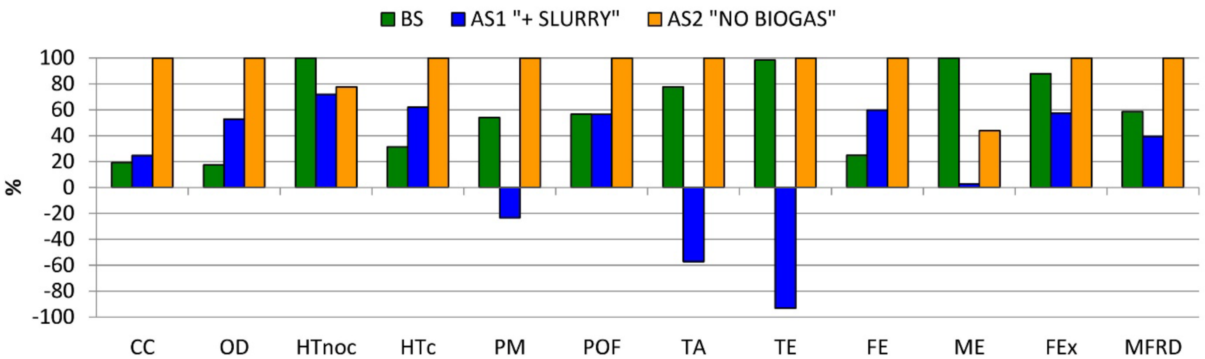

Fig 2 Relative comparison among the three scenarios

Figure 3 and Figure 4 show the input and output contribution that characterises the two alternative scenarios in terms of environmental impact. Negative values are a benefit to the environment, while positive values (greater than zero) describe a negative effect on the environment. For AS1 "+ SLURRY" scenario, for all the evaluated impact categories there are benefits related to the replacement of N fertilisers and/or the replacement of the traditional storage of slurry in open tank. Thanks to this latter effect, the benefits for PM, TA and TE are higher than the impacts (for such reason the value shown in Figure 2 is below zero). The impact of slurry transport is small, except for HTnoc and MFRD. In contrast, for AS2 "NO BIOGAS", there are no benefits and the credits for AD of slurry and N fertiliser substitution are lost because the biogas production is stopped. Consequently, in AS2, all items are greater than zero. For both scenarios, the replacement of electricity produced from biogas by electricity from non-renewable sources is the main cause of increase of the environmental impact.

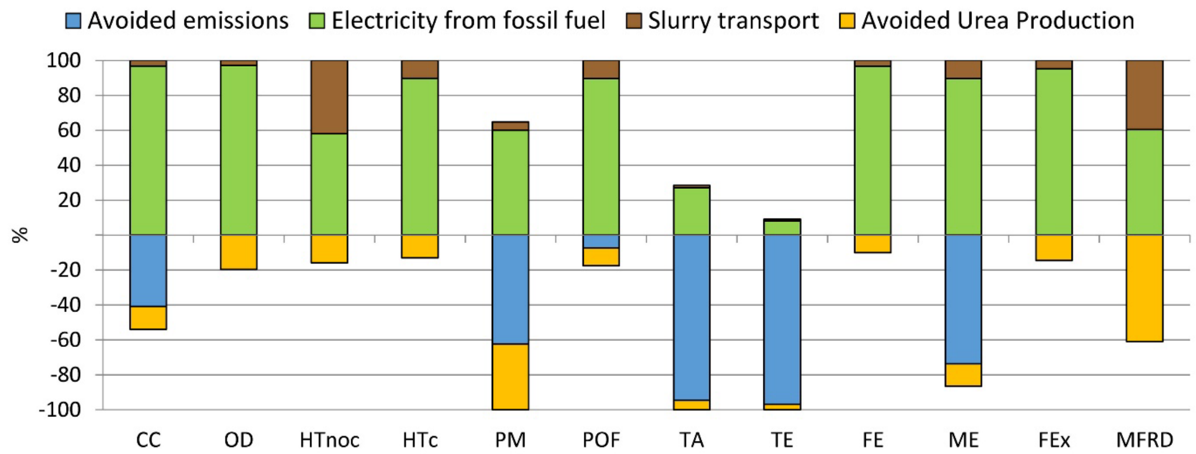

Fig 3 Hotspots for AS1 "+ SLURRY" scenario

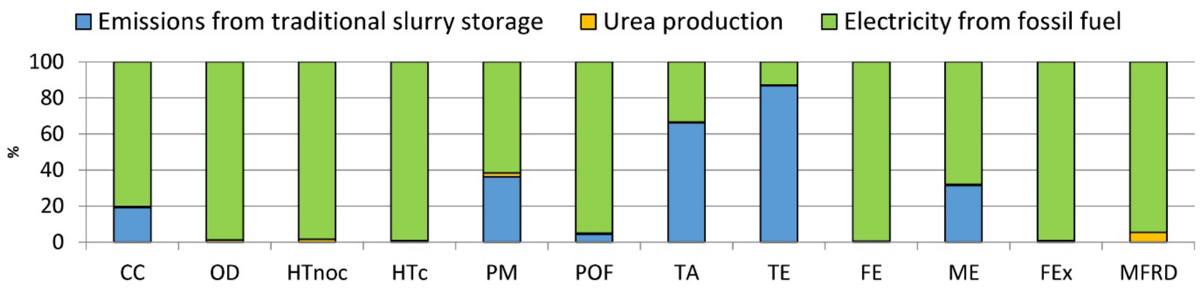

Fig 4 Hotspots for AS2 "NO BIOGAS" scenario

4. Conclusions

Thanks to the subsidy framework, the growth of agricultural AD plants for bioenergy production has been remarkable. Nevertheless, it is also necessary to analyse its effects in terms of environmental impact, not only considering greenhouse gas emissions but also a full set of environmental indicators. In particular, it is important to plan a new subsidy framework encouraging the development of a sustainable energy supply chain based on a comprehensive set of environmental indicators.

The results of this study show that the subsidy framework pre-2013, which had the size of the plant (power > 1 MW electricity) as only constraint for the fed-in-tariff, was consistent with the objective of reducing emissions of climate-changing gases. However, renewable electricity produced requires a sustainable management system in terms of climate change as well as in terms of toxicity-related impact categories, eutrophication, acidification and particulate matter formation compared to the alternative solutions.

Therefore, the outcomes of this study can support the decision of policy makers to drive the future towards a more sustainable direction and, in particular, towards the introduction of a subsidy modularity in function of the environmental performances.

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