Improvement of human health and environmental costs in the European Union by air scrubbers in intensive pig farming

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Abstract

Intensive pig farming is responsible for significant air pollutant emissions. This study explores the effect that the large-scale implementation of air cleaning technologies (wet acid scrubbers) for pig housing facilities could have in the European Union. Emissions related to the housing stage of NH_3, PM10, NMVOC and indirect N_2O from large pig farms (> 1000 heads of sows or fattening pigs) are first estimated in the actual situation (current scenario - CS), considering implementation rates and removal efficiencies of the different emission abatement techniques available. Subsequently, alternative scenarios (AS1 and AS2) are simulated with a growing implementation rate of the wet acid scrubber (35% and 65% of the concerned pig farms in all Member States). A comparison between the scenarios was carried out, taking into account emissions reduction, consumables for scrubber operation and environmental credit given by the avoidance of synthetic mineral nitrogen fertilizer production. The annual impact on human health of 21212 disability-adjusted life years (DALY) was significantly reduced in AS1 (15%) and in AS2 (40%), showing that the environmental trade-off given by the consumables is largely overwhelmed by emission abatement. At the same time, the current environmental cost to society of the concerned emissions was estimated at 4154 million € per year (of which 89% due to NH_3), which also was reduced in alternative scenarios (-668 and -1765 million € for AS1 and AS2). The abatement of NH_3, on which the wet acid scrubber expresses the

greatest removal efficiency, was fundamental both for reducing the reduction of human health impact and environmental costs, demonstrating the key environmental role of this pollutant and the growing need to find solutions for its containment in the EU.

Acronyms and abbreviations

AS – Alternative scenario
BAT - Best available techniques
CS – Current scenario
DALY - Disability-adjusted life years
EC – European Commission
EU – European Union
IED – Industrial Emissions Directive
N_2O – Dinitrogen monoxide
NH_3 - Ammonia
NMVOC – Non-methane volatile organic compounds
NO_x - Nitrogen oxides
PM – Particulate matter
SO_2 – Sulphur dioxide
TAN – Total ammoniacal nitrogen
UN – United Nations
VOC – Volatile organic compounds
WAS – Wet acid scrubber
WHO - World Health Organization
YLD - Years lost due to disability
YLL - Year of life lost

1. Introduction

The agricultural sector is the major responsible of ammonia (NH_3) emissions in the EU, accounting for 92% of them in 2017 (EEA, 2019a). In particular, the livestock sector contributes to about 80% of the agricultural share due to NH_3 emissions from effluents, occurring during permanence in housing facilities, storage and field application. The deal of livestock effluents management is that even when it is possible to conserve ammoniacal nitrogen at a certain stage (e.i. during the permanence in animal housing), this still remains available to volatilize for subsequent ones (handling, storage, field spreading) (Reis et al., 2015). Agriculture also contributes to PM pollution, by means of direct emissions from livestock (Cambra-Lopez et al., 2010) and mechanization (Lovarelli & Bacenetti, 2019) and, indirectly, by means of NH_3. In fact, the latter may react with sulphur dioxide (SO_2) and nitrogen oxides (NO_x) while in the atmosphere, leading to the formation of secondary sulphate and nitrate particles, major components of fine particular matter (PM2.5) (Lovarelli et al., 2020). Indeed, Backes et al., (2016) for Europe and Zhao et al. (2017) for China have shown that the reduction of NH_3 emissions of agricultural origin can contribute contain PM2.5 pollution.

Efforts made by the European Commission (EC) and Member States under the Convention on Long-range Transboundary Air Pollution (UN, 2020) and the protocols that extend it have already led to significant improvements in NH_3 emissions, achieving a 24% decrease from 1990 to 2017 (EEA, 2019a). For the livestock sector the reduction has primarily been due to a decrease in livestock numbers (especially cattle), changes in the handling and management of effluents and improved feeding techniques (Jacobsen et al., 2019). In recent years, however, the downward NH_3 emission trend has slowed down and since 2014 it was even found to be positive (+2.3% from 2014 to 2017) (EEA, 2019a). Moreover, international policies adopted in recent decades for the abatement of anthropogenic emissions of SO_2 and NO_x, also involved in PM2.5 formation, have led to greater reductions in relative terms than those of NH_3 (Reis et al., 2015), which favors greater focus on the latter.

The application of engineering principles and precision techniques for monitoring and manage livestock production processes basically allows to improve animal welfare (Berckmans, 2014) and health (Lovarelli et al., 2020). Especially thanks to the consequent superior productive and reproductive animal performances, this is also accepted as a way to make livestock systems more environmentally sustainable (Tullo et al., 2019). Hence, the use of specific technologies can play a role in solving environmental challenges, if these present a positive balance in conserving the natural environment and contrasting the negative impact of human activities (Aarras et al., 2014).

Air scrubbers are air cleaning devices used to control and remove pollutants from exhaust air, commonly adopted for industrial streams, but which can also be used in pig and poultry housing facilities (Van der Heyden, 2015). For the latter sector air scrubbers are normally installed with ammonia as the main target substance for which to reduce emissions, but also involve, to a lesser extent, abatements of other pollutants as VOC and PM, since these are partially captured by washing water (Van der Heyden, 2015).

Air scrubbers represent an end-of-pipe technique, i.e. a technique that reduces final emissions by some additional process but does not change the fundamental operation of the core process (Santonja et al., 2017). In the Best Available Techniques[1] (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs the air cleaning systems are listed in the techniques to be considered BAT (EC, 2017).

As regards the pig sector, the wet acid scrubber (WAS), which involves the capture of NH_3 by means of an acid solution, is currently the most widely applied air cleaning technology (**Table 1**). It entails greater removal efficiency of NH_3 (normally in a range between 70% and 99% of the background air concentration) and lower water consumption (and consequently also less output stream, which translates into lower management costs) compared to bioscrubber (or biotrickling filter), the main alternative technology currently available.

Table 1 around here

This technology is increasingly promising in environmental terms and could play an important role in the near future for air pollutants control from the agricultural sector in the EU. This could contribute

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[1] According to the Directive 2010/75/EU on Industrial Emissions (IED), 'techniques' refers to the technology used to prevent and/or reduce emissions and the way in which the installation is designed, built, maintained, operated and decommissioned; 'available techniques' means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator; 'best' means most effective in achieving a high general level of protection of the environment as a whole.

to fall within the PM2.5 concentration thresholds set by the Air Quality Directive, as well as within the National Emission Ceilings of air pollutants, set by Directive 2016/2284/EU, to be achieved by all Member States by 2030. Moreover, looking for environmentally-friendly food systems falls within the objectives of the European Green Deal (EC, 2019), and in particular of the Farm to Fork Strategy (EC, 2020a).

In this study, large-scale implementations of the WAS in EU pig housing facilities are simulated and potential benefits on human health are assessed. In addition, economic considerations are made related to saving the society damage costs given by air pollutants from pig housing thanks to their containment. To the best of the authors' knowledge, this is the first study that: focuses on scenarios of a large-scale implementation in the EU of an air cleaning technology in pig housing, estimating the consequent emissions abatement obtainable; in this context, carries out an environmental assessment in an endpoint perspective, focusing on the impact on human health, and makes economic considerations beyond operating costs by coupling emissions with environmental costs.

2. Methods

In order to explore the consequences that the large-scale implementation in the EU pig housing facilities of the WAS could have, methodology has been structured as follows: section 3.1 defines the analysis reference framework and describes how the starting emission inventory was built; in section 3.2 different scenarios are modeled, in order to be able to compare the current situation with an hypothetical alternative in which the WAS technology is widely adopted in pig farming; finally, sections 3.3 and 3.4 deal with the methods used to quantify human health impact and environmental costs, respectively. A schematic overview of the methodologies is illustrated in **Figure 1**.

Figure 1 around here

2.1. Definition of the reference framework and emission inventory

Quantifying the magnitude of emissions is a key component for the development of control policies for atmospheric pollutants (Rebolledo et al., 2013). Therefore, an inventory of NH_3, PM10 and NMVOC emissions related to pig production was first built. These have been selected as they are among the pollutants that cause the greatest public concerns related to pig farming activities and, at the same time, their emissions are the most affected by the implementation of the technology addressed in this study (i.e. the WAS). Only emissions that occur at the housing stage were computed, being the stage affected by the WAS. On the other hand, emissions from handling, storage and distribution of effluents were not considered. The reference pig population of each Member State was taken from the Eurostat database for the year 2018 (Eurostat, 2020a). The calculation only concerned animals raised in large farms (i.e. sows and fattening pigs bred in farms with more than 1000 heads of the same category), as these reflect intensive rearing practices and may be realistically involved in the installation of the WAS. The pig population housed in these farms actually represents the majority of the EU pig population, accounting for 78% and 75% of total sows and fattening pigs, respectively (elab. on Eurostat, 2020a). More details on the concerned pig population on which the emission inventory was built can be found in Tables S1 and S2 (supplementary materials). NH_3, PM and NMVOC emission factors (kg of pollutant · head^{-1} · year^{-1}) were derived using sources from official EU publications and databases (**Table 2**). Regarding pig nitrogen excretion, despite the availability of national emission factors, it was preferred to use a single European average reference (EEA, 2019b) due to the poor harmonization encountered across country-specific inventories, an issue already highlighted by *Velthof et al.* (2015).

Table 2 around here

NH_3 emitted by livestock systems may determine, after re-deposition, the formation of dinitrogen monoxide (N_2O) through nitrification and incomplete denitrification processes. These N_2O emissions, referred to as indirect, have been included in the assessment, being directly connected to NH_3, and computed considering the emission rate of 0.01 kg N_2O-N · kg NH_3-N emitted^{-1} (IPCC, 2019). The combination of the emission factors with the concerned pig population completed the starting emission inventory.

2.2. Scenario modeling

The emission inventory in its starting condition defines emissions of the main air pollutants from pig housing facilities in a condition of absolute lack of control measures, which does not actually correspond to the current condition as different emission reduction techniques are already widespread in pig farms. Therefore, first the current scenario (CS) was defined, i.e. a scenario in which the reduction techniques are applied at the housing stage to the current diffusion. Two alternative scenarios (AS1 and AS2) were subsequently modeled in which, compared to CS, the air cleaning technique is implemented at increasing rates, and considering that this occurs exclusively through the WAS technology.

Emission reduction techniques were divided into two categories: *air cleaning* and *feeding and housing management*. The first refers to the air scrubbing technique, the latter include all the other measures adopted at the pig housing stage with the aim of reducing NH_3 emissions. These are mainly represented by: precision feeding strategies, presence of deep pit (in case of a partly slatted floor), frequent slurry removal (by means of vacuum systems or flushing) and slurry cooling systems (Pexas al., 2020a). The removal efficiencies considered for the two categories of techniques are shown in **Table 3**.

Table 3 around here

The removal efficiencies remain fixed across scenarios, which instead are differentiated by the diffusion (implementation rate) of the techniques themselves. The implementation rates considered for the three scenarios are shown in **Table 4**. Since no official nor detailed data on the diffusion across the EU of *feeding and housing management* techniques have been found, they were assumed to affected 50% of the total concerned pig population. This was considered fixed for the three scenarios, as the analysis was focused on the variability given by different implementation rates of *air cleaning* techniques. The assumption was made considering that the pig farms addressed in this study largely coincides with those subjects to the IED for operating permits[2]. These are officially required to monitor and report their environmental performances, demonstrating to apply one or more of the techniques listed in the BAT conclusions document, which also includes those of feeding

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[2] Farms with more than 2000 places for production of pigs (over 30 kg) or with more than 750 places for sows, as specified in Section 6.6 of Annex I to Directive 2010/75/EU on Industrial Emissions (IED).

and housing management. However, to check how this methodological choice affected the results, a sensitivity analysis was carried out in this regard.

Table 4 around here

With regard to air cleaning, the actual diffusion of this technique is also currently unknown. and Air scrubbers are fairly widespread in Belgium, the Netherlands (*Van der Heyden et al.* (2015), Denmark and Germany (*Santonja et al.* 2017) (hereinafter, north-continental countries), while in the other Member States this technology is uncommon. According to *Blonk Consultants* (2019), in The Netherlands about 35% of pig farms practice *air cleaning* techniques. This share was extended to the other north-continental countries, assuming the same implementation rate between them for CS. Implementation rate of *air cleaning* techniques was assumed at 5% for all other Member States. AS1 simulates a situation in which all Member States where the use of *air cleaning* techniques is currently uncommon reach the implementation rate of the north-continental ones. AS2 instead simulates a situation in which all Member States increase their implementation rate up to 65%, which corresponds to the current European average implementation limit (maximum feasible applicability) of this technology (elab. on *Klimont & Winiwarter*, 2011). In particular, the gap in the implementation rate of *air cleaning* between CS and the alternative scenarios has been assumed to be bridged exclusively by the adoption of the WAS.

In all three scenarios, the implementation rates of the two emission reduction techniques were considered to be uncorrelated, i.e. independent events. This leads to the possible occurrence of four cases in the simulation: application of *feeding and housing management*; application of *air cleaning*; application of both *feeding and housing management* and *air cleaning*; neither of the two techniques applied. These were determined with the following equations:

$$PA_{1,s,ms} = IR_{F\&H} - \left(PA_{3,s,ms}\right) \tag{1.1}$$

$$PA_{2,s,ms} = IR_{AC,s,ms} - \left(PA_{3,s,ms}\right) \tag{1.2}$$

$$PA_{3,s,ms} = \left(IR_{F\&H} IR_{AC,s,ms}\right) \tag{1.3}$$

$$PA_{4,s,ms} = 1 - \left(PA_{1,s,ms} + PA_{2,s,ms} + PA_{3,s,ms}\right) \qquad (1.4)$$

Where:

- $PA_{1,2,3,4}$: probability that a case of emission reduction technique application occurs (four cases: *feeding and housing management* [1], *air cleaning* [2], *feeding and housing management* and *air cleaning* [3], neither of the two techniques applied [4]), {%};
- s, ms : scenario (CS; AS1; AS2), Member State;
- $IR_{F\&H}$: implementation rate of *feeding and housing management* emission reduction techniques, {%};
- IR_{AC} : implementation rate of *air cleaning* emission reduction techniques, {%};

The whole process of estimating the emission concerned and adjusting to the different scenarios can be mathematically resumed as follows [Eq. (2)]:

$$E_{p,s} = \sum_{ms,c} PP_{ms,c}\, LH_{ms,c}\, EF_{p,c} \;\; \left[PA_{1,s,ms}\left(1 - Re_{F\&H,p}\right) + PA_{2,s,ms}\left(1 - Re_{AC,p}\right)\right.$$

$$\left. + PA_{3,s,ms}\left(1 - Re_{F\&H,p}\right)\left(1 - Re_{AC,p}\right) + PA_{4,s,ms}\right]$$

Where:

- E : total emission from EU large pig farms at the housing stage, {Gg · year^{-1}};
- p, s, ms, c : pollutant (NH_3; PM10; NMVOC), scenario (CS; AS1; AS2), Member State, pig category (sows; fattening pigs);
- PP : pig population, reference year: 2018, {heads};
- LH : share of population hosted in large farms (> 1000 heads per pig category), {%};
- EF : emission factor at the housing stage, {kg · head^{-1} · year^{-1}};
- $PA_{1,2,3,4}$: probability that a case of emission reduction technique application occurs, Eq. (1.1), Eq. (1.2) Eq. (1.3), Eq. (1.4), {%};
- $Re_{F\&H,AC}$: removal efficiency of different techniques (two techniques: *feeding and housing management* [F&H], *air cleaning* [AC]), {%}.

2.3. Human health impact assessment

Human health represents an endpoint environmental impact indicator[3]. In fact, midpoint impact indicators can be useful for identifying reduction targets and measures for specific environmental concerns, but often they cannot be easily understood or even show contradictory trends across different categories. For this reason, endpoint results represent a more direct and clearer tool for decision making, if supported by relevant and transparent information (Kägi et al., 2016).

The disability-adjusted life years (DALY) concept was adopted to quantify the human health impact. This metric is used by the WHO to account the overall burden associated with health problems. One DALY represent the loss of one healthy year and is calculated as the sum of the years of life lost (YLL) due to premature mortality and the years lost due to disability (YLD) (WHO, 2008). In the context of the present study, the DALY indicator is meant to be a measurement of the gap between the current health status (in CS) related to emissions from the housing stage of intensive pig farming and an improved health situation achievable with the large-scale implementation of the WAS technology (in AS1 and AS2). It is necessary to consider that the level of detail remains approximate in spatial terms, given the complexity of accounting for human health and some variability depending on the location, the pollution source and the target population involved, together with numerous other factors. However, this study aims to quantify the extent of the overall impact that large-scale adoption of WAS technology could have, rather than measuring the variation of human health precisely in geographical terms within the EU.

The inventory data to carry out the assessment included emission from housing facilities of the concerned pig population, adjusted for each scenario according to *Eq. (2)*. In AS1 and AS2, the consumable inputs necessary for the WAS operation were considered. As for electricity, a consumption of 10.3 kWh · kg of treated NH_3-N^{-1} was considered, according to *De Vries & Melse* (2017). Other inputs considered were water (250 L · kg of treated NH_3-N^{-1}, according to *De Vries & Melse*, 2017) and acid chemicals (1.5 L of sulfuric acid (H_2SO_4) · kg of removed NH_3^{-1}, according to

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[3] Midpoint environmental impact categories are indicators (e.i. climate change, particulate matter formation, ozone depletion, etc.) that convert the emission of substances to the environment and/or the resource scarcity into a series of potential impacts in the middle of environmental cause-effect chain, rather than expressing the actual damage level. Endpoint indicators, on the other hand, reflect the midpoint impact categories at a further level of the cause-effect chain, associating them with different stressors and pathways into three areas of protection (human health, ecosystem quality and resource scarcity) which represent the main environmental concerns at the human society level.

Sigurnjak et al., 2019). Impacts related to capital goods (production, use, depreciation and final disposal of materials that make up the WAS machine) were excluded due to lack of information, however considering their human health impact negligible compared to that of operational consumable inputs over multiple years lifespan (Li et al., 2019). The discharge water produced by the WAS operation can be viewed as an effluent to be valorized through the agronomic exploitation of its nutrients. This could lead to the replacement of considerable amounts of nitrogen fertilizer. In AS1 and AS2 the environmental credit given by the avoidance of synthetic mineral fertilizer production has therefore been included, assuming to replace a nitrogen dose equal to the ammoniacal nitrogen captured by means of WAS operation. Urea has been used as a replaced fertilizer, given its widespread use on a European scale. All the outputs (emissions) and inputs (both consumed and avoided) have been considered for each scenario and the overall human health impact was derived from their combination. Background data relating to all inputs were taken from the Ecoinvent® database v3.5 (Weidema et al., 2013). Table S3 reports the list of different Ecoinvent® processes used.

The characterization factors of environmental impacts (i.e. correlations between emitted/avoided pollutants and DALY) were obtained from the established ReCiPe method (v 1.13 / Europe, H/A) (Goedkoop et al., 2009). The assessment was performed by using SimaPro software v.8.5 (Pré-Sustainability, 2018).

2.4. Environmental costs assessment

Environmental costs, even referred to as *external, shadow* or *damage costs*, arise when the production or consumption of a good or service imposes, due to additional amounts of pollutants emitted to the environment, one or more negative effects on a third party (Allacker & de Nocker, 2012). Environmental prices proposed by the CE Delft EU-28 Environmental Prices Handbook (De Bruyn et al., 2018a) were used in this study. These are indicators of the social marginal value of preventing emissions, coming express in € per kilogram pollutant (De Bruyn et al., 2018a). The Handbook reports monetary values referring to 2015 for the loss of welfare in EU-28 due to environmental pollution: relationship between emissions and endpoint impacts are built, for each pollutant, on concentration-response functions for human health, ecosystem services, damage to buildings/materials, resource availability and nuisance (De Bruyn et al., 2018a). The environmental prices for pollutants concerned in this study are shown in **Table 5**. These were applied to the emission inventory adjusted for each scenario, according to *Eq (2)*. It should be noted that these values refer to 2015, therefore they may have undergone some changes over the years due to inflation, variations in emissions trends and/or in the value attributed by people to environmental goods or ecoservices (since some prices are determined by contingent valuation methods). However, in the present study the conservative approach of assuming that these prices remain constant over time was adopted, as suggested by the Handbook.

Table 5 around here

3. Results

In the current scenario (CS), representing the real situation in the EU for 2018, emissions of the concerned pollutants from intensive pig housing facilities (farms with more than 1000 heads of sows or fattening pigs) account for 212.2 Gg of NH_3, 9.3 Gg of PM10 and 132.8 Gg of NMVOC (**Table 6**). These values respectively represent 6%, 11% and 15% of total agricultural emissions of the relative pollutants reported by the EEA for 2017 (EEA, 2019a). Still considering the EEA reference, NH_3 emissions in CS represent 43% of the total from the swine sector manure management in the EU. Indirect N_2O emissions account instead for 2.75 Gg, equal to 728.8 Gg of CO_2 eq, according to the characterization factor proposed by the Fifth Assessment Report of IPCC (IPCC, 2013).

In the alternative scenarios (AS1 and AS2), great emission reductions compared to CS are obtained. NH_3, being the pollutant on which the WAS expresses the highest removal efficiency, is the one that faces the most significant reductions, of 17% and 45% respectively for AS1 and AS2. The capture of a large quantity of ammonia also leads to the avoidance of the production of significant amounts of synthetic mineral nitrogen fertilizer (64.0 and 169.2 Gg of urea per year, respectively for AS1 and AS2) that would be necessary to provide for the same nitrogen dose. On the other hand, the consumption of inputs necessary for the WAS operation is considerable.

Table 6 around here

3.1. Human health impact

The estimated emissions for CS translate into an annual human health impact equal to 21212 DALY. These are mostly (95%) a consequence of particulate matter formation, which in turn is primarily due to ammonia emissions (88%) and, to a lesser extent, to PM10 direct emissions (12%). The remaining DALY portion (5%) is instead a consequence of climate change through indirect N_2O emissions. NMVOC emissions are not included in the DALY evaluation neither in CS nor in the alternative scenarios due to data limitation, as the ReCiPe LCIA method (Goedkoop et al., 2009) provides characterization factors for individual compounds but not for unspecified NMVOC. The total DALY in the alternative scenarios are gradually reduced with the increase in the WAS implementation rate. In particular, the human health impact is reduced to 18007 DALY (-15%) for AS1 and 12730 DALY (-40%) for AS2. **Figure 2** shows the DALY variation for AS1 and AS2 compared to CS, divided by different contributors. The increase in the WAS implementation in the alternative scenarios leads to a growing consumption of inputs necessary for their operation, which implies a positive DALY variation (+386 for AS1 and +1021 for AS2). In particular, the positive variation due to the consumables in both AS1 and AS2 is given mainly by electricity consumption (81%), followed by acid chemicals (17%) and water (2%). However, the trade-off due to consumables is largely overwhelmed by the DALY values negative variations given by emission reduction. The reduction of ammonia emission is the one that most contributes to mitigation, representing alone 87% of the DALY negative variation given by overall emissions reduction in both AS1 and AS2. The results also show that avoiding the production of synthetic mineral fertilizers contributes to further reducing the DALY in the alternative scenarios, as a consequence of their production being highly energy consuming.

Figure 2 around here

3.2. Environmental costs results

The overall annual environmental cost given by the sum of the individual emissions of the current scenario (CS) turns out to be 4154 million €$_{2015}$ (range of 2426-6041). Considering the EU population for the same year (i.e. 512 million inhabitants, Eurostat 2020a), these environmental costs lead to an average annual social weight of about 8 €$_{2015}$ per capita. NH_3 is the primary cause of this, accounting for 3714 million €$_{2015}$ (range of 2122-5347), or about 89% of the total. This result depends both on the large amount of NH_3 emitted, compared to PM10 and indirect N_2O, and on its relatively high environmental price per kg, compared to NMVOC, mostly as a result of increased morbidity and mortality associated with increasing PM2.5 formation (De Bruyn et al., 2018a). **Figure 3** shows the environmental costs save for AS1 and AS2 compared to the current scenario as a result of reduced emissions of NH_3 (**Figure 3.a**) and PM10, NMVOC and indirect N_2O (**Figure 3.b**) by means of WAS implementation.

In AS1 and AS2 can be saved respectively 668 million €$_{2015}$ (range of 386-968) and 1765 million €$_{2015}$ (range of 1019-2557) per year related to the effects of the overall emissions. Despite a wide variability given by the uncertainty of environmental prices of pollutants, these reductions in environmental costs are still significant quantities, which can contribute to improving the influence of livestock farming on EU social well-being. Both in AS1 and AS2, NH_3 emission reduction is responsible for 94% of the cost reduction compared to the CS, which again highlights the role of primary importance of this pollutant, and consequently the need to constantly improve the control of its emission.

Figure 3 around here

3.3. *Sensitivity analysis*

To test the robustness of the results, a sensitivity analysis was carried out by changing key variables of the scenario modeling. The first change was made to the implementation rate of *feeding and housing management* techniques, which had been assumed to be 50%, fixed for the three scenarios. Results variation was arbitrary explored for 25% (low) and 75% (high) implementation rates of these techniques. The second change regarded the removal efficiency of the *air cleaning* technique, that have been tested for removal variations in different performance conditions. The achievable reductions were therefore varied considering 70% for NH_3, 40% for PM10 and 30% for NMVOC in low performance conditions and 90% for NH_3, 60% for PM10 and 40% for NMVOC in high performance conditions. In each analysis performed, indirect N_2O emissions, inputs consumed for WAS operation and avoided nitrogen fertilizer production were modified accordingly. The setting of the analysis has been reported in detail in Table S4, while the results in absolute terms are shown in Tables S5 and S6.

Despite the wide variability tested (±50% of the baseline value) for the implementation rate of *feeding and housing management* techniques, the absolute values (both in terms of DALY and environmental costs) undergo a limited change (constant across scenarios) of ±8.6% compared to the values of the baseline scenarios for CS, AS1 and AS2. Even regards the removal efficiency of the scrubber, there is a reduced variation in the results under the different tested performance conditions. In this case, however, the variability compared to the baseline scenarios gradually widens as the implementation rate of the *air cleaning* technique increases, going from ±1.9% for CS to ±4.8% for AS1, finally reaching ±12.7% for AS2.

4. Discussion

The consequences of the large-scale implementation in the EU pig sector of the WAS go far beyond the farms' boundaries, leading to net positive environmental and economic endpoint effects on the impact of intensive pig farming.

In AS1 a great reduction on human health impact and environmental costs is achieved with the increased WAS implementation rate of all Member States at the current level of implementation of the north-continental countries. WAS implementation should therefore be a target primarily for those countries where it is currently under-used. In AS2 there is an even more significant reduction, more than double compared to AS1. The north-continental countries are in fact major players in the EU swine market and host alone 43% of sows and 37% of fattening pigs on the respective total EU populations hosted in large farms (> 1000 heads of the same category) (elab. on Eurostat, 2020a), therefore an increased implementation rate even in these countries boosts the human health impact and environmental costs reduction.

Reductions obtained in this study could be further accentuated by means of future improvements in the WAS operation, so as to increase its removal efficiencies and minimize the consumption of inputs. For instance, the coupling of this machine with microclimatic smart tools that activate its operation only when the air pollutants concentration exceed fixed thresholds can be a way of reducing electricity consumption, which emerged as the main contributor to the trade-off consumables impact in the alternative scenarios. Electricity itself in a long-term perspective is destined to weigh less and less from an environmental point of view on the performance of the WAS, since the EU aims to constantly increase the energy mix share deriving from renewable sources (Ingrao et al., 2018).

As shown in Table 1, the relatively high implementation and running costs currently represent the main obstacle to the widespread application of WAS technology in pig farms in the EU. However, its diffusion in north-continental countries proves that this technique is actually economically viable in intensive livestock systems (Melse et al., 2009). *Pexas et al.* (2020b) recently performed a comparative cost-effectiveness analysis of several abatement measures to mitigate, among others, ammonia emissions from pig housing, but did not include any air cleaning technology. Future studies will have to deepen the costs of air scrubbing to identify ways of making its performance fully sustainable even from an economic point of view.

Furthermore, the relationship between a better environmental condition inside the pig facilities given by air scrubbing and a possible improvement in animal efficiency (e.g., better feed conversion rate) and welfare have never been considered in literature. An improvement in animal welfare could enhance the fattening and reproductive performances and the slaughtering yield, thus bringing direct economic benefits to farmers. The working and health conditions of agricultural operators directly involved in pig farming are also likely to be improved thanks to a better environment inside the animal's housing facilities. All these factors could be determinant for the decision-making of farmers towards the implementation of air scrubbers and need further future study.

The reuse of discharge solution from WAS as fertilizer is also a factor that can influence the farmers decision towards the implementation of this technology, allowing to reduce synthetic mineral fertilizers costs for European mixed crop-livestock systems. However, discharge water from air cleaning technologies is still defined as 'livestock manure' in the EU legislation in force (EC, 1991). Therefore, this product falls within the application limits at a maximum rate of 170 kg N $\cdot$ ha^{-1} in Nitrate Vulnerable Zones, leading it to compete with “real” manure, thus limiting the adoption of the WAS technology in these areas due to the lack of benefit for farmers from this point of view. This contributes to the paradox that nutrient surplus regions are also among the largest consumers of synthetic mineral fertilizers for meeting crop requirements (Sigurnjak et al., 2019). Currently, research on behalf of the EC is being carried out to promote the sustainable recovery of nutrients from manure which could possibly solve this issue (Huygens et al., 2019), favoring a growing implementation of WAS technology in the near future.

Pig meat production in EU-28 accounted for 23.8 Mt of carcass weight in 2018, or 49.8% of the total meat production. In the same year, the output value at basic prices of the pig sector was an estimated 36300 million €, or approximately 21% of the output from all animal products and 8.3% of the total agricultural output (Eurostat, 2020a). Hence, this sector plays an important role in the agricultural economy of the EU, but it is necessary to look for an increasingly sustainable production that also contains the environmental costs associated with it. As for the pig housing phase, this study has shown that the WAS large-scale implementation appears to be a viable option for significantly alleviate the huge environmental costs of air pollutant emissions. The question remains on how to internalize these costs in the production chain. Environmental management strategies (in this case, the installation of WAS technology) entail costs and farmers may generally find it difficult to bear their full economic weight by aggravating existing production costs. On the other hand, *Nguyen at al.* (2012) estimated that the load of environmental costs on the market price of pork would lead it to at least double its value. *De Bruyn et al.* (2018b) instead made a smaller estimate according to which the pork market price would increase by about 50%. In any case, the hypothesis of fully charging the environmental shadow cost of pork production to the final consumer is unlikely to happen as the price is a key factor in the food choice and the attitude of most consumers already undergoes substantial variations for food taxes (Thow et al., 2014) or subsidies ranging from 10% to 20% (Hoek et al., 2017). Nevertheless, consumers have a primary role in making food chains more sustainable (Grunert, 2011). While a recent study has shown that EU consumers are not willing to pay for improving pig welfare beyond the medium level (Denver et al., 2017), they have recently been increasingly interested in promoting environmental sustainability in the agri-food sector (EC, 2018). At present there is still a gap between the positive attitude towards this concept and the market everyday behavior (Rejman et al., 2019). However, if appropriately encouraged by a targeted product positioning strategy, EU consumers may have a greater propensity to purchase environmentally sustainable pork, knowing that this would bring benefits for society as a whole, in terms of human health. For this reason, future studies could explore the willingness to pay of European consumers for this type of product to verify whether, at least partially, the environmental costs can be met by consumers.

This study was focused on the intensive pig farming, but the same method and considerations could be extended to poultry housing facilities. In fact, the WAS technology has been proven to be applicable even for the poultry sector with good performances (Van der Heyden et al., 2015).

Finally, carrying out this analysis highlighted the current lack of detailed data that cover livestock systems in the EU by type of feeding, housing and manure management. There is a future need for improved information in these areas, because they are increasingly crucial for an accurate estimate of emissions, which in turn can influence mitigation strategies and policies.

5. Conclusions

Large pig farms (> 1000 heads of sows or fattening pigs) host the majority of pig population in the EU and are responsible for significant air pollutant emissions, a considerable part of which occurs at the housing stage. End-of-pipe air cleaning techniques are among the possible measures to control and reduce these emissions. However, they are currently little adopted on a European scale, despite their removal efficiency have already been proven be great, in particular with regard to ammonia.

This study explored the emission reduction achievable with increased implementation rates of the wet acid scrubber technology in intensive pig farms across the EU, demonstrating that it would bring a largely positive endpoint effect on human health, and also lead to significant alleviation of current environmental costs on society of air pollution related to intensive pig farming.

Further assessments are to be done to better investigate various issues regarding the wet acid scrubber, including cost-effectiveness, influence on animal welfare and production performance, impact on working conditions of agricultural operators and discharge water management. Consumer behavior towards a more sustainable pig production is also a study field to be deepened in the future. Nonetheless, what emerged clearly is that there is vast room for improve the environmental sustainability of intensive pig farming at the housing stage and the use of the wet acid scrubber can push strongly in this direction. Therefore, in our vision, its implementation should be increasingly encouraged by EU and/or national policies, especially in countries other than north-continental ones, where its use is currently uncommon.

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Table 1 – Main considerations to be taken into account regarding the installation of the wet acid scrubber in pig housing facilities.

Pros	**Cons**
- Very effective for ammonia emission abatement (with fluctuations given by ventilation rate, pollutant load, relative humidity and temperature of incoming air, etc.) (Van der Heyden et al., 2015); - Effective for VOC and PM emission abatement (Van der Heyden et al., 2015); - Could also have relevant capture effects for CH_4 and N_2O (Mostafa et al., 2020); - The water discharged contains high nitrogen concentration (3-9% according to Sigurnjak et al., 2019) and can be used as fertilizer with good agronomic performances (Martin et al., 2018); - Currently represents the most suitable air cleaning technology in economic (Santonja et al., 2017) and environmental (De Vries & Melse, 2017) terms. Confirming the latter, the WAS does not promote N_2O formation, which instead occurs for bioscrubbers as side effect of the NH_3 abatement reaction, causing an environmental trade-off with climate change (Dumont, 2018); - Can be designed for specific target substances according to the needs; can be combined with other technologies to form multi-stage scrubbers (Van der Heyden et al., 2015).	- Requires significant investment and operating costs. *Melse et al.* (2008) reported the former at 32.8 €/animal place while the latter at 8.2 €/animal place/year. Hence, considering the depreciation, the WAS would cost 10.3 €/animal place/year in total; - Involves a considerable water consumption and water input and discharge flows suffer from some uncertainty (Santonja et al., 2017). In any case, it requires efforts to manage an effluent stream; - Safety measures are required for the storage and handling of chemicals, specific staff training may be needed (Santonja et al., 2017); - If used with other acids other that sulphuric acid, the effluent solution may need to be disposed (Santonja et al., 2017); - It may not be suitable for facilities without centralized ventilation systems (Santonja et al., 2017).

Table 2 – Parameters and emission factors used to build the emission inventory for NH_3, PM10 and NMVOC.

Item	**Unit of measure**	**Category**		**Source**
		Sows (and piglets)	**Fattening pigs**	
N excretion	kg N · head^{-1} · year^{-1}	34.5	12.1	EEA (2019b)
Proportion of N excreted as TAN	kg TAN · kg N^{-1}	0.7	0.7	EEA (2019b)
Proportion of excreta handled as slurry	Dimensionless	0.91	0.91	Eurostat (2020b)
NH_3-N emissions from TAN of slurry (during housing)	kg NH_3-N · kg slurry TAN^{-1}	0.35	0.27	EEA (2019b)
NH_3-N emissions from TAN of manure (during housing)	kg NH_3-N · kg manure TAN^{-1}	0.24	0.23	EEA (2019b)
PM10 emission factor (from animal husbandry)	kg PM10 · head^{-1} · year^{-1}	0.17	0.14	EEA (2019b)
Default values for Live Weights	Kg	190 (WE)[a]; 204 (EE)[a]	61 (WE)[a]; 59 (EE)[a]	IPCC (2019b)
Default values for volatile solid excretion	kg · 1000 kg live weight^{-1} · day^{-1}	2.4 (WE)[a]; 2.0 (EE)[a]	4.9 (WE)[a]; 5.3 (EE)[a]	IPCC (2019b)
NMVOC emission factor (during housing)	kg NMVOC · kg VS excreted^{-1}	0.007042	0.001703	EEA (2019b)

[a] WE: Western Europe, including AT, BE, CZ, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MT, NL, PT, SE, SI; EE: Eastern Europe, including BG, CY, EE, HR, HU, LT, LV, PL, RO, SK.

Table 3 – Emission reduction techniques considered and their assumed removal efficiencies. Indirect N_2O depends directly on emitted NH_3, therefore it is not individually influenced by the different reduction techniques.

Concerned air pollutant	Feeding and housing management	Air cleaning
NH_3	30 % [a] [b]	80 % [d]
PM10	25 % [a]	50 % [d]
NMVOC	20 % [c]	35 % [d]

[a] *Blonk Consultants* (2019).

[b] consistent with the reference removal efficiencies of these techniques reported by the NEC Directive (2016/2284/EU) and the Ammonia Guidance Document (ECE/EB.AIR/120).

[c] assumed considering information reported by *Ni et al.* (2012).

[d] average removal efficiencies of the ranges reported by *Van der Heyden et al.* (2015).

Table 4 – Implementation rates of emission reduction techniques for the three scenarios. Percentages express the share of the concerned pig population that is affected by emission reduction techniques across the specified countries.

		Scenario		
Emission reduction technique	**Countries**	**CS**	**AS1**	**AS2**
Feeding and housing management	All Member States	50 %	50 %	50 %
Air cleaning	North-continental countries (BE, DE, DK, NL)	35 %	35 %	65 %
	All others Member States	5 %	35 %	65 %

Table 5 – Environmental prices for atmospheric pollutants considered for the assessment, expressed in €$_{2015}$/kg. Source: *De Bruyn et al.* (2018a).

Pollutant	Lower value[b]	Central value[b]	Upper value[b]
Ammonia [a]	10.0	17.5	25.2
Particulates, < 10 µm	19.0	26.6	41.0
NMVOC	0.84	1.15	1.84
Dinitrogen monoxide	5.78	15.0	25.0

[a] consistent with the values previously reported by *Brink & van Grinvsen* (2011), which identified an average price of 14 € (but in a wider range of 4-30 €) per kg NH_3-N emitted to the environment in the EU.

[b] central value is calculated according to standard economic principles and is the one recommended for most applications. However, lower and upper values express thresholds given by the uncertainties in people's assessment of environmental quality and have been reported to reflect the intrinsic variability of environmental prices.

Table 6 – Resulting air pollutants emission from intensive EU pig housing facilities (farms with more than 1000 heads of sows or fattening pigs) in the three scenarios; consumable inputs necessary for the WAS implementation (AS1 and AS2); amount of mineral fertilizer avoided by recovering and valorizing the discharge water as nitrogen fertilizer (AS1 and AS2).

Item		Unit of measure	**CS**	**AS1**	**AS2**
Pollutant	Ammonia (NH_3)	Gg · year^{-1}	212.2	176.5	117.7
	Particulate matter (PM10)	Gg · year^{-1}	9.27	8.34	6.82
	Non-methane volatile organic compounds (NMVOC)	Gg · year^{-1}	132.8	123.6	108.8
	Dinitrogen monoxide (N_2O) – indirect, from NH_3	Gg · year^{-1}	2.75	2.29	1.53
Consumables for WAS operation	Electricity	GWh · year^{-1}	-	379.1	1002.8
	Water	dam^3 · year^{-1}	-	9197.4	24326.8
	Acid chemicals	dam^3 · year^{-1}	-	53.6	141.8
Avoided synthetic nitrogen fertilizer production	Urea	Gg · year^{-1}	-	64.0	169.2

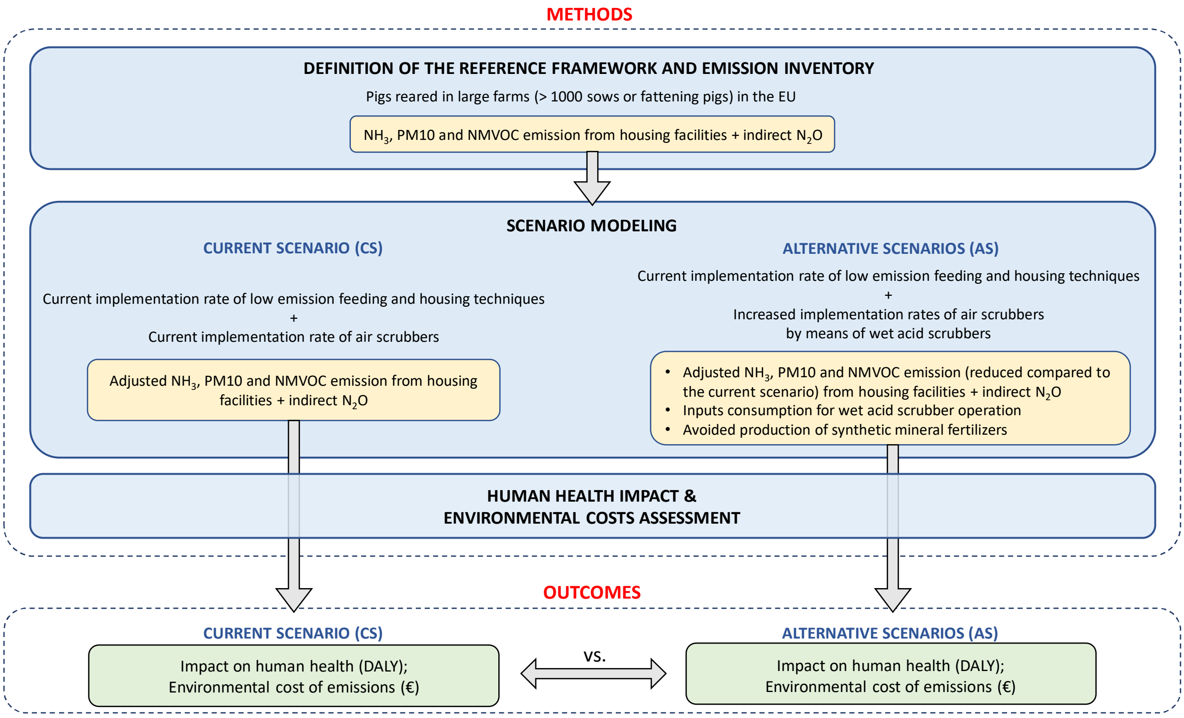

Figure 1 – Conceptual framework of the assessment.

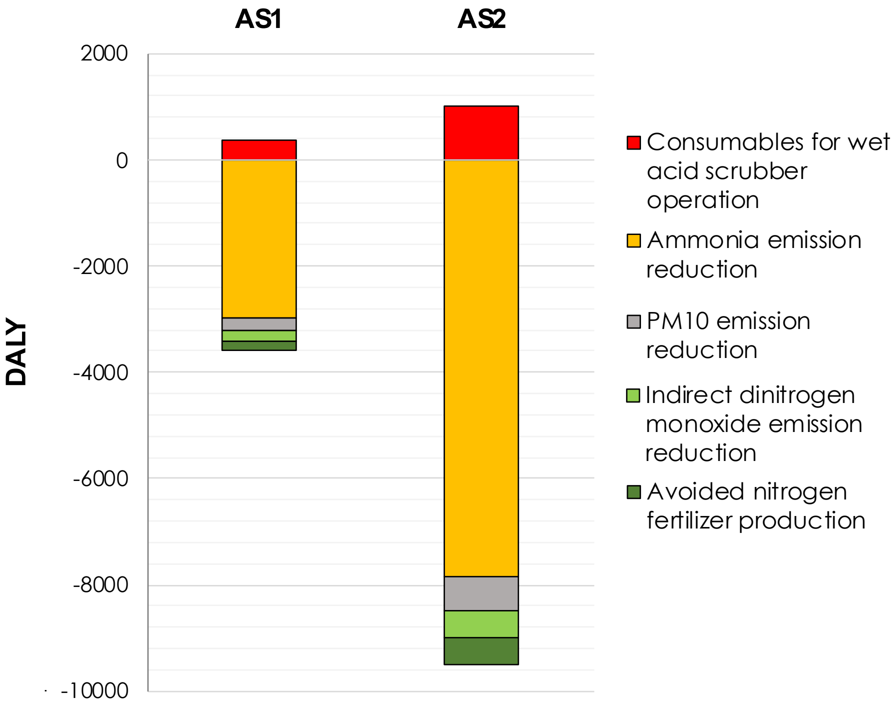

Figure 2 – Variation for AS1 and AS2 in the human health endpoint impact, expressed as disability-adjusted life year (DALY), compared to CS, divided by contributors. The consumables show positive values because compared to CS their increased consumption represents an additional environmental burden, while the emissions reduction and the avoidance of mineral fertilizer production are negative because they involve environmental credits compared to CS.

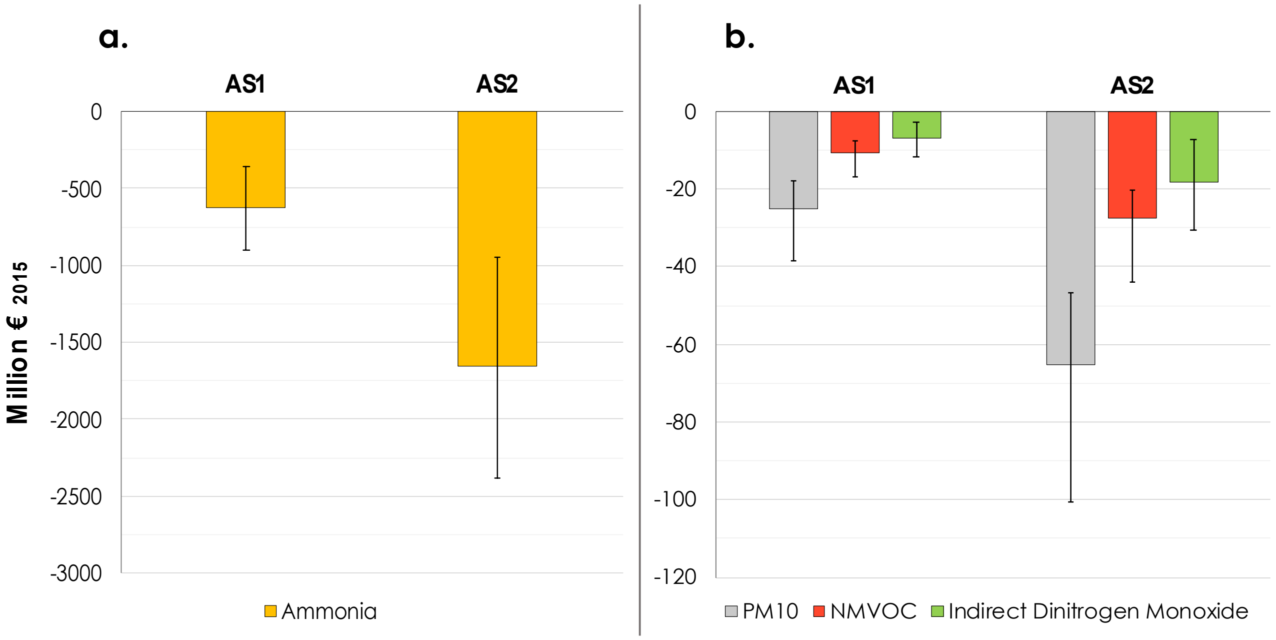

Figure 3 – Environmental costs save for AS1 and AS2, expressed as million €$_{2015}$ reduction with respect to CS. The graph has been split because of the different order of magnitude of the environmental cost saving between ammonia and the other pollutants. The error bars refer to the variability given by the upper and lower thresholds of environmental prices as shown in Table 5.