



Analyses and recommendations regarding four systems in the PigStun project that provide alternatives to high CO₂ stunning

Deliverable D4

May 2025

Work package: WP4

Nature: Deliverable

Code: D4

DOCUMENT CHANGE RECORD			
Version	Date	Notes / Change	Author
V1.0	15.01.2025	Final draft	Knoell <i>et al.</i>
V1.1	22.01.2025	Editorial changes	Gerritzen/Spolder
V1.2	28.04.2025	Editorial changes and regression fixes	Eisermann/Knöll et al.
V1.3	05.06.2025	Minor editorial changes	Knöll

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2. Introduction

In EU pig slaughterhouses two stunning methods are most commonly applied: electrical stunning and carbon dioxide stunning at high concentration.

Carbon dioxide gas stunning of pigs in groups is widely used because of its efficiency and reduced pre-slaughter stress, as pigs are handled and stunned in small groups. However, exposure to high concentration of CO₂ during stunning raises concern because it's aversive, causing hyperventilation and painful irritation of the mucous membranes (EFSA 2004 and 2024).

Electrical stunning is another commonly used method for stunning pigs at slaughter and results in immediate unconsciousness of the animal. But prior to stunning the animals need to be lined up in a row. To keep the animals moving whilst going from a group to a single line often involves stress and (painful) stimuli such as brushes and electric prods.

The general objective of the PigStun project is to encourage EU pig slaughterhouses using high CO₂ concentration for stunning pigs to convert to systems that are less aversive. This is done by testing promising alternative systems and improving strategies with respect to animal welfare. These alternatives are described in deliverable D3, along with descriptions of the tests and potential ways in which they could be implemented in practice. The parameters assessed during the tests are described in deliverable D2.

This deliverable (D4) provides results and conclusions from these tests as well as from estimates on social, environmental, economic and meat quality impacts. It also presents insights from stakeholders on the proposed alternatives, to reach general recommendations and facilitate a change away from conventional high concentration CO₂ stunning of pigs.

For ease of reading, the executive summary and recommendations are described before the results are addressed. In the comparative results section, the main outcomes for the different fields that were studied are described: Animal welfare, meat quality, economic, social and environmental impacts and ease of conversion. Detailed results for each system are presented at the end of the document after the report of feedback from stakeholders.

3. Executive Summary

To support the move away from current high CO₂ stunning systems, PigStun tested novel approaches and stunning systems along two lines of thinking: The first one looked at different Controlled Atmosphere Stunning (CAS) systems and using inert gasses. The second one aims to reduce stress during pre-stun handling, allowing a calmer entry into the stunner. This applies to the electrical stunning system and in different extent to the innovative gas systems.

We find that the alternatives tested have the potential to increase animal welfare.

It has to be acknowledged that most of the innovative ideas in the project have not yet been developed to commercial high-throughput scale (except for electrical stunning). For the gas stunning alternatives, no studies have yet been done at commercial scale to mitigate the reduced capacities that were observed. For this, the implementation phase that follows this project will require further scientific monitoring to ensure that measures for successful commercialisation do not counteract the observed animal welfare benefits.

Description of the alternative systems

Induction phase in Controlled Atmosphere Stunning (CAS) systems

Three systems that can use inert gases as alternatives to conventional high CO₂ were evaluated in the PigStun project. Inert gasses, such as argon and helium, have previously been shown to cause very little or no stress during the induction phase. In one system the question if high concentration CO₂ stunning can be optimised to reduce the negative effects of exposure to CO₂ is addressed. Data from these three systems were evaluated to test their feasibility as a replacement for conventional high throughput high concentration CO₂ stunning.

The Argon Retrofit system is an alternative that can be used following conversion of an existing Dip-Lift or Paternoster high concentration CO₂ stunning system. It provides stable atmospheres of inert gases such as argon or argon-nitrogen mixtures at very low oxygen levels (<1%). Comparisons to regular CO₂ stunning (local CO₂ control) were conducted inside the same stunner.

The Helium system consists of a newly designed technical system where the gondola moves up and lifts the animals into the gas, instead of going down. Data from this system is compared to data from a commercial Dip-Lift stunner at the same location (local CO₂ control). Because Helium is much lighter than air, existing commercial stunning systems cannot be converted to Helium.

The Optimised CAS process focuses on two distinct aspects related to animal welfare risks. It aims to reduce pre-stunning stress in the handling phase and to reduce the duration of negative effects of exposure to high concentration CO₂ in the CAS induction phase.

The Argon Retrofit and the Helium System are both tested under commercial like conditions (however not at high throughput) with Argon and Helium respectively and compared to local CO₂ conditions, while the Optimised CAS process was used in the Box System under experimental conditions using either CO₂, Argon or Helium.

Pre-stun handling

The PigStun project worked on different approaches to reduce stress in the pre-stunning phase: for groups of pigs in gas stunning systems, and for groups of pigs that need to be lined up in a single row for the electrical stunning system. Pre-stun handling is important for welfare, but it is acknowledged that reduced stress handling does not fully mitigate the aversive effects of stunning with CO₂.

Prior to gas stunning

The improved pre-stunning handling for gas stunning aims to minimise stress levels of groups of pigs. The different alternative CAS systems had different approaches: in the Helium System, animals were driven along the raceway and into the stunner by a robotic arm moving a single door, and for the Optimised CAS process, a pre-handling system was used whereby pigs were moved in a box with 3 animals (Box system). After entering the box, the animals did not have to walk and were rested for 45 minutes inside the stunner, prior to entry in the gas atmosphere. This allowed them to lay or sleep as a group before and during the exposure to the gas¹.

For the Argon Retrofit system it is in the primary concept of retrofitting, that no explicit changes to the pre-handling were implemented and only implicit changes due to the use of inert gases in the pit of the stunner could be expected.

Prior to electrical stunning

The Improved Electrical Stunning system focusses on pre-stunning handling, the design of raceways and the entrance of pigs into the stunner. The improvements of the Improved Electrical Stunning system consist of reducing the maximum number of animals per stunner per hour by installing more stunners, guiding pigs in small groups from lairage to the raceway, ensuring a modified route up to the raceway, allowing pigs to freely choose into which raceway they are walking to enter the stunner. Finally, a modified electric prod (lower voltage than conventional) can only be used at the point where animals have to step onto the conveyor in the stunner.

Study approach

Data on the four potential alternatives to conventional high CO₂ stunning were collected as described in deliverables D2 and D3, for four different fields of interest: 1) Animal welfare, 2) Meat quality, 3) Economic, environmental and social impact and 4) Ease of conversion. The data were analysed by different science groups not directly involved with any of the potential alternatives; IRTA for Animal welfare, DTI for Meat Quality and for ease of conversion and AU for Economic, environmental and social impacts.

Benchmark values were obtained from literature and commercial slaughter plants as described in deliverable D3 as a reference for values during conventional high concentration CO₂ stunning. To assess the economic data, the cost per pig after implementing a given alternative system was estimated. Most of the economic parameters included in these calculations were obtained as expert opinions. With these parameters the costs were calculated for four exemplary slaughterhouses (study cases).

The four systems were tested in the set ups:

The Argon Retrofit and the Helium System were both tested under commercial like standardised conditions with Argon and Helium respectively. Data obtained and analysed for these alternatives are qualitatively compared to high concentrations of CO₂ based on data collected in the same system (Argon) or the same location (Helium).

The Optimised CAS process was tested in the Box System under standardised experimental conditions using either CO₂, Argon or Helium.

¹ Already during the project it was decided that the Box system (which is part of the Optimised CAS system) is not commercially viable. The alternatives proposed to the Box system include improved handling of pigs through an automated walkway, which includes 'guiding plates' to move pigs forward towards the stunner either in a conventional pit ('backloader') or a tunnel shaped walkway ('tunnel'). They are both described in deliverable D3 as part of the Optimised CAS system, but neither could be tested in the PigStun project.

Data for the Improved Electrical Stunning system were collected at a commercial site already operating this system.

For the Box system and Electrical stunning system, no conventional high concentration of CO₂ stunner was available as a control group, and data was analysed and discussed in relation to high CO₂ based on benchmark values.

The within system analyses involve comparisons per study, between Ar or He and their respective local CO₂ control, or between the three gasses Argon, Helium, CO₂. Additional comparisons were made across systems and to Benchmark values, especially for the Optimised CAS system, or between Improved Electrical stunning and benchmark values or study cases. Detailed tables with all results per system can be found in Appendix A: Detailed results.

The Results section comprises analyses for each field of interest, comparing the same indicators across the testes systems.

Feedback from stakeholders was gathered through interviews with representatives from selected slaughterhouses, as well as comments obtained during a Workshop where the preliminary results were presented to interested stakeholders.

Results

Animal welfare

Pre-stun handling

Pre-stunning stress was reduced in both the Argon Retrofit and Helium systems, with the benefit for the Argon Retrofit system being limited to less resistance by pigs to enter the stunner. While the lack of local control conditions hinders interpretation, both the Box System tested for the Optimised CAS process and the Improved Electrical Stunning very likely reduced pre-stunning stress compared to commercial exposure to CO₂ and conventional automatic electrical stunning, respectively.

Induction phase in Controlled Atmosphere Stunning (CAS) systems

Stunning systems using argon and helium showed significant potential for reducing stress and improving animal welfare during induction compared to high concentrations of CO₂. Regardless of the system, the use of inert gases (argon and helium) reduced aversion and respiratory distress compared to high concentration CO₂ and therefore significantly improved animal welfare during induction of unconsciousness (measured until the loss of posture). Although details differed between specific systems, the stunning process overall took longer when exposed to argon or helium than with CO₂. With the appropriate stunning parameters, effective stunning can be achieved for all systems.

Meat quality

From a meat quality standpoint, none of the tested systems performed better than conventional CO₂ stunning. In test with Argon in a commercial dip lift system no differences in meat quality were found between the Argon Retrofit system and the local CO₂ control measurements conducted in the same stunner. However, blood spot levels at the local CO₂ control were already at the high end of what is expected for CO₂ stunning. During tests in the semi commercial Helium System a moderate increase in blood spots and drip loss was observed in the Helium group compared to the local CO₂ control condition. When inert gases were used in the Box System for the optimized CAS process, it led to elevated blood spots, drip loss, and PSE, with decremental effects for argon being the most severe as compared to CO₂. Although no local CO₂

stunning was used as a control, the electric system showed more quality issues regarding blood spots, drip loss and PSE compared to all CO₂ systems tested, including benchmark studies.

Overall, the meat quality was considered to be more affected in the Box system for the optimised CAS process for argon, and in part also for helium, compared to the Argon Retrofit system and the Helium system, respectively. The reason for this is not known as multiple aspects of the systems, as well as the environments and gas atmospheres under which they were tested and analysed, differed.

Ease of Conversion

The commercial readiness and throughput differed highly between the tested systems, ranging from currently running implementations at high throughput (Improved Electrical System), over systems that are runnable at small commercial scale, but need final steps for commercial readiness at high throughput (Argon Retrofit System, Helium System), to exploring optimal stunning conditions at currently low throughput rates with fundamental necessary changes to reach commercialization (Optimized CAS System).

The Improved electrical system is currently the only alternative solution in the PigStun project that was assessed in a high throughput setting. It is estimated that conversion from conventional electrical stunning to this system is a practical, doable solution to improve animal welfare, while changing from CO₂ stunning would require substantial reconstructing.

Evaluation on ease of converting of a commercial conventional CAS system to one of the alternatives is based on assumptions as none were tested at commercial scale. Based on the current insights, it appears that the Argon Retrofit system is closer to being a realizable way to convert from CO₂ stunning compared to the Helium System.

The Box system tested in the project will not be developed further by the industrial partner as it is unlikely to be commercially viable. However, alternatives approaches were suggested during the course of the project, including the use of automated moveable gates that encourage animals to move rather than push them to the stunner. Furthermore, the use of sensors to monitor and optimize O₂ and CO₂ concentrations, and thereby improving welfare in the induction phase, has been suggested. While the later appears to be a rather easy conversion to make these suggestions have not been tested within the scope of the project.

Environmental and social impact

The use of inert gases in systems is expected to have a lower risk of toxic levels of gas, compared to CO₂, as they are considered non-toxic and only sufficient oxygen concentrations must be ensured to avoid accidents.

From an environmental standpoint, the Improved Electrical Stunning system is favourable, as efficiency and availability of electricity is high compared to any gas used for CAS systems.

Regarding alternative gasses, the Argon Retrofit system would be the best choice among gas stunning systems when installed into an existing CO₂ system. Helium is a non-renewable resource, while argon can be re-produced in practically unlimited quantities.

Economic impact

The best alternative for any given slaughterhouse seems to depend on the type of system that is currently in place. This affects the investment costs in particular and may also be related to differences in prices of resources and current scale of production. Additionally, comparisons on running costs between alternatives are not easy to make as information is missing regarding key items, and the missing items differ between alternatives. Despite the lack of these key data, it can be argued that the alternatives with either argon or

helium will increase the costs per pig stunned compared to CO₂. The average cost per pig when implementing the alternatives in the studied conventional CO₂ stunning systems is estimated to be lowest for a CO₂ based Optimised CAS system (backloader), followed by the Improved electrical stunning process, the Argon Retrofit system and finally the Helium stunning system.

Feedback from stakeholders

Feedback from stakeholders indicates that it is unlikely that slaughter companies will voluntarily move away from a well-known and well-tested system regarding reliability, practicability and cost to a less familiar and less tested system. Legislative or consumer driven incentives appear to be a prerequisite for moving away from conventional high concentration CO₂ stunning.

Conclusions and Recommendations

The following conclusions and recommendations aim to provide suggestions for reducing the use of conventional high concentration CO₂ stunning, based on activities in the PigStun project including results from the tested alternatives, literature research and discussions with experts.

For Slaughterhouses

Pre-Stunning handling

1. Reducing pre-stun stress through improved handling will pose a significant improvement to animal welfare and may increase meat quality and worker satisfaction.
2. Irrespective of adopting new stunning methods, the pre-stunning phase should be further optimized by technical and organizational means, including the training of personnel to use low stress methods.
3. Operators should consider switching to one of the tested systems, as they have the potential to increase welfare during pre-stunning handling. Depending on the given alternative, this is either because of prior conditions being changed compared to traditional plants or because of the pigs showing less resistance to entering the gas.

Switching to alternatives to CO₂ at high concentration stunning systems

4. The tested systems pose the opportunity to significantly increase animal welfare for pigs at slaughterhouses, and slaughterhouses should consider the possibility of changing to one of them. This includes considering how to deal with lower throughput rates and increased cost of additional stunning equipment.
5. The suitability of alternatives to CO₂ stunning depends on the conditions at each slaughterhouse. The following aspects should be taken into consideration:
 - a. Operators planning to rebuild their facility or to build a new slaughterhouse, should consider the specific impacts of each system on throughput, meat quality and cost, to identify which slaughterhouse specific measures could be implemented to compensate for drawbacks.
 - b. The Argon Retrofit System is currently considered feasible in the short term for slaughterhouses currently stunning using CO₂ at high throughput, but the specific needs and conditions of each slaughterhouse need to be considered for choosing the alternative stunning system best suited to each slaughterhouse.
 - c. Helium as stunning gas can be a feasible alternative. However, Helium cannot be used in an existing dip lift or paternoster system and requires a completely new installation of stunning equipment.
 - d. For slaughterhouses currently using electrical stunning, the Improved Electrical stunning is considered a feasible solution to improve animal welfare.

- e. Within the solutions envisioned for the Optimised CAS process, the Box system was deemed economically not viable by the manufacturer. One of the two envisioned solutions, the 'Tunnel' is likely only feasible when a new slaughterhouse is built or a complete rebuild of the slaughterhouse is planned. The second, the 'Backloader' or a paternoster system appears to be relatively easy to apply in any current system.
6. To confirm that the animal welfare benefits of the proposed alternatives are maintained when they are scaled up to commercial high throughput rates, their first commercial implementations should be carefully scientifically monitored and the 'before' and 'after' situation compared.
7. For alternative CAS stunning systems, the necessary time that animals need to be exposed to the stunning gas atmosphere depends on the specific atmosphere inside the stunning device. Changes in the gas atmosphere, like increased residual oxygen content or gas mixtures with low concentrations of CO₂, will require longer exposure durations. Sufficiency of the exposure duration needs to be confirmed at each slaughterhouse using animal numbers large enough to ensure conformation of maximum re-stun rates, that can be detected and dealt with swiftly by the staff.
8. Slaughterhouses considering a switch from high concentration CO₂ stunning to any of the tested alternatives should consider the market impact of potential meat quality changes.
9. Willingness to adopt new methods increases when stakeholders gain positive personal experience with the alternatives systems. Operators of first realisations of each system at target throughput rate should allow external slaughterhouse operators to observe the system in practice.
10. The indicators for detecting inadequate stuns and the need to re-stun animals differ between stunning methods. Slaughterhouse staff, animal welfare officers as well as local authorities need to be trained appropriately when the stunning method is changed.

For Policy makers

11. The alternative CAS stunning systems using inert gases are already permitted by regulation, but key parameters like gas concentration and exposure time are often not yet defined. Regulators should prepare for the potential adoption of these methods in practice, by establishing clear regulatory guidelines and welfare standards for these alternative stunning methods.
12. To encourage widespread adoption and improved welfare outcomes, it is recommended to promote research and dissemination of best practices for alternative methods.

For retailers

13. Retailers play a key role in influencing the way meat is produced. To support a move towards higher welfare alternatives, retailers should use their influence when sourcing pork to increase animal welfare at slaughter.
14. To boost public awareness of welfare at slaughter, there should be better communication about welfare at slaughter from retailers to consumers.
15. To incentivise slaughterhouses and help consumers to make informed choices, retailers should consider including aspects of welfare at slaughter into welfare labels.
16. Retailers should consider including financial compensation to slaughterhouses to offset additional costs from methods that increase animal welfare.

System-Specific Recommendations

Argon Retrofit System

17. The Argon Retrofit system has been tested in a low throughput commercial setting (Dip-Lift). It is recommended that Argon Retrofit is tested in a high-throughput system at commercial scale, ideally using a paternoster system.
18. The Argon Retrofit system does not include explicit measures to reduce pre-stunning handling stress, although pigs seem less reluctant to enter the stunner compared to high CO₂. A change to this system should ideally be accompanied by measures to reduce pre-stunning handling stress.

19. The tested Argon Retrofit system established a gas atmosphere with a residual oxygen content well below 1% (<0.8%, mean <0.6%). At a dwell time of 250s no animals had to be re-stunned. It is recommended to use these parameters as a starting point.
20. Argon is extracted from the atmosphere in an energy intensive process. It is therefore recommended from an environmental and economic point of view to strive for a high degree of reuse of the gas.

Helium System

21. The Helium system was tested at a low throughput level. It is recommended that Helium is tested in a high-throughput system at commercial scale.
22. The tests revealed a moderate decrease in pH₄₅ of about 0.2 and increases in blood spots and drip loss. Slaughterhouses wanting to switch to the Helium System should apply known measures to counteract these changes.
23. The Helium System established gas atmosphere with a residual oxygen content below 1% (mean <0.8%). At a dwell time of 200s, the rate of necessary re-stuns was 1%. Slaughterhouses should consider increasing the exposure duration to further reduce necessary re-stuns.

Optimised CAS process

24. The system was tested in the Box System under experimental settings at a very low throughput level. The high throughput visions for the Optimised CAS process differ conceptually from the tested system. To ensure transfer of these results to the envisioned systems, more research is needed before commercial implementation is possible.
25. The tests showed that even under these optimal conditions a distinct benefit of inert gases compared to CO₂ remained. It is recommended that it is implemented with inert gasses to induce unconsciousness.
26. The tests in the Box system showed severe issues regarding meat quality for the Argon but also the Helium condition. It is recommended to identify and resolve the source of these issues.

Improved Electrical Stunning

The Improved electrical stunning alternative incorporates several measures to reduce pre-handling stress, including lowering throughput rates to reduce driving pressure, handling pigs in small groups and giving them a free choice in which single line or raceway they enter.

27. To ensure reduced pre-stunning stress, slaughterhouses adjusting to the Improved Electrical Stunning system should scientifically monitor the changes in animal welfare before and after the transition.
28. A remaining concern regarding electrical stunning is the shorter lasting unconsciousness compared to CO₂ stunning. To address this concern, stun-to-stick intervals should be as short as possible and head-to-heart stunning should be used with parameters that ensure triggering cardiac fibrillation, including sufficient duration of 50-100Hz current through the heart.

4. Study Approach

Data about the four potential alternatives were collected as described in Deliverable D2 and D3 for four different fields of interest, 1) animal welfare, 2) meat quality, 3) Economic, environmental and social impact and 4) Ease of conversion. Obtained data is analysed as described in Appendix B: Analysis Methods by different science groups not directly involved with any of the potential alternatives; IRTA for Animal welfare, DTI for Meat Quality and for ease of conversion and, AU for Economic, environmental and social impacts.

Benchmark values from existing conventional slaughter plants were also obtained, to allow for a qualitative comparison if data for local control conditions could not be collected in the project. Benchmark values were obtained through

- assessment of the available scientific and grey literature (WP2 task T2.1);
- through standardized measurements of meaningful indicators as developed in T2.2. Some of the benchmark indicators are general for all stunning methods but some will be specific for CAS or electrical stunning;
- interviews with the food business operators of the case study companies (WP1);
- discussions within the PigStun consortium, which consists of academic and industry partners (WP1).

Benchmark data were obtained from slaughter plants (labelled A–C in this Results section for animal welfare and 1-2 for meat quality) in different EU Member States. Not all benchmark values were obtained from all Benchmark slaughterhouses (meat quality in 2 and video analyses in 3 slaughterhouses).

For the Argon Retrofit and Helium systems, the control condition was the respective exposure to CO₂ at high concentration (a quantitative analysis), as these were performed in situ controlling for other factors. In the Box system the differences between 3 gas atmospheres using either CO₂, Argon or Helium are analysed under standardised conditions and related to benchmark values or study cases For the Box System, the control conditions were the Benchmark values (a qualitative analysis), as there was no possibility to collect data for a local control condition. The CO₂ condition in the Box System included the same modifications from the Box system, thus making it unable to reflect classical CO₂ stunning procedures. The benchmarks, which represent classical stunning methods, can be used as a reference, but the differences cannot be quantified statistically as several other factors differed across both conditions and the analysis. Similarly, the Improved Electrical Stunning was compared qualitatively to the benchmarks on a subset of the parameters, as PigStun could only investigate the 'after conversion' situation, and no case-control could be set up.

This report evaluates the benefits and challenges of four alternative stunning systems to conventional CO₂ at high concentrations. As such, for some parameters only noteworthy differences or aspects of specific systems are mentioned, and others that are less relevant or cannot be compared may be omitted.

5. Results

Animal Welfare

Introduction

Animal welfare data were collected from each alternative concerning i) the pre-stunning stress ii) the aversiveness during the induction phase of stunning and iii) the effectiveness of the stunning. Results are compared across alternatives and benchmarked with three slaughterhouses equipped with high concentrations of CO₂. Based on these comparative results benefits and challenges of each system are proposed in relation to three aforementioned categories.

- 1) Pre-stunning stress: Assessment of the animal reactions during initial handling and loading in the system.
- 2) Aversiveness during induction: Assessment of the animal reactions during the inhalation of the gases and before the loss of posture.
- 3) Effectiveness of stunning: Measures the time to unconsciousness and other effectiveness markers

Details on the methods for video analysis can be found in the section Appendix B: Analysis Methods.

Parameter Analysis

Pre-Stunning Stress

Minimizing handling stress during the entry into the stunning system is critical. The indicators assessed in this parameter are:

Entering Overview

The exposure to CO₂ in the Box system for the Optimised CAS process reduced pre-stunning stress as it improved entering scores, both in ordinal scores (Figure 1) and mean scores (95% confidence interval (CI95) from 0 to 0.17, Figure 2), when compared to CO₂ benchmarks (CI95 from 0.8 to 1.1). Pigs often laid down during the 45 minutes before gas exposure, minimizing stress when exposed to the gas. This calmness was attributed to the slow operational pace (three pigs per hour), the gentle handling by researchers or technicians, and the 45-minute waiting time after entering the box.

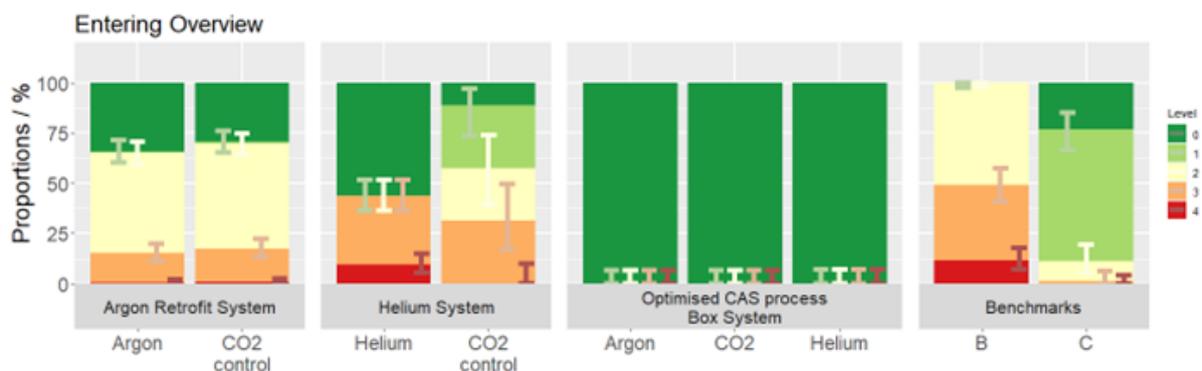


Figure 1. Proportions of Entering Overview scores in the alternative CAS systems and Benchmarks. Levels range from 0 to 4, and colours vary from dark green to red respectively. The borders on the colours represent the mean proportions, and the error bars represent the 95% confidence intervals. The levels were scored as 0 = none, 1 = reluctance to move, 2 = aversive physical contact, 3 = painful physical contact, 4 = lasting painful physical contact. A

detailed description of these scores is provided in the ethogram in the appendix. B and C represent two Benchmark slaughterhouses. The labelling (means and CI95) applies to all figures.

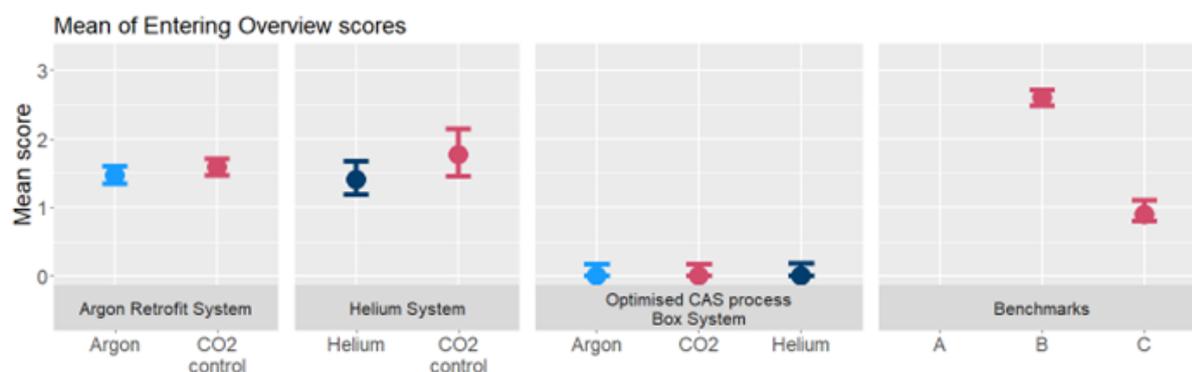


Figure 2. Mean Entering Overview scores, including their 95% confidence intervals in the alternative CAS systems and Benchmarks.

Reluctance to move and Aversive Physical Contact

The reluctance of pigs to move at the crate entrance and descend into the pit was significantly reduced in the Argon Retrofit system (Figure 3), likely due to the absence of the aversive perception of increasing CO₂ concentrations, as handling procedures were consistent across treatments. Similarly, no pigs exposed to Helium in the Helium system exhibited hesitation (Figure 3) or aversive physical contact (Figure 4) at the crate entrance or during entry into the controlled atmosphere.

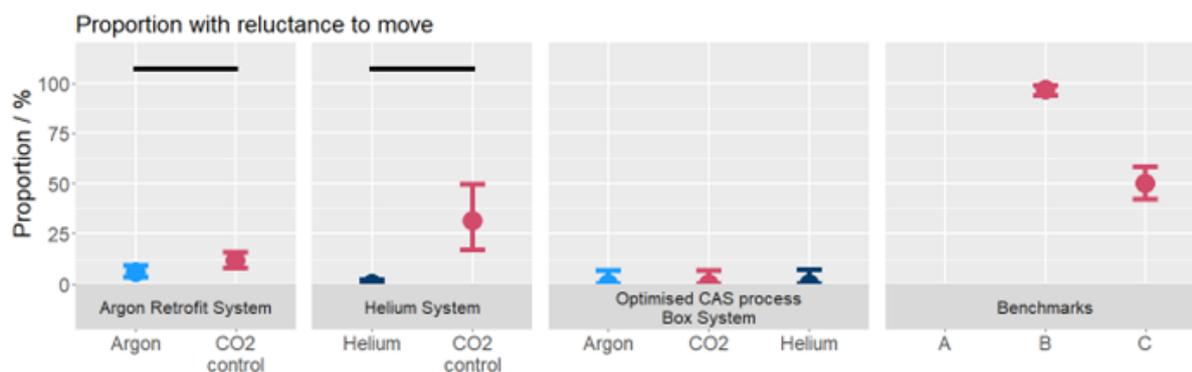


Figure 3. Proportion in % of animals that presented reluctance to move in the alternative CAS systems and Benchmarks. All proportion figures include means and 95% confidence intervals.

This reduced reluctance in the Helium system compared to the local CO₂ control condition may stem from either a less stressful perception of the gas or reduced stress during entry, as the stunners for CO₂ and Helium differ in design, including animals being moved into the stunner by a robotic arm in the Helium system.

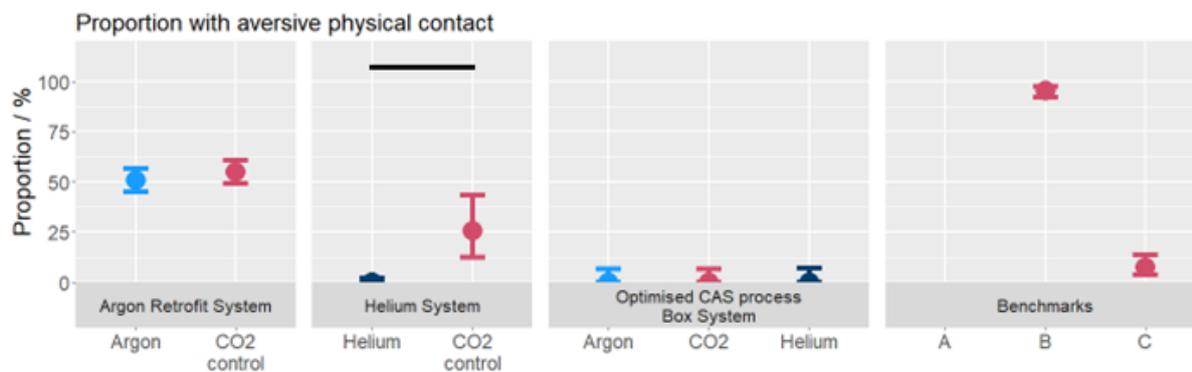


Figure 4. Proportion (%) of animals that presented aversive physical contact in the alternative CAS systems and Benchmarks.

Assessing Behavioural Indicators of Fear, Pain, and Handling Efficiency in Pigs Under Improved Electrical Stunning Conditions

For the Improved Electrical stunning, reluctance to move in the raceway (Table - A 84) was observed in 57 out of 180 pigs (31.7%) , with a 95% confidence interval (CI95) of 24.9% to 39%. This reluctance, characterized by pigs stopping or refusing to move when coerced along the narrow pathway leading to the stunning area, can cause delays and stress during the slaughter process. High proportion of pigs showing reluctance to move often indicate fear, pain, or ineffective raceway design and management, while calm, efficient movement reduces stress and ensures smoother operations. Compared to the higher percentage of animals showing reluctance to move in the CO₂ benchmark (95% confidence interval of 42% to 58%, Table - A 100 and Figure 3), electrical stunning showed a substantial decrease in reluctance to move. Note that the Improved Electrical stunning is not included in these figures regarding animal welfare parameters, as the direct comparison between these measures is not possible.

Reluctance to enter the stunner (Table - A 85) —observed in 62.8% of pigs (113 out of 180), with a 95% confidence interval of 55.3% to 69.9%—occurs when pigs hesitate or resist approaching the stunning device. This behaviour may result from stressors such as loud noises, poor handling, or unfamiliar environments. High levels of reluctance to enter the stunner impact both animal welfare and operational efficiency, underscoring the need for improved handling practices and facility design. When compared to the percentage of pigs showing reluctance to move for the CO₂ benchmarks, the Improved Electrical stunning showed no significant difference in reluctance to enter (62.8%) relative to benchmark means (50% to 96.5%, Table - A 100 and Figure 3).

The use of brushes (Table - A 86) to motivate the pig to walk in the raceway in the Improved Electrical Stunning was recorded in 93.9% of cases (169 out of 180) with a 95% confidence interval of 89.3% to 96.9%. Brushes, used to guide or calm pigs, are a humane handling tool that induces less pain and fear than electric prods. Proper brush use reflects good handling practices when applied gently and effectively. However, excessive reliance on brushes could indicate either a high reluctance to move or handlers' overdependence on external tools to maintain flow. When compared to Aversive Physical Contact (APC) score for the CO₂ benchmarks, the brush use proportion (93.5%) fell within the benchmark range (3.49% to 97.55%, Table - A 101 and Figure 4), though the broad interval of the benchmark limits the conclusiveness of the comparison.

(Lasting) Painful Physical Contact and Use of Electric Prods in Stunning Systems

For the Improved Electrical stunning, low voltage electric prods (Table - A 87) were used on 18.3% of the pigs (33 out of 180), with a confidence interval of 13% to 24.8%. These devices deliver a mild shock to encourage movement when pigs are reluctant, representing a more forceful intervention compared to other handling methods. While legal in many contexts, electric prod use is controversial due to animal welfare

concerns. Frequent reliance on prods may indicate poor handling practices, ineffective raceway design, or stress-inducing conditions. Best practices aim to minimize their use.

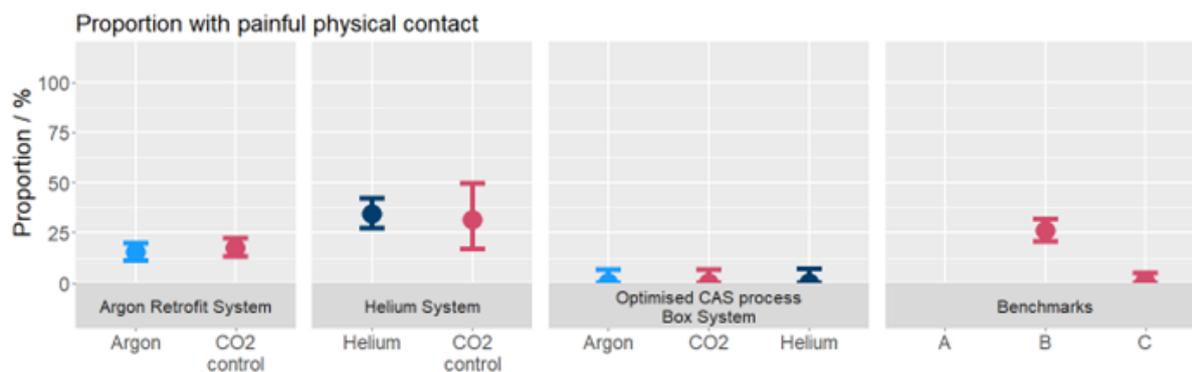


Figure 5. Proportion (%) of animals that presented painful physical contact in the alternative CAS systems and Benchmarks.

Comparison of the magnitude of aversion between the electric prod use and the handling during the entrance to CAS stunners is difficult. Within the categories of the ethogram used for video analysis for entering the CAS systems, it can be compared to either Painful Physical Contact (PPC) or Lasting Physical Contact (LPC). When compared to CO₂ benchmarks, Improved Electrical stunning showed no difference for Painful Physical Contact (benchmark CI: 0.02% to 31.84%, Table - A 102 and Figure 5). However, for Lasting Painful Contact (benchmark CI: 0% to 10.46%, Table - A 103 and Figure 6), the 18% prod use for Improved electrical stunning suggests an increase in physical distress, highlighting potential welfare concerns associated with prod use.

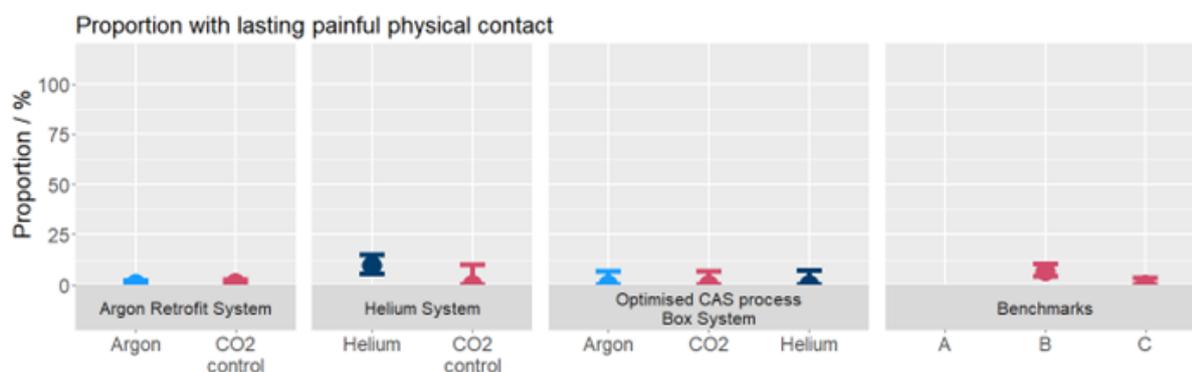


Figure 6. Proportion (%) of animals that presented lasting painful physical contact in the alternative CAS systems and Benchmarks.

Aversiveness during induction

A critical welfare concern is the extent of animal stress and pain during gas exposure or electrical application:

Initial Reaction Overview

Non-reactivity during exposure was significantly higher in both the Argon Retrofit system and the Box system for the Optimised CAS process when compared to CO₂. In the Argon Retrofit System, 51% of pigs showed no reaction during descent/exposure to Argon (Ar), compared to only 11% under CO₂ conditions (Figure 7 and Figure 8). Similarly, in the Box system, non-reactivity was observed in 48% of pigs exposed to Ar and 54% to Helium (He), compared to just 4% in CO₂ (Figure 7 and Figure 8). Additionally, the CO₂ Box system potentially improved mean initial reaction scores relative to CO₂ benchmarks, with a confidence interval (CI) from 1.26 to 1.7, compared to the best CO₂ benchmark, with a CI from 1.78 to 2.09 (Figure 8).

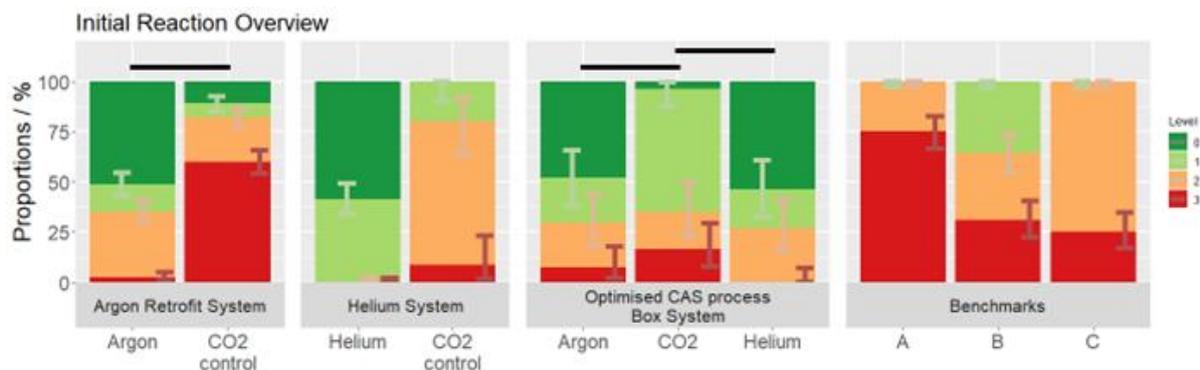


Figure 7. Proportion (%) of the Initial Reaction Overview scores in the alternative CAS systems and Benchmarks. The scores range from 0 (dark green) to 3 (red). 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation.



Figure 8. Means of the Initial Reaction Overview scores in the alternative CAS systems and Benchmarks. 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation.

Response to Atmosphere

In both the Argon Retrofit System and the Helium system the duration between the first response to the gas and the onset of unconsciousness (loss of posture) was not significantly different between the Ar and He and their corresponding CO₂ controls. However, in the Box system, the duration between the first response to the gas and the onset of unconsciousness (loss of posture) was the longest when pigs were exposed to He (CI95: 42.47, 56.47), followed by Ar (CI95: 20.01, 28.49), with CO₂ (CI95: 16.35, 19.85) showing the shortest duration (Figure 9). When compared to all other CO₂ exposures (Argon Retrofit [CI95: 12.13, 14.51], Helium system [CI95: 0.75, 6.14], and benchmarks [CI95: 8.9, 11.57]), the pigs exposed to CO₂ in the Box system showed a longer time between the first response and the loss of posture (CI95: 16.35, 19.85). These differences are influenced by the operational characteristics of each system and the concentration levels of the gases used. Note that a lower negative time of first response to atmosphere relative to loss of posture indicates a longer duration between the first response and loss of posture.

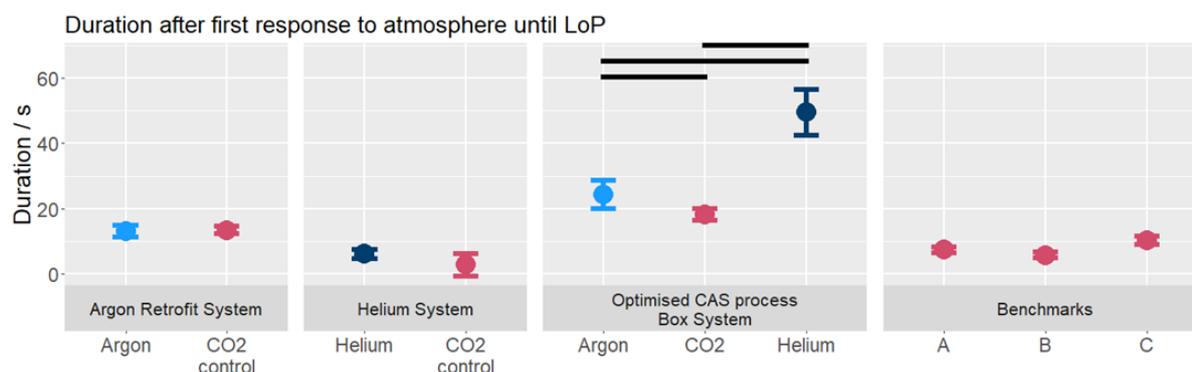


Figure 9. Duration (s) after first response to atmosphere until Loss of Posture in the alternative CAS systems and Benchmarks. In the benchmark results, the first animals showing a behaviour of that gondola is assessed, instead of for each individual animal, which shifts the data compared to the systems, limiting direct comparability.

In the Helium system exposure to He showed significantly higher response rates (Figure 10) to the atmosphere than the local CO₂ group in the same experiment. Meanwhile, in the Box system, both alternative gases (Ar and He) showed a significant decrease in this response compared to CO₂ in the box system.

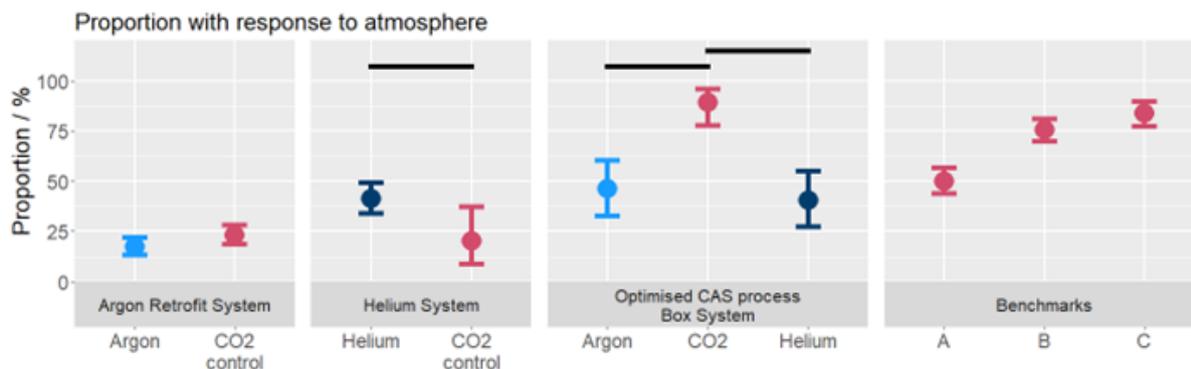


Figure 10. Proportion (%) of animals that presented a response to the atmosphere in the alternative CAS systems and Benchmarks.

Agitation and Strong Agitation

In the Box system, the time between the first sign of agitation and the onset of unconsciousness (measured as loss of posture, LoP) was significantly shorter in both Argon (Ar) and Helium (He) conditions compared to CO₂-Box (Figure 11). However, the duration from the first response to the gas to the onset of unconsciousness was longer in CO₂-Box (CI95: 9.87, 15.21) than in Benchmark conditions (CI95: 3.61, 6.04). Note that a lower negative time of first (strong) agitation relative to loss of posture indicates a longer duration between the first (strong) agitation and loss of posture.

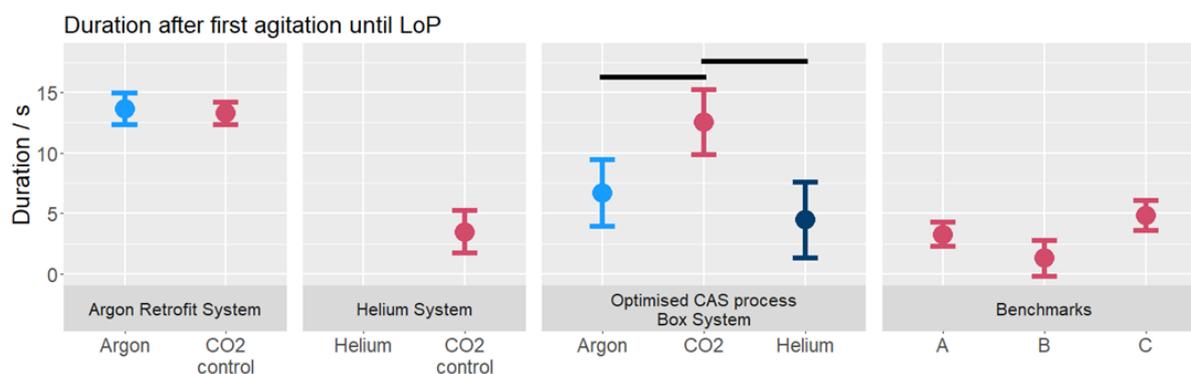


Figure 11. Duration (s) after first agitation until Loss of Posture (LoP) in the alternative CAS systems and Benchmarks. In the benchmark results, the first animals showing a behaviour of that gondola is assessed, instead of for each individual animal, which shifts the data compared to the systems, limiting direct comparability.

The proportion of pigs displaying agitation (Figure 12) and strong agitation (Figure 13) were significantly lower in the Argon Retrofit and Helium Systems.

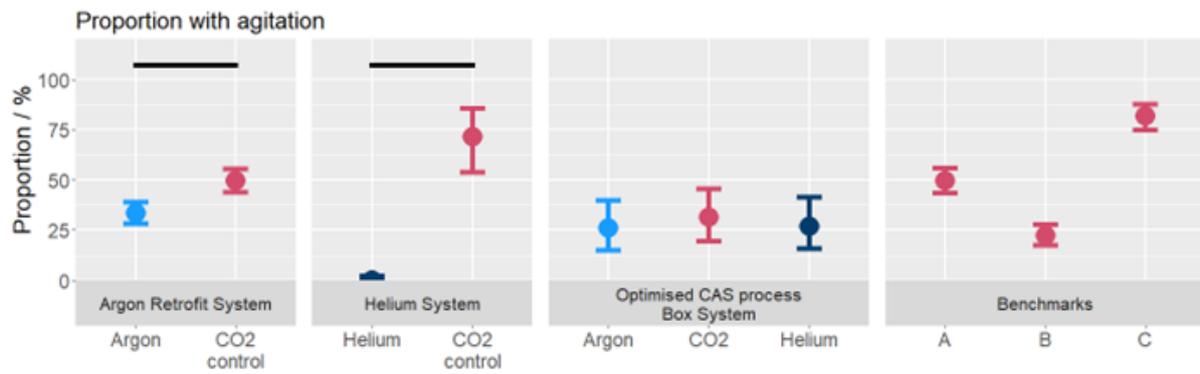


Figure 12. Proportion (%) of animals that presented agitation in the alternative CAS systems and Benchmarks.

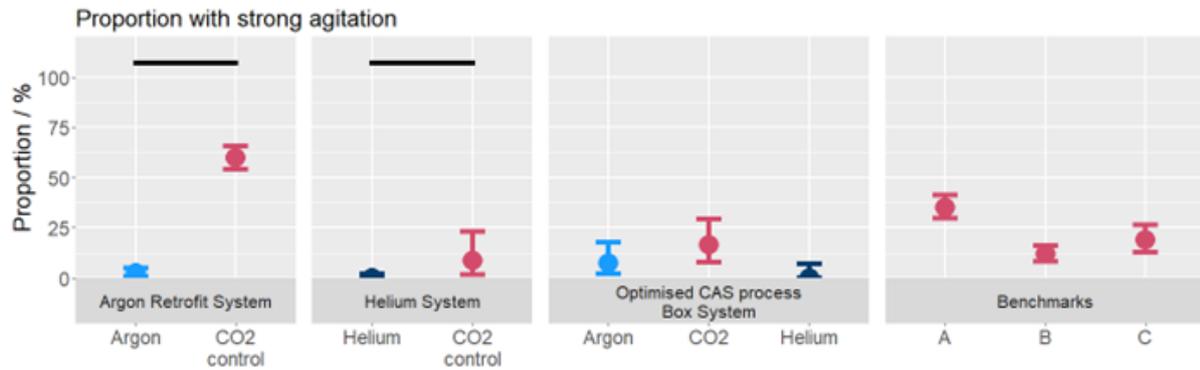


Figure 13. Proportion (%) of animals that presented strong agitation in the alternative CAS systems and Benchmarks.

The elapsed time between strong agitation and the onset of loss of consciousness (assessed by the Loss of Posture or LoP) was reduced in the Argon Retrofit system (Figure 14).

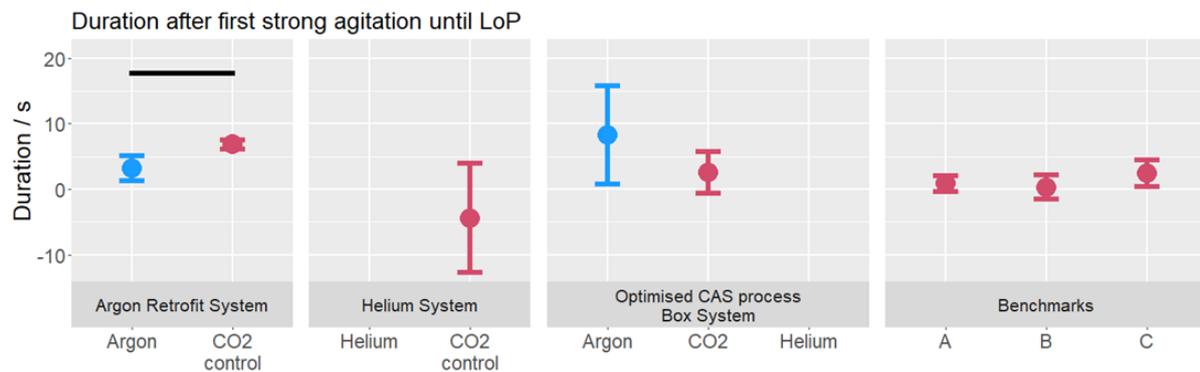


Figure 14. Duration (s) after the first strong agitation and Loss of Posture (LoP) in the alternative CAS systems and Benchmarks. For the He conditions in both the Helium System and the Box System for the Optimised CAS process, no strong agitation was observed; subsequently no time of first strong agitation can be shown. In the benchmark studies, the first animals showing a behaviour of that gondola was assessed, instead of for each individual animal, which shifts down the data compared to the systems, limiting direct comparability.

Abnormal Breathing

In the Argon Retrofit system, no pigs exhibited abnormal breathing before loss of posture, unlike the local CO₂ control condition, where hyperventilation occurred in 59% of cases (Figure 15), indicating that Ar does not cause respiratory distress. In the Box System, both Ar (15%) and He (33%) significantly reduced the proportion of pigs showing respiratory distress (abnormal breathing) during the induction phase compared to CO₂ (72%).

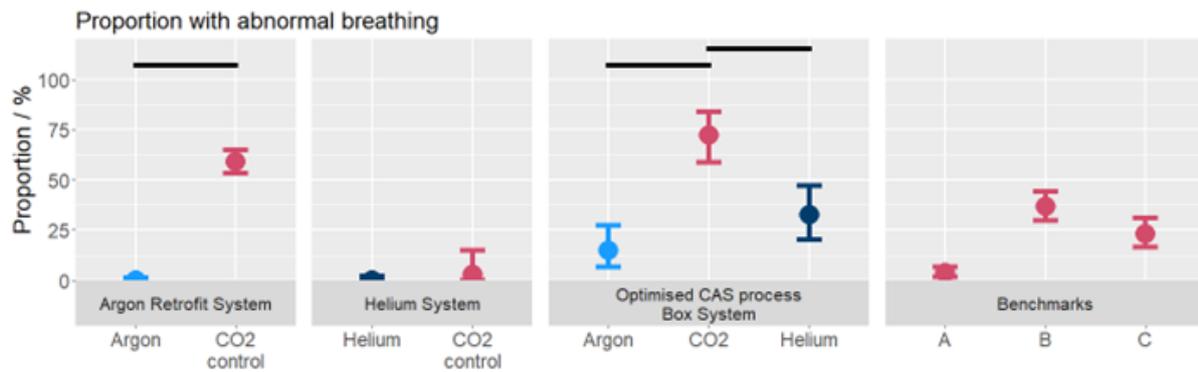


Figure 15. Proportion (%) of animals that presented abnormal breathing in the alternative CAS systems and Benchmarks.

However, unlike in the Argon Retrofit system, respiratory distress did not entirely disappear for neither Ar nor He. This may be attributed to higher residual oxygen levels or challenges in determining the onset of loss of posture, especially when animals are lying down. It is important to note that abnormal breathing after loss of posture is not indicative of welfare concern, as animals are progressing to deep unconsciousness by that time. CO₂ in the Box System also showed a potential increase in abnormal breathing (CI95: 58.36, 83.54) compared to benchmarks (CI95: 29.81, 44.02).

In the Box system, the time from the first signs of abnormal breathing to loss of posture was significantly longer for Helium compared to Argon and CO₂, with Argon also showing a longer duration than CO₂ (Figure 16).

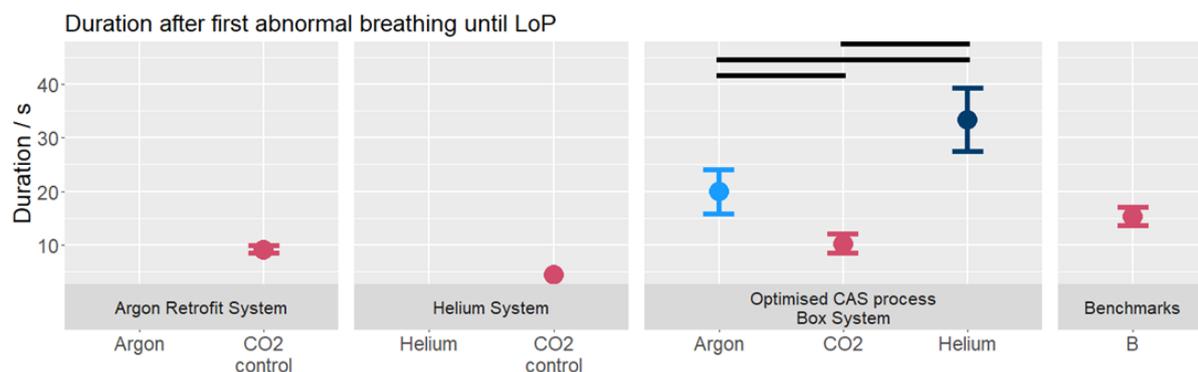


Figure 16. Duration (s) after first abnormal breathing and Loss of Posture (LoP) in the alternative CAS systems and Benchmarks. In the benchmark results, the first animals showing a behaviour of that gondola is assessed, instead of for each individual animal, which shifts the data compared to the systems, limiting direct comparability.

Effectiveness of Stunning

Loss of Posture

The time to loss of posture was longer with He compared to CO₂, reflecting a slower onset of unconsciousness (Figure 17). In the Box System, He required more time to induce loss of posture than both Ar and CO₂, with Ar also taking longer than CO₂. This increase also occurs in CO₂-Box (CI95: 38.54, 41.88) even when compared to the last animals showing LoP in benchmarks (CI95: 28.66, 32.11). These findings highlight a trade-off between welfare benefits and operational efficiency, as extended times may impact throughput. No difference in time to loss of posture was found in the Argon Retrofit system, both compared to the local CO₂ control and the benchmarks.

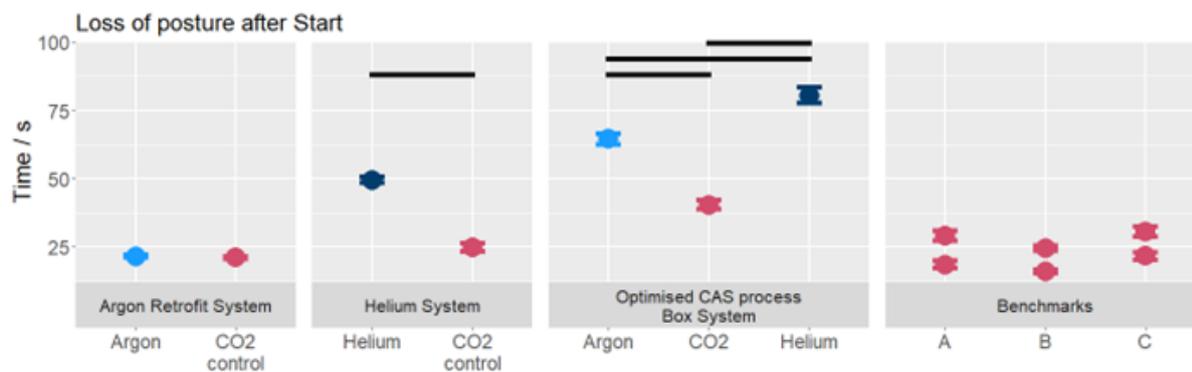


Figure 17. Duration (s) between Start and Loss of Posture (LoP) in the alternative CAS systems and the Benchmarks. In the benchmark results, the time at which the first and last animals showed loss of posture was measured, thus the double annotation for each benchmark.

Lying

In the Argon Retrofit system, the time to lie still after loss of posture was significantly longer with Ar compared to CO₂, indicating a slower progression to deep unconsciousness (Figure 18). Similarly, in the Box System, He required more time to induce lying than both Ar and CO₂, with Ar also taking longer than CO₂.

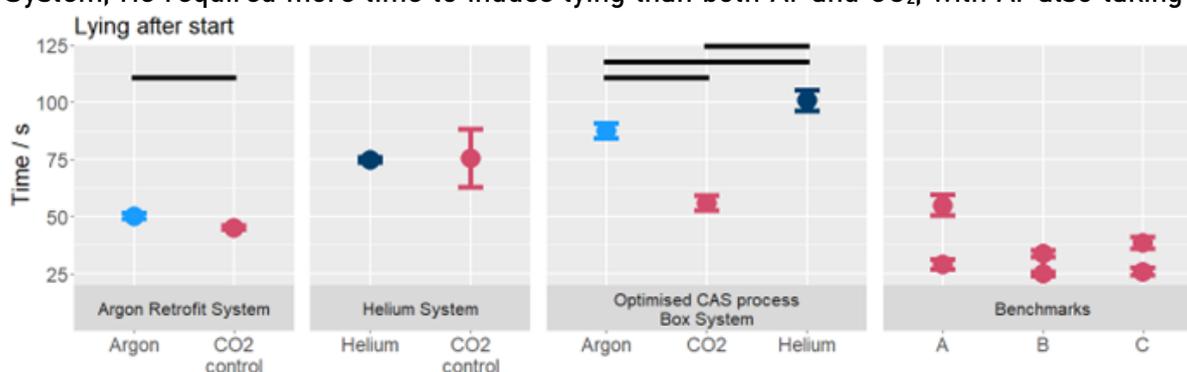


Figure 18. Duration (s) between Start and Lying in the alternative CAS systems and Benchmarks. In the benchmark results, the time at which the first and last animals showed lying was measured, thus the double annotation for each benchmark.

These results underscore a trade-off between welfare benefits and operational efficiency, as prolonged times may affect throughput. While He in the Helium system also required more time to induce the onset of unconsciousness (Start to Loss of Posture, Figure 17), no significant differences were observed in the duration from start to lying (Figure 18). This may be attributed to a shorter duration between Loss of Posture and Lying (Figure 19). Meanwhile, exposure to Ar, in the Argon Retrofit as well as in the Box system, implied a significantly longer time between loss of posture and lying (Figure 19).

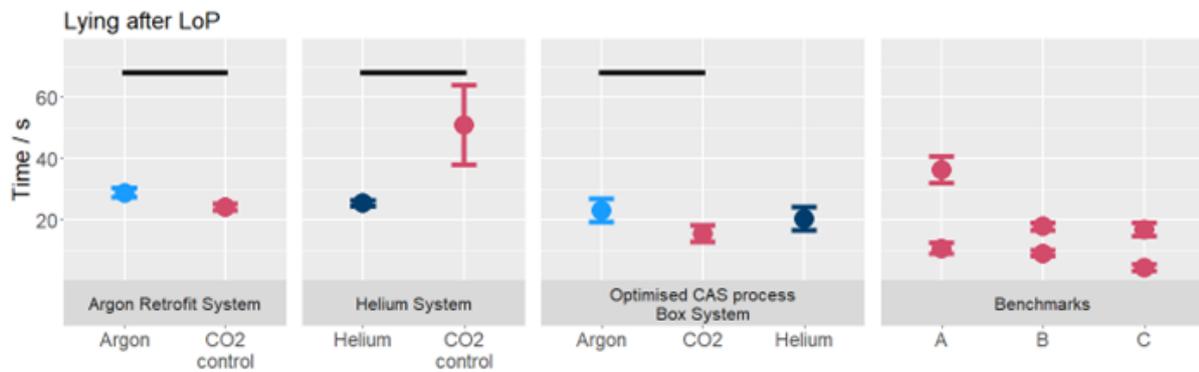


Figure 19. Duration (s) between LoP and Lying in the alternative CAS systems and the Benchmarks. In the benchmark results, the time at which the first and last animals showed loss of posture was measured, thus the double annotation for each benchmark.

Last Movement

Both Ar and He exhibited significantly longer durations to the last movement compared to CO₂ across the Argon Retrofit, Helium, and Box systems (Figure 20), with Ar taking longer than He in the Box System. Interestingly, even CO₂ in the Box System appeared to have a longer duration (CI95: 175.34, 198.3) than its benchmark counterparts (CI95: 155.7, 169.9, but note that group analysis for benchmarks shifts data to earlier times) and even the inert gases (Ar and He) in Argon Retrofit and Helium System, respectively.

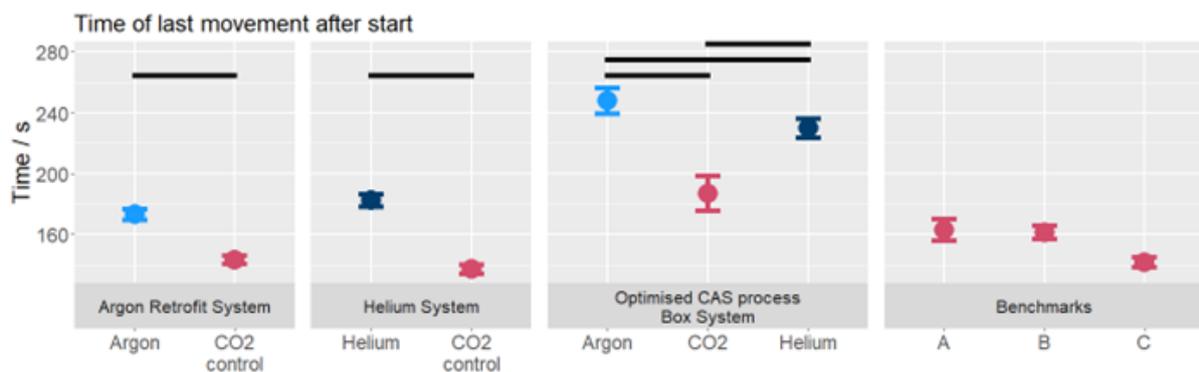


Figure 20. Duration (s) between Start and Last Movement in the alternative CAS systems and Benchmarks. In the benchmark results, the first animals showing a behavior of that gondola is assessed, instead of for each individual animal, which shifts the data compared to the systems, limiting direct comparability.

Similar patterns were observed for the duration from loss of posture to last movement (Figure 21), except for the Box System, where the last movement for He does not occur later than for CO₂, and the last movement for CO₂ itself is in a similar range to the CO₂ benchmarks.

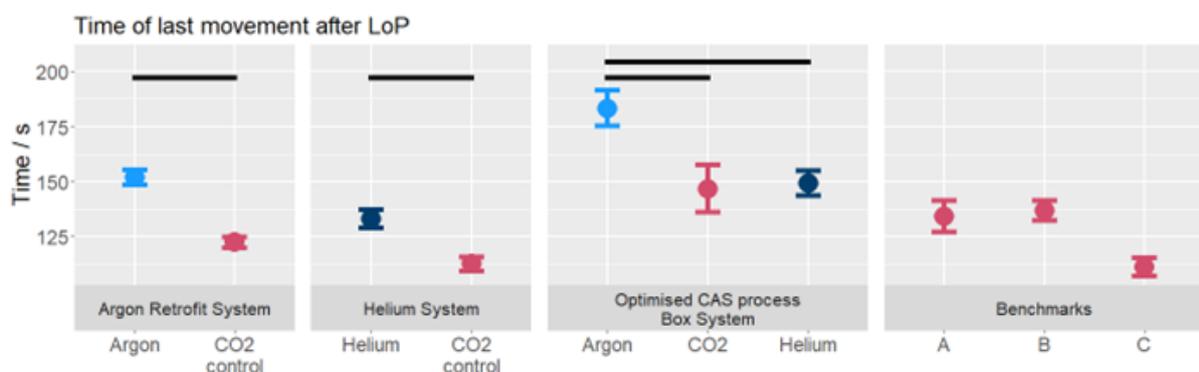


Figure 21. Duration (s) between LoP and Last Movement in the alternative CAS systems and Benchmarks. In the benchmark results, the first animals showing a behaviour of that gondola is assessed, instead of for each individual animal, which shifts the data compared to the systems, limiting direct comparability.

Cycle duration

In the Argon Retrofit and Helium System both Ar and He required a significantly longer cycle duration to their respective CO₂ counterparts (Figure 22), which were in line with the cycle durations of the benchmark values.

The cycle durations in the box system were set at much longer period to prevent recovery during the long stun to stick interval during experiments. Therefore, cycle durations can't be compared for the box experiment.

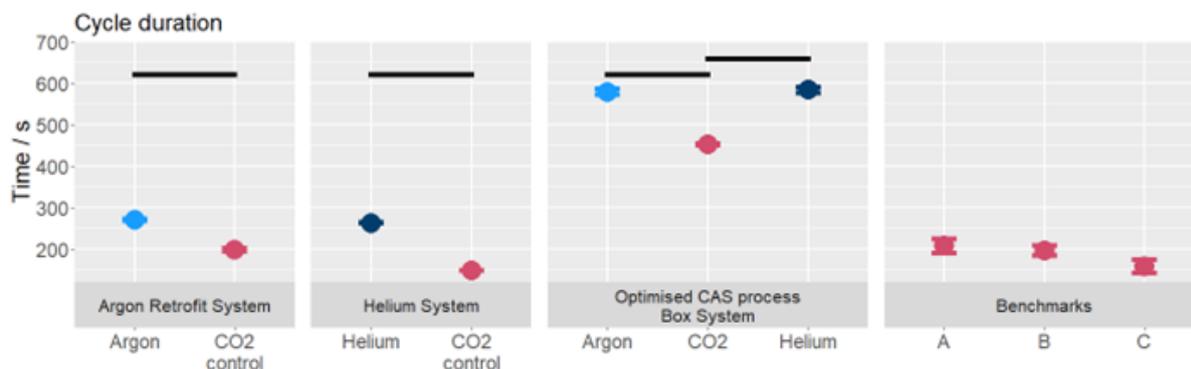


Figure 22. Duration (s) of the whole cycle in the alternative CAS systems and Benchmarks.

Stunning Effectiveness

Stunning effectiveness has been a concern regarding exposure to inert gases and for electrical stunning. When animals show signs of ineffective stunning or recovery after stunning, such as presence of breathing or corneal and palpebral reflexes, animals must be re-stunned to ensure unconsciousness until death. Rates of re-stunning animals of more than 5% have been previously reported (Llonch et al. 2012; Atkinson et al. 2020) for inert gas mixtures with low concentrations of CO₂. The re-stun rates in the systems assessed here (Figure 23) were all below those levels and in the rate of those found in the CO₂ benchmarks. To be able to statistically differentiate re-stun rates at rates below 2%, larger animal numbers are needed.

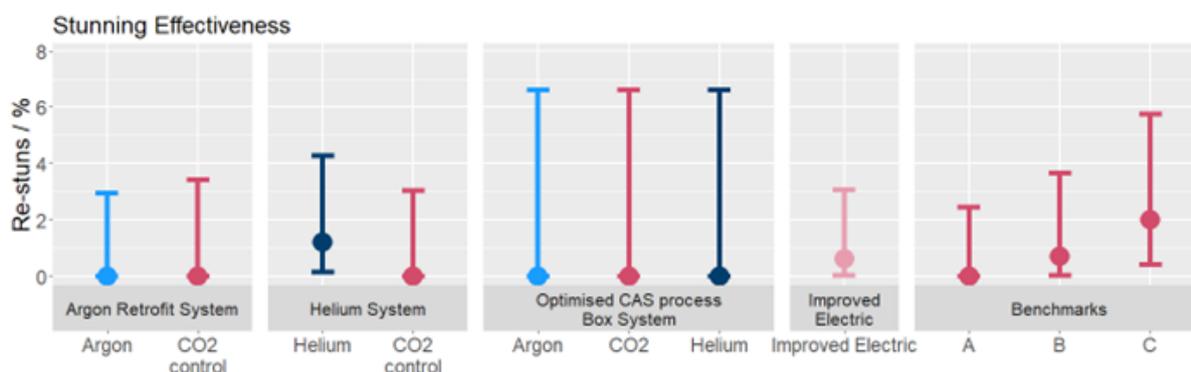


Figure 23. Re-stun rate (%) as the metric of the stunning effectiveness in the alternative CAS systems and Benchmarks.

Summary

The report comprehensively evaluates four alternative stunning systems: the Argon Retrofit system, the Helium system, the Box system for the Optimized (CAS) process, and Improved Electrical Stunning. Each

system was assessed based on key welfare parameters, including pre-stunning stress, aversion during the induction phase, and the effectiveness of stunning. Comparative analysis revealed distinct strengths and challenges associated with each method, highlighting a trade-off between aversion reduction, efficiency, and operational constraints. A detailed overview of (unique) benefits and challenges can be found in the appendix.

- **Argon Retrofit System:** The system significantly reduced aversion during the induction phase compared to CO₂, with fewer pigs showing agitation or respiratory distress. However, it was also associated with limited improvements in handling.
- **Helium:** Helium stunning eliminated strong reactions and respiratory distress. It showed promise for non-reactivity indicators, suggesting superior welfare outcomes during induction compared to CO₂.
- **Box System for the Optimised CAS Process:** This approach balanced pre-stunning calmness with reduced aversion but was hindered by longer durations between first response and unconsciousness. Additionally, respiratory distress persisted to some degree even during the exposure to inert gases, especially with Argon.
- **Improved Electrical Stunning:** This approach is highly effective in ensuring immediate unconsciousness and preventing respiratory distress. Brushes had to be used on almost all animals to drive them to the stunner and electric prods were used on 18% of the animals to enter the stunner.

Conclusions

Reducing aversion during stunning is critical for improving animal welfare. The inert gases (Argon and Helium) consistently demonstrated lower agitation levels and respiratory distress compared to CO₂. These findings underscore the potential of gas alternatives to improve welfare parameters during induction.

For electrical stunning, careful handling and proper equipment design (e.g., minimizing the use of electric prods and improving raceway layouts) potentially mitigates pre-stunning stress. Stunning reliability is a paramount concern, as failures can lead to significant animal suffering. Electrical stunning systems show high effectiveness in inducing immediate unconsciousness but require sufficient training and rigorous adherence to operational protocols to ensure proper electrode placement. Current parameters that induce immediate unconsciousness and cardiac fibrillation are needed to avoid insufficient stunning effectiveness or early recovery.

Comparative evaluations reveal that each system offers unique advantages and challenges. Argon and Helium gases reduce aversion during induction to unconsciousness, while Improved Electrical Stunning ensures immediate unconsciousness and the lower throughput rate per stunner will likely improve pre-stunning stress, but still demands precise handling and monitoring. Although the low-voltage stimulator used in the Improved Electrical Stunning System is less painful compared to the traditional electric prod, its use is highly undesirable from an animal welfare perspective.

Meat Quality

Introduction

Benchmark Data

To contextualize the obtained data on meat quality in terms of its level and variation, five Benchmark data sources of recent date are included. These consist of two Benchmark sites where data were collected as part of the PigStun project (Benchmarks 1 & 2), and three studies recently published from Poland (Rybarczyk et al. 2015), Denmark (Aaslyng & Hviid 2020), and Greece (Mantis et al. 2019). The benchmark sources do not

contain all the same parameters measured at the four PigStun systems and are therefore not present in some of the charts.

Process Variation Across Systems

Given that the data on meat quality in the four systems were collected at four different slaughterhouses, it cannot be assumed that the processing (e.g. stun-stick interval, scalding, cooling process...) are identical, which is a requirement for a direct comparison of the results as they all have distinct effects on meat quality. To illustrate this, information on key process parameters for each abattoir were collected.

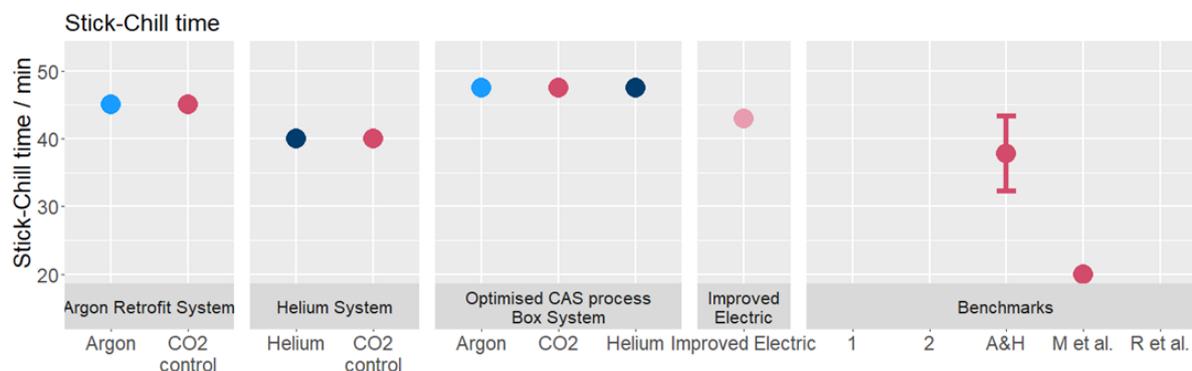


Figure 24. Time in minutes from kill to the start of chilling. Error bar indicates standard deviation.

Only minor differences in the time from sticking to the start of chilling (Figure 24) were observed, and these differences are not expected to significantly influence the measured meat quality parameters.

The scalding and dehairing processes add heat to the carcasses and can thus increase carcass temperature, thereby accelerating the pH drop and the associated denaturation of myofibrillar proteins. This may result in higher drip loss, paler meat, and, if extreme, development of pale, soft, and exudative (PSE) meat. Large differences were observed between the systems (Figure 25).

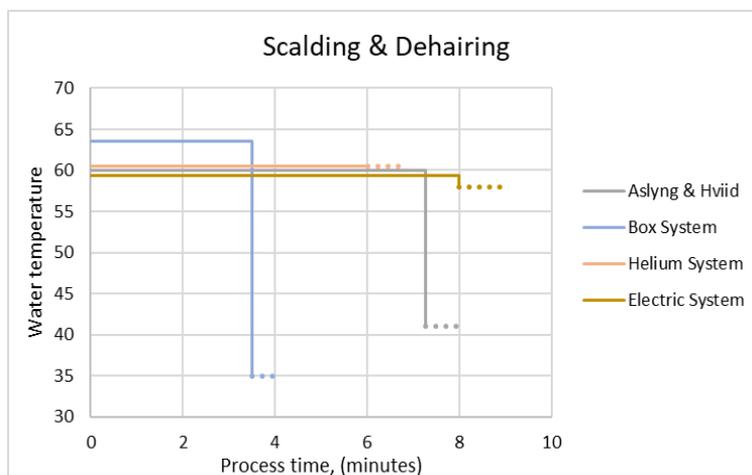


Figure 25. Time and temperature for scalding and dehairing process. Solid lines: scalding; Dotted lines: dehairing.

The Box system for the Optimised CAS process had the shortest time of 3.5 minutes scalding at 63.5 °C followed by dehairing for 0.5 minutes at 35 °C. The Improved Electrical stunning system took more than twice as long, with a scalding time of 8 minutes at 59.6 °C, followed by dehairing for 1 minute at 58 °C. The Helium system had a total time of 6.7 minutes at a constant temperature of 60.2 °C. The Argon Retrofit system used 60 °C, but no time has been reported.

Based on the obtained information on the chilling processes used at each system and the T24 measured in the loins, chilling profiles for the core of the loin muscle were estimated for each system (Figure 26).

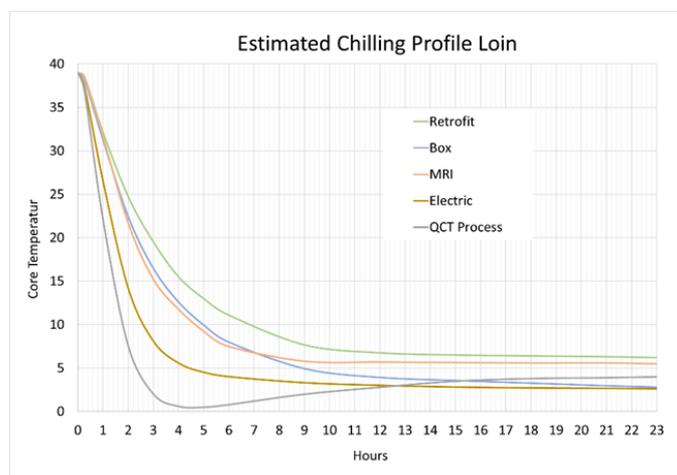


Figure 26. Estimated chilling profiles for the core of the loin.

The postmortem glycolytic processes are greatly reduced below 15 °C (Bendall 1973), and the time to reach 15 °C is therefore one way to compare the effects of different chilling rates on pH drop after slaughter and thereby the effect on meat quality. The Improved Electrical stunning system, being the fastest, reached 15 °C after approximately 1.9 hours, while the slowest, Argon Retrofit, reached 15 °C after 4.2 hours, with the Box system and Helium system in between. Thus, the most efficient chilling (Electric) is more than twice as fast as the slowest system (Argon Retrofit). Many high-throughput slaughterhouses use a highly efficient Quick Chill Tunnel (QCT) process, and a typical temperature profile for such a process has been included for comparison. The time to reach 15 °C for the QCT process is 1.4 hours.

The weight of the carcass can influence meat quality via its effect on the chilling rate: bigger carcasses have a larger volume to chill, and therefore the temperature drops at a slower rate, influencing the rate of the pH drop during the chilling process. The within-system difference in weight for the Helium system must be noted (Figure 27). The pigs used for the CO₂ trials had an average weight of 93 kg, while the pigs used for the Helium trials weighed 108 kg, meaning that 16% more carcass volume had to be chilled for the Helium trials, which can influence the chilling rate and the derived meat quality parameters.

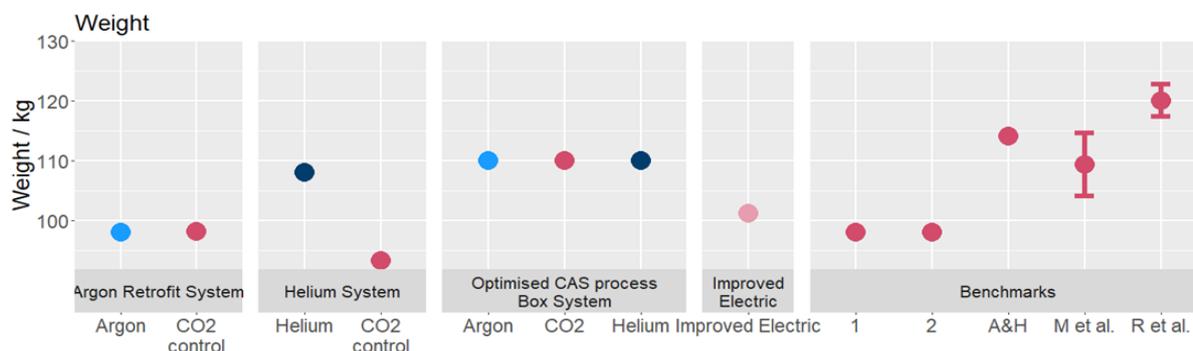


Figure 27. Weight of the live pigs. Error bars indicate standard deviation.

The above check on the process variations shows that the live weight, scalding and dehairing processes, and the chilling process vary significantly among the situations in the four system studies of the project. This means that no direct, statistical comparisons of meat quality levels *across systems* can be made, and these results must be treated with care.

Of course, the meat quality assessments *within systems* can be analysed statistically.

Meat Quality Across Systems

Blood Spots in Hams

In Figure 28 and Figure 29, the distribution and mean score of the obtained data on blood spots are presented. No difference between CO₂ and Argon (Ar) is observed in the Argon Retrofit system; however, for the Helium system, a clear negative effect of Helium (He) on blood spots is evident compared to the CO₂ control. For the Box system, both He and Ar have negative effects on blood spot formation compared to the Box CO₂, with Ar being the most severe.

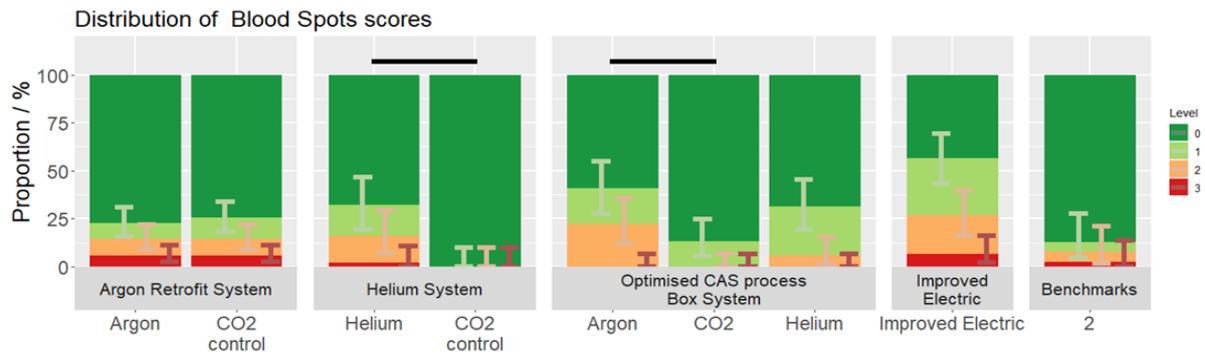


Figure 28. Distribution of blood spots. Blood spots were scored as 0 = no blood spots, 1 = <5 blood spots, 2 = <30 blood spots, 3 = >30 blood spots.

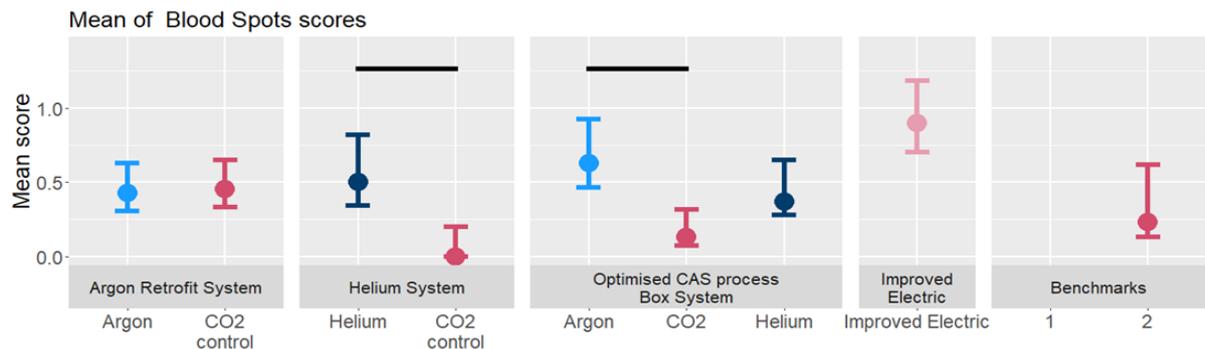


Figure 29. Mean value for blood spots. Error bars indicate 95% confidence interval. Blood spots were scored as 0 = no blood spots, 1 = <5 blood spots, 2 = <30 blood spots, 3 = >30 blood spots.

Comparing across systems and including the benchmark, the Electrical system appears to have the most severe effect on the development of blood spots, with only 43% of the assessed meat cuts having no blood spots (Figure 28). Comparing the control conditions with CO₂ for the three systems using gases indicates that the conditions at the slaughterhouse and the stunner used for the Argon Retrofit trials in itself has a more severe effect on blood spot formation than the two other systems, since both the Helium system CO₂ control and Box CO₂ have lower mean values for blood spots compared to CO₂ control used at the Argon Retrofit trials.

Temperature and pH in Hot Carcasses

Determining the pH 45 (pH₄₅) minutes after sticking is a traditional method for measuring the rate of pH drop, which is the single most important factor in the development of drip loss, pale/light meat colour, and PSE. Except for Ar and He in the Box system, the systems resulted in pH₄₅ levels that are also found in the benchmark studies (Figure 30).

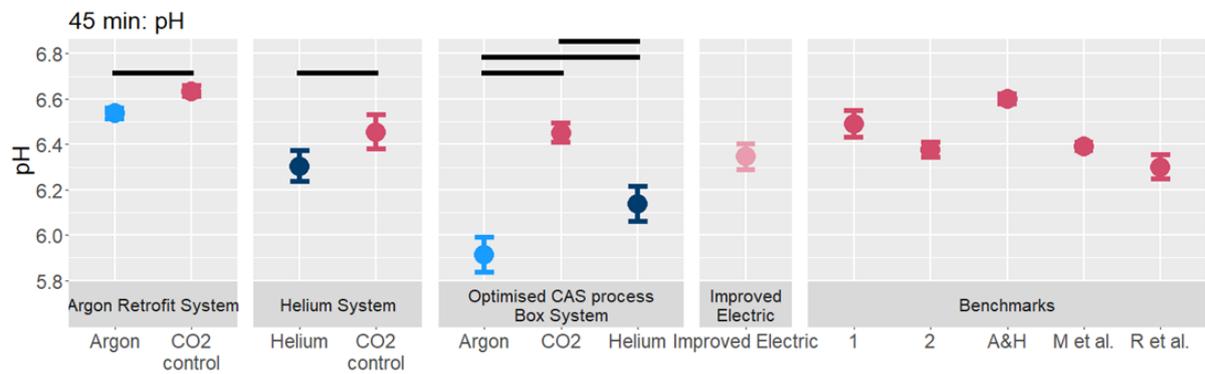


Figure 30. pH in loin measured 45 minutes after kill. Error bars indicate 95% confidence interval.

For the Box system, both He and Ar resulted in a much lower pH₄₅ than the corresponding CO₂ condition, with Ar resulting in the lowest pH₄₅. For the Helium system, He result in lower pH₄₅ than with CO₂. In the Argon Retrofit system, Argon resulted in a slightly lower pH₄₅ than observed with CO₂.

Comparing the control conditions (CO₂) across systems, it seems that the control for Argon Retrofit system has a slightly higher pH₄₅ compared to the control for the Helium and the Box system. No control conditions exist for the Improved Electrical stunning; however, the pH₄₅ for the trial seems to be lower than in the Argon Retrofit, Helium system, and Box system.

The temperature in the muscles 45 minutes after sticking is of interest because the development of poor meat quality is accelerated when the pH is low in combination with a high temperature. The core temperature of the loin at commercial slaughterhouses is typically in the range of 38–40 °C (Rybarczyk *et al.* 2015, Aaslyng & Hviid 2020, Mantis *et al.* 2019). For the Benchmark 2, the Box, Argon Retrofit system, and the Improved Electrical stunning, the temperature levels are lower than this, which most probably is due to the temperature measurements being performed more superficially rather than in the core of the muscle, and as such not due to the stunning system itself (Figure 31).

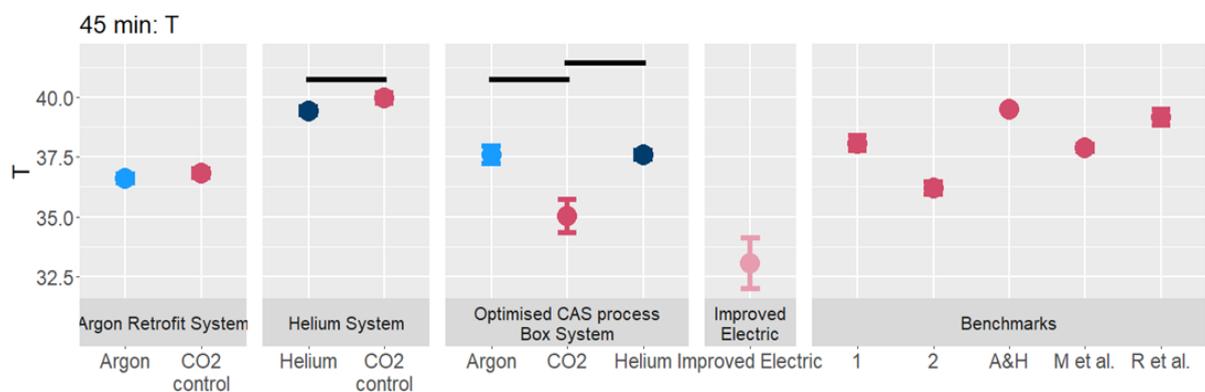


Figure 31. Temperature in loin 45 minutes after kill. Error bars indicate 95% confidence interval.

The T₄₅ results for the Box system are somewhat inversely related to the pH₄₅, which can be explained by a larger effect on temperature due to higher anaerobic metabolism in the Ar and He trials, resulting in lower pH compared to the CO₂ trial using the Box system.

Temperature and pH in Cold Carcasses

The pH in meat 24 hours after slaughter can be affected by a range of factors, including genetics, feeding, transport time and conditions, and lairage time and conditions. Since these factors are not standardized or controlled in the PigStun trials, it makes no sense to compare them in search of an effect of stunning system on the pH₂₄ (Figure 32).

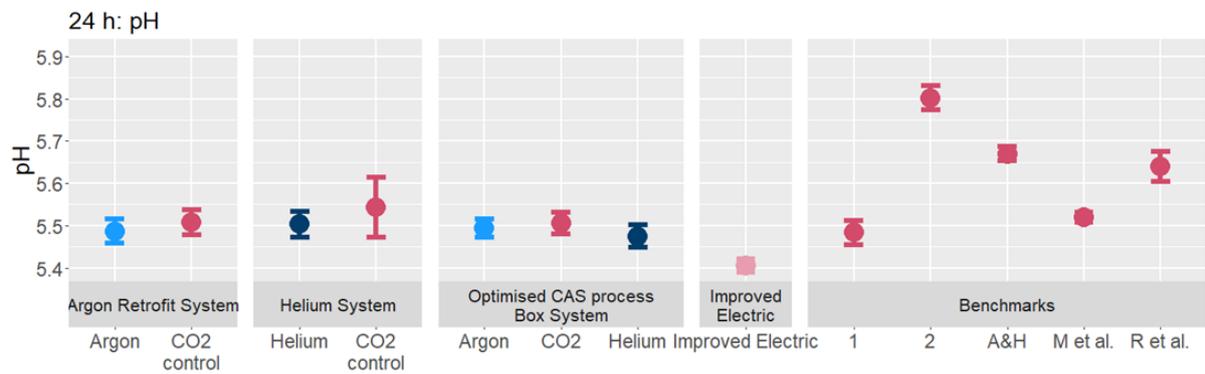


Figure 32. pH in loin 24 hours after kill. Error bars indicate 95% confidence interval.

The temperature 24 hours after slaughter is solely an effect of the chilling process and carcass size and is not affected by the stunning method (Figure 33). As shown earlier in Figure 26, the temperature moves asymptotically towards the ambient temperature in the final chilling phase.

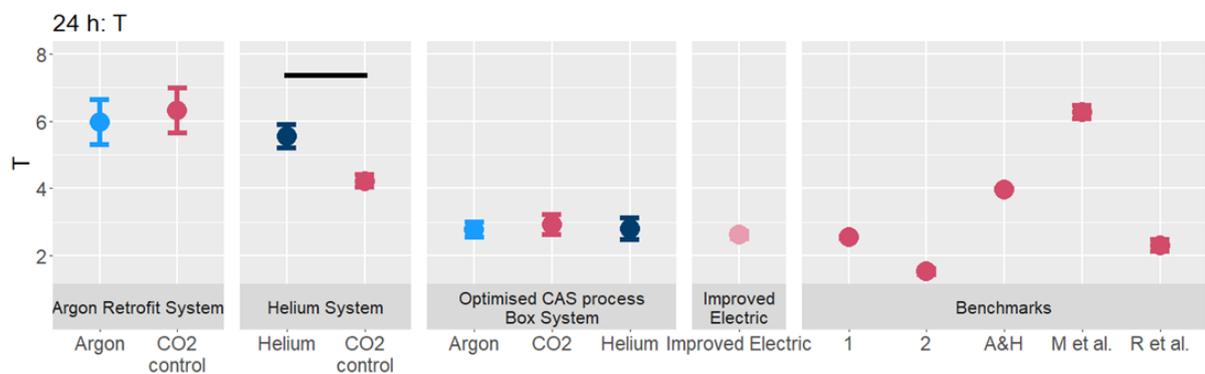


Figure 33. Temperature in loin 24 hours after kill. Error bars indicate 95% confidence interval.

The largest difference in T₂₄ between the Helium system and the local CO₂ control condition might be due to the large difference in carcass size between the CO₂ and He trials, thus the heavier carcasses have not reached ambient temperature at the time of recording meat temperature.

Drip Loss

The levels of drip loss vary significantly both within systems and across systems; however, except for Ar in the Box system, the levels are of a magnitude also found in the benchmark studies (Figure 34). Since the process conditions vary significantly among the four systems tested, and these conditions are known to influence drip loss formation, a comparison across systems cannot be made.

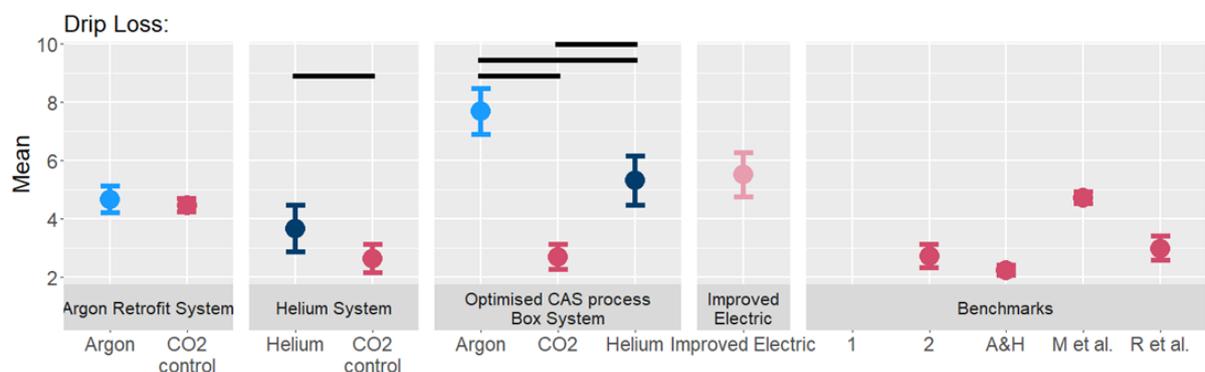


Figure 34. Drip loss from loin sampled 24 hours after kill. Error bars indicate 95% confidence interval.

For the Box system, a highly significant difference for the two tested inert gases (Ar and He) is observed, with Ar being the most severe compared to the control using CO₂. For the Helium system, Helium seems to result in higher drip loss compared to the local CO₂ control, and for the Argon Retrofit system, no effect of Argon is observed compared to the control using CO₂.

Colour

Due to incomprehensible differences or lack of differences in several of the colour values within systems, an across-system or within-system evaluation cannot be made (Figure 35, Figure 36, Figure 37).

The problems lie in the following. The L-value is a measure of the lightness/paleness of the meat and is the most important colour characteristic for pork. The lightness is mainly due to the scattering of light from the meat, and the structural changes in the myofibrillar lattice after slaughter that give rise to this increased scattering are the same structural changes that result in drip formation. Thus, the drip loss and L-value should be highly correlated (Joo *et al.* 1995, Warris & Brown 1987).

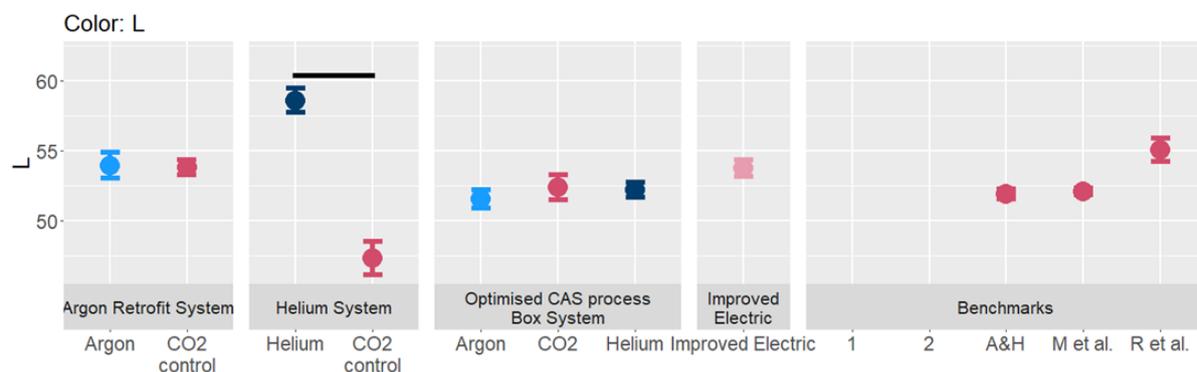


Figure 35. CIELAB L* value measured in loin 24 hours after kill. Error bars indicate 95% confidence interval.

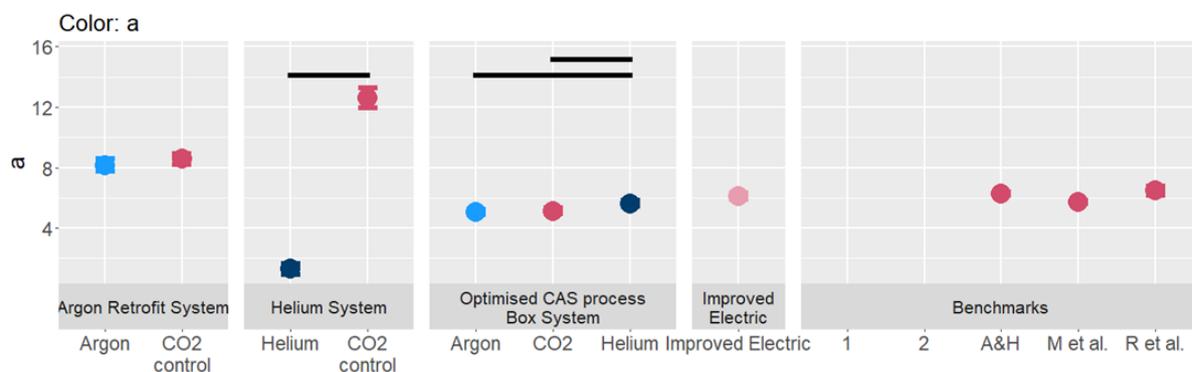


Figure 36. CIELAB a* value measured in loin 24 hours after kill. Error bars indicate 95% confidence interval.

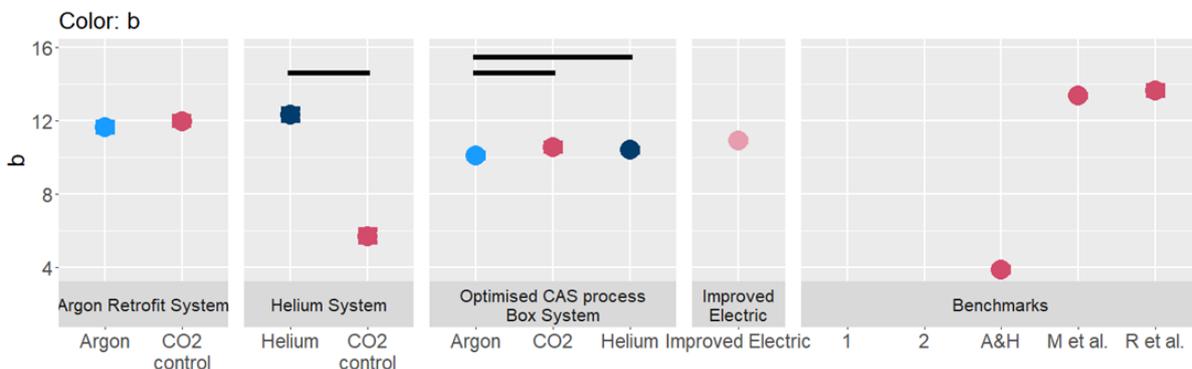


Figure 37. CIELAB b* value measured in loin 24 hours after kill. Error bars indicate 95% confidence interval.

For the Box system, there is a very big difference in drip loss between the three trials; however, no difference was found for the L-value. The opposite is the case for the Helium system, with a very big difference in L-value, but only minor differences in drip loss. The a-value for the Helium System is very different from both the three other systems and the benchmark studies. An a-value of 12 is extreme for pork loin and is what can be found in beef, and a-values below 2 are extremely low.

Pale, Soft and Exudative (PSE)

To determine the level of PSE in various cuts requires a visual and textural evaluation of the specific cut by a person experienced in this. This implies that, for example, the hams have to be deboned for evaluation by an expert. This is the reason why most studies that include an estimation of PSE use different parameters, typically measured in the loin. In the literature, PSE in loin has thus been defined by a pH₄₅ below 5.8 (Kim, Warner & Rosenvold, 2014), by a pH₄₅ below 6.0 (Bendell *et al.* 1966), or different combinations of drip loss and L-values measured in the loin (Joo, Kauffman, Kim & Park, 1999). PSE has not been directly determined in the PigStun project, which is why the PSE levels in loin and hams have to be indirectly estimated based on the parameters related to PSE. Since both the L-value and drip loss in the PigStun are confounded with the slaughter and chilling process, they cannot be used for comparison. Therefore, the pH in the hot carcasses (pH₄₅) is used for estimating PSE levels in loin and ham.

PSE in Loin

Figure 38 shows that in the Box system approximately 30% of the loins from Ar, 13% from He, and 2% from Improved Electrical stunning have a pH₄₅ below 5.8 and are therefore with a high degree of certainty PSE.

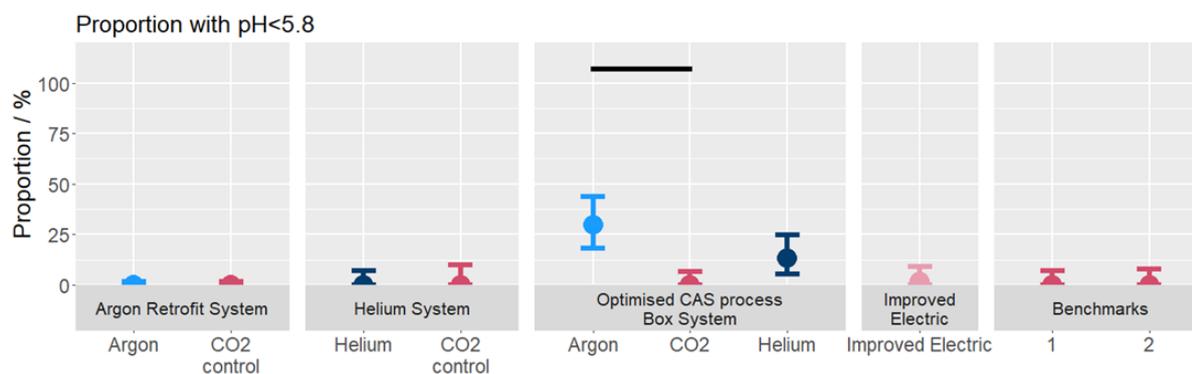


Figure 38. Proportion of loins with pH 45 minutes after kill below 5.8. Error bars indicate 95% confidence interval.

Since PSE can also develop with pH₄₅ above 5.8, the actual levels of PSE in loins are probably higher than Figure 38 suggests.

PSE in Ham

Since the hams are chilled slower than the loin, due to the physical dimensions of hams, the PSE level is higher compared to PSE in the loins, and from experience at DMRI PSE levels in hams are at least twice the level of what is seen in loins from the same carcass. If this approach is used on the data in Figure 38 and using only the mean values, it implies that PSE in hams is only occurring in Ar and He in the Box system, and with Improved Electrical stunning at a PSE level twice of that of the loins.

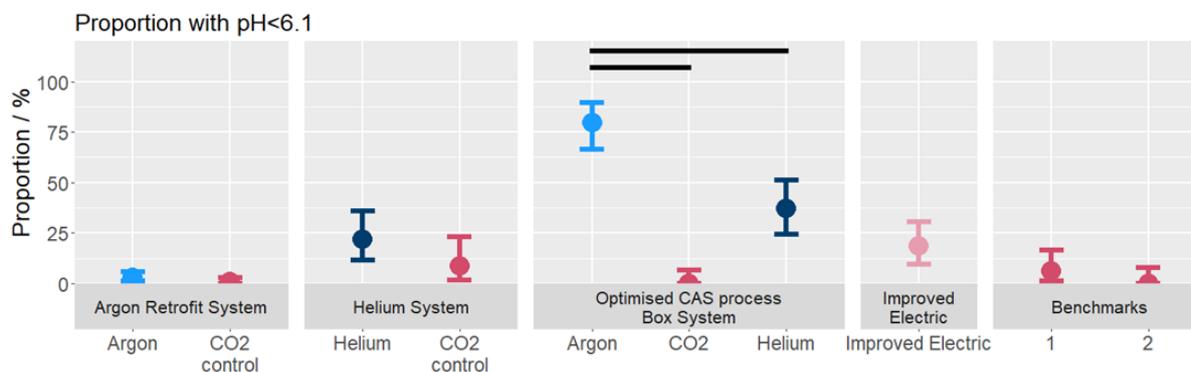


Figure 39. Proportion of loins with pH 45 minutes after kill below 6.1. Error bars indicate 95% confidence interval.

This is obviously wrong since the uncertainty, represented by the upper confidence interval for all the systems, is not taken into consideration. Another approach is therefore used to estimate the PSE levels in hams.

In the benchmark study from Aaslyng & Hviid (2020), all the hams were deboned and evaluated for PSE spots, which were not found in any of the hams. The lowest pH45 observation in the loins was 6.1 (Aaslyng & Hviid, 2020), thus implying that if pH45 in a loin is not lower than 6.1 and the chilling process is efficient, as the ones used in the benchmark study, the probability for PSE to occur is very low in both loins and hams. This also implies that if pH45 is somewhere below 6.1 in the loin, the probability for PSE to develop in the hams from the same carcass is increased.

Estimated PSE levels

Based on the above information, an estimate for the proportion of PSE in loins and hams for the four systems is provided in Table 1.

Table 1: Estimated PSE levels in loin and ham using an efficient carcass chilling process.

	Box System			Helium System		Argon Retrofit		Improved Electrical
	Argon	CO ₂	Helium	CO ₂	Helium	Argon	CO ₂	
PSE Loin, %	33	0	12	1	6	< 1	< 1	5
PSE Ham, %	66	0	24	2	12	1	< 1	10

Since the appropriate threshold for pH45 in loins to develop PSE in hams is unknown—apart from being below 6.1—the lower 95% confidence interval limit from Figure 39 has been used to give a conservative estimate of the proportion of PSE in hams, with 50% of that value used for the PSE proportion in loins. PSE levels for Ar and He in the Box system are estimated to be high in both loins and hams, while no PSE is estimated in CO₂. A medium-sized level of PSE is estimated in the Helium system, and low levels are estimated in the local CO₂ control. Almost no PSE is estimated in the Argon Retrofit system, and no difference in PSE between CO₂ and Ar is expected in that system. The Improved Electrical system is estimated to result in medium levels of PSE, comparable to the levels of He in the Helium system.

It must be stressed that there is a high degree of uncertainty in these estimates.

Summary

Key process parameters varied significantly between the four studies of the systems. The systems were tested separately from each other at different facilities, and factors including genetics, feeding, and

transport time, were not standardized. Therefore, no statistical comparisons of meat quality levels can be made across systems. The described comparison across systems is, therefore, associated with a high degree of uncertainty.

The analyses of data within system studies is statistically valid.

Five meat quality parameters were evaluated:

- **Blood spots:** No difference between CO₂ and Argon is observed in the Argon Retrofit system. For the Helium system, a clear negative effect of Helium is evident compared to the CO₂. He and Ar in the Box system have negative effects on blood spot formation compared to CO₂, with Ar being the most severe. Comparing across systems, the Improved Electrical stunning system appears to have the most severe effect, with only 43% having no blood spots.
- **Drip Loss:** The levels of drip loss vary significantly both within systems and across systems. Ar and He in the Box system show a highly significant difference, with Ar being the most severe compared to CO₂. The Helium system seems to result in higher drip loss compared to CO₂, and no difference is found between the Argon Retrofit system and CO₂.
- **Colour:** Due to unexplainable differences or lack thereof in several of the colour values within and across systems, an evaluation was not made.
- **Cold carcass pH:** No differences were identified within the systems studies between the treatments. Across systems a comparison is not possible, due to the non-standardised genetics, feeding and handling of live animals between systems. These factors highly influence the cold carcass pH and thusly masks the effect of the different stunning systems.
- **PSE:** A conservative estimate for the proportion of PSE in loins and hams for the four systems is given. Ar and He in the Box system are estimated to result in high levels of PSE, while no PSE is estimated in CO₂ for that system. A medium-sized level of PSE is estimated in the Helium system. Almost no PSE is estimated in the Argon Retrofit system. The Improved Electrical system is estimated to result in medium levels of PSE. It must be stressed that there is a high degree of uncertainty in these estimates.

Conclusions

No strong conclusions can be drawn on the effects of the gas alternatives on meat quality. Only few effects within systems were found. Meat quality was considered to be more affected in the Box System for Ar, and in part also for He, compared to the Argon Retrofit system and the Helium system, respectively. The reason for this is not known, as multiple aspects differed between the systems, as each stunning system uses different techniques to transport animals and to establish the gas atmospheres and used different target residual oxygen levels. As such, meat quality could have been influenced by several factors, such as the residual oxygen level (higher in Box System), intensity of movements and time until last movement occurred (later in the Box System). Additionally, the environments under which each system was tested differed, which includes animal genetics, ambient temperatures, pre-stun handling and the carcass processing and chilling systems.

Economic, environmental and social impacts

Introduction

This section aims to give insights into the economic, environmental and social impact once the alternative stunning systems are installed in a high throughput slaughterhouse. Results presented here were obtained through questionnaires applied to the alternative system leads (with 1 to 3 experts per alternative) about relevant parameters together with follow-up emails and one-on-one meetings. It has to be noted that most parameters correspond to estimates made by the system leads rather than actual empirical measurements

(see Table - B 4 and Table - B 5 in the section Economic, environmental and social impact of Appendix B: Analysis Methods for economic parameters).

Results for the social and environmental impact are described qualitatively and summarised in tables by parameter for each of the alternative stunning systems. Economic impact was described through the estimation of the cost per pig. This was done through considering the estimated necessary changes for implementing the alternative stunning system into a slaughterhouse that currently uses either a high concentration CO₂ stunning system or a conventional electrical stunning system and maintains a high throughput. The study cases previously reported and described in D1 were used here. For estimating the effect of implementing the alternative stunning system, changes were made so that the new system would maintain their previous daily throughput i.e. through adjusting the number of lines, slaughter hours per day.

Economic Impact

Table 2 shows the expected cost per pig (in eurocents) per study case after implementation of the alternative stunning system. The cost per pig when using The Tunnel solution for the Optimised CAS process was not estimated as most of the parameters needed are not yet known. Table 3 shows the cost per pig once the Argon Retrofit system is installed in conventional paternoster system considering the installation of a paternoster system that compensates for the reduction in throughput. Table - A 122 reports some important aspects to consider when interpreting the cost per pig in Table 2 and Table 3.

Table 2: Cost per pig (eurocents) for each study case implementing the relevant alternative stunning system. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system. Study case CO₂-2 uses a dip-lift system. Study case E-1 is Electrical-1, reported in D1 with a conventional electrical stunning system. To interpret the cost per pig correctly, please refer to Table - A 122 in the table under Economic, environmental and social impact.

Case study	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4	E-1
Backloader system for the Optimised CAS process	97.8	67.4	49.2	88.5	-
Helium stunning system ^{1,2}	199.9	143.9	171.5	121.8	-
Argon retrofit system (Dip-lift)	-	135.1	-	-	-
Argon retrofit system (Paternoster)	162.1	-	87.3	186.8	-
Improved electrical stunning process	109.1	81.0	94.5	69.5	87.2
Current cost per pig for study cases	73.5	51.8	35.8	63.9	35.2

¹ Helium stunning system includes a system that allows the recovery of helium. When first used, the system needs to be filled in and then only a percentage of the total amount needs to be re-filled daily. The cost per pig reported here considers a throughput of 90 pigs per hour per stunner and only includes the daily re-fill of the tower with helium considering a tower of 9 m³. To calculate the daily re-fill, it was assumed that the recovery system would be able to recover 90% of the total initial fill, as estimated by the experts (not yet consistently measured). Cost per pig with including the initial fill is 47318, 20218, 14818 and 14661 cents for CO₂-1, 2, 3 and 4, respectively.

² The total cost per pig for a completely optimised system with a throughput of 180 pigs per hour per stunner (by doubling the size of the stunner to a capacity of 10 pigs) would be with/without the initial fill: 23655/96, 10115/78, 7414/91, and 7336/67 cents for CO₂-1, 2, 3 and 4, respectively.

Table 3: Cost per pig (cents) for study cases with a conventional CO₂ paternoster stunning system (CO₂-1, CO₂-3 and CO₂-4) implementing Argon Retrofit system. This calculation considers a new stunner that will compensate for the reduction in throughput. Please to interpret the cost per pig correctly refer Table - A 122 for more details.

Case study	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4	E-1
Argon Retrofit system (paternoster)	116.3	-	55.3	102.0	-
Cost per pig for study cases	73.5	51.8	35.8	63.9	35.2

The background to the above data and the details obtained from the study cases are described in the Appendix to this deliverable D4. The technical and cost parameters used to calculate the cost per pig are an estimate or are unknown. Additionally, some cost parameters are highly dependent on the slaughterhouse and location i.e. labour, electricity, gas and water cost. This makes it difficult to draw any conclusions.

However, these calculations for fitting alternatives into the study cases (see also Appendix A: Detailed results) made a few aspects become clear:

- Argon retrofit system: The price for argon is relatively similar to CO₂ and the system can be implemented in a working slaughterhouse. However, due to the relatively low throughput, more lines should be implemented as longer hours of slaughter will not compensate enough. Considering that the exact installation costs are not available, the cost per pig is about 2 to 3 times higher as compared to the study cases.
- Helium stunning system: The daily cost per pig (i.e. only including the daily refill of ~10% of the total amount in the calculation) would be between 2 and 5 times more expensive than the cost per pig in a conventional CO₂ stunning system. When both the initial fill and daily refill of helium are included in the cost per pig, this is 25 to 67 times more expensive than a conventional CO₂ system. If doubling the size of the gondola would be possible, it is estimated that the cost per pig would be reduced by half the price. However, the price of helium is volatile and could easily increase depending on the political landscape. Additionally, this alternative would only work as a reversed dip-lift system i.e. one gondola going up and down. This means that it would be difficult to implement this system in a conventional paternoster system while reaching the same level of throughput as before due to the need of space. Note that the maintenance cost is not included in either of the two calculations.
- Optimised CAS process Backloader system: The study cases with a current paternoster system would have to pay 0.7 times less, and 1.2 and 1.08 times more for their current cost per pig respectively, when implementing a backloader system that uses CO₂. The study case with a dip-lift would have to pay 1.3 times more than their current cost per pig. However, the cost per pig does not include the maintenance cost, and the cost per pig may increase if the system is implemented with argon or helium.
- Improved electrical stunning: This system is about 2.5 times more expensive than the conventional one, and 2 to 3 times more expensive than the study cases with a conventional CO₂ stunning system.

Conclusion on Economic impact

The best alternative for any given slaughterhouse seems to be influenced by the type of system that is in place. This affects the investment costs in particular and may also be related to differences in prices of resources and current scale of production. Additionally, comparisons on running costs between alternatives are not easy to make as information is missing regarding key items, and the missing items differ between alternatives. Despite the lack of these key data, it can be argued that the alternatives with either argon or helium will increase the costs per pig stunned compared to CO₂. The average cost per pig when implementing the alternatives in the studied conventional CO₂ stunning systems is estimated to be lowest

for a CO₂ based Optimised CAS system, followed by the Improved electrical stunning process, the Argon Retrofit system and finally the Helium stunning system.

Environmental Impact

The responses from the experts on each alternative were summarized and included in Table 4, Table 5 and Table 6. It is important to note that the results from the optimized CAS process are based on the use of carbon dioxide. It is possible to use other gases in the CAS process system, and the use of alternative gases would likely give different results. Furthermore, unless otherwise specified, the results for the Optimized CAS-system in Table 4, Table 5 and Table 6, apply to both the backloader system and the tunnel system.

Table 4: Comparison of the environmental impact of the four alternatives for stunning in terms of efficiency (exposure time, pigs per hour, lairage time, and stun-to-stick time).

Alternative	Optimized CAS process (Using CO ₂)	Helium stunning system	Argon Retrofit System	Electrical stunning
Exposure time	Unchanged or slightly reduced compared with the traditional CO ₂ stunner	200 s	270 s	3 s
Pigs per hour	700 pigs per hour	50 -however a maximum of 90 pigs per hour is feasible.	40% reduction from stunning with traditional CO ₂ stunner	650, 170 per stunner
Lairage time	Unchanged compared with the traditional CO ₂ stunners.	3 hours	Unchanged compared with traditional CO ₂ stunner.	3 hours
Stun to stick time	Unchanged compared with the traditional CO ₂ stunners	25 s for 5 animals – differs along with group size.	Unchanged compared with traditional CO ₂ stunners	2-5 sec

In terms of exposure time, the Improved Electrical Stunning system has the shortest duration compared to the three other gas alternatives. The second shortest exposure time was observed in the Optimized CAS process if using carbon dioxide, followed by the helium system and Argon Retrofit system. Regarding the stun-to-stick time, the Improved Electrical Stunning had the shortest duration compared to the other alternatives with gas. This means that either more workers need to be present at a time or the throughput must be adjusted to ensure that sticking occurs within the timeframe. On the other hand, the pigs in the electrical stunning system are processed individually, and with gas stunning, the pigs are stunned in groups, which will also result in a higher workforce. The Helium system has the second lowest stun-to-stick time, while the optimized CAS system and Argon Retrofit system were estimated to have the same duration.

In terms of pigs per hour, the optimized CAS system had the highest throughput with 700 pigs per hour. The throughput for the Improved Electrical Stunning was slightly lower with a throughput of 650 pigs per hour with four stunners. For the Argon Retrofit system it was estimated that a 40% reduction in throughput compared with the conventional carbon dioxide system, could be expected. Therefore, the Argon Retrofit system would be lower than the optimized CAS-system and the Improved electrical stunning. The lowest throughput is the Helium system with an average of 50 pigs per hour. It was estimated that 90 pigs per hour would be feasible.

Stunning with CO₂ and electrical stunning have been used for a long time, and it can be assumed that these systems are already optimized to a high degree. With respect to the new alternatives, optimizations are

likely to occur over time to increase efficiency. Additionally, the slaughterhouse design and whether it is a paternoster system or dip lift can affect the variation between the alternatives.

In conclusion, the optimized CAS process and the Improved Electrical Stunning system would have the lowest environmental impact in relation to efficiency.

Table 5: An overview of the environmental impact of the four alternatives for stunning in terms of resource use (water, energy and gas).

Alternative	Optimized CAS process (Using CO ₂)	Helium stunning system	Argon Retrofit System	Electrical stunning
Water resources	Backloader: Unchanged to traditional CO ₂ stunners Tunnel system: Not possible to estimate	Not possible to estimate for helium stunning only.	Unchanged to traditional CO ₂ stunner	3000 L/day
Energy use	Backloader: Higher than traditional CO ₂ stunners because of the automated runway. Tunnel system: Not possible to estimate	Not possible to estimate for helium stunning only.	Unchanged to traditional CO ₂ stunner at same exposure duration	Electricity: 144 kWatt per day
Gas for the stunner	Backloader: Unchanged to traditional CO ₂ stunner Tunnel system: Not possible to estimate	Not possible to estimate for helium stunning only.	Likely similar to traditional CO ₂ stunner	None

Information on the four alternatives regarding resource use at a commercial scale are based on estimations. For the Optimized CAS process (backloader system) and Argon Retrofit system, all the parameters were assumed to be unchanged compared to traditional CO₂ systems. However, the backloader system was estimated to have higher energy consumption than the traditional CO₂ systems because of the automatic railway installed. It can be assumed that the water use, wastewater, and use of disinfectant would be the same between the 3 alternatives with gas (carbon dioxide, helium, argon). The assumption is based on the system design being very similar and therefore cleaning interval would mostly be assigned to the individual cleaning procedures and maybe the country-specific legislation for hygiene in the slaughterhouse. The high difference in the use of water within systems can be seen in Deliverable 1, where the water for cleaning in the carbon dioxide systems, was between 3 and 65 m³ per day. The energy use might be higher for the alternatives with gas, where longer exposure time is required (helium and argon), compared with carbon dioxide. This causes a longer time for the pigs to be in the stunner, and therefore also a longer time with the use of energy per pig. The use of energy (electricity, gas, diesel, etc.) in the alternative gas systems compared with the electrical stunning system, scarce information could be drawn. However, when looking at the electrical stunning system used as a case study in Deliverable 1, it could be seen that the electricity use per day on average, was lower for electrical stunning compared with the case slaughterhouses using carbon dioxide. The Improved Electrical Stunning has extended the commercial system with three extra stunners, so they instead of one, now have four stunners. Additionally, it is stated in Deliverable 3, that the throughput rate in the Improved Electrical Stunning system will be 75% compared with the original system. These factors will increase the energy use per pig. Thus, the Improved electrical stunning uses more energy per pig compared to the original system, but still less than the CO₂ systems.

Electrical stunning uses fewer resources than the alternatives with gas. Additionally, the multi-phase system with carbon dioxide may use slightly less resources than for helium and argon, caused by the longer

required time in the stunning system. However, the experts from the Argon Retrofit system, estimated no differences from the conventional carbon dioxide systems.

Table 6: Comparison of the environmental impact of the four alternatives for stunning in terms of availability.

Alternative	Optimized CAS process (Using CO ₂)	Helium stunning system	Argon Retrofit System	Electrical stunning
Obtaining	Easy	Hard	Medium	Easy
Suppliers	Many - 5-10 large suppliers and local suppliers	Few - 5-10 large suppliers. Few local suppliers buy from the big companies.	Medium - 5-10 large suppliers and local suppliers	Many
Recovery	Theoretically possible - no systems yet. However not economically viable.	Theoretically possible - already established systems, but none for stunning	Theoretically possible - No systems yet -. However not economically viable.	Not possible - not economically viable
Supply	Very secure- prioritized when shortage	Unstable - medicine industry prioritized	Secure	Easy
Price	Cheap	80-100 times more expensive than carbon dioxide	4-5 times more expensive than CO ₂	Cheap

In terms of availability, the Improved Electrical Stunning system is the best choice, on almost all parameters including price, supply safety, number of suppliers, and obtaining. Electricity is relatively easy to produce, however, the source of generation will also affect the environmental impact. When derived from renewable energy such as wind or solar, electricity has a significantly lower environmental impact compared to generation with fossil fuels. Another advantage of electricity is that it does not need to be transported physically in gas tanks, instead, it can be transported through electrical networks.

The availability of helium was critical in almost all parameters in Table 6. Helium is very hard to obtain, there are few suppliers, the price is very high, and the supply is not secure, due to the medicine industry being prioritized. Only with the potential of reuse or recovery of helium, there could be an advantage. Another limitation of using helium is that the slaughterhouses will be dependent on the delivery of gas from Russia, the United States, Algeria, and Qatar.

Economically, stunning with carbon dioxide seems to be most affordable compared to the other alternatives with gas (helium and argon) regarding the parameters presented in Table 6. Carbon dioxide is easy to obtain, there are many suppliers, the price is low, and the supply is very secure and prioritized when shortage. In terms of recovery, according to an expert from Air Liquid, it would be theoretically possible, but not economically viable. Another important factor is that carbon dioxide is produced mainly as a by-product of industrial emissions and chemical processes.

Stunning with argon is costlier than carbon dioxide and electricity, but less expensive than helium. The number of suppliers is sufficient, and the supply is secure. Argon is easier to obtain than helium, but harder to obtain compared with carbon dioxide and electricity.

Conclusions on Environmental Impact

The environmental impact in terms of efficiency, resource use, and availability, appears to be lowest for the Improved Electrical Stunning. This was mainly based on high availability with low cost, safe supply, and that electricity is easy to obtain. Also, in terms of efficiency, the Improved electrical stunning was one of the alternatives with the highest throughput and shortest exposure time. If the electricity is derived from renewable energy, this further reduces the environmental impact. The alternative with the second lowest impact is the envisioned Optimized CAS process, as it would have a high throughput in pigs per hour and a lower exposure time than helium and argon. In terms of resource use, the Optimized CAS process uses both gas and electricity for stunning and it is therefore assumed that the resource use was higher than for electrical stunning. The availability for the Optimized CAS process was high as well, with low cost, a secure supply, and many suppliers. However, the gas supply remains reliant on physical transportation and can be delivered without such logistical constraints. The second-highest environmental impact in terms of efficiency, resource use, and availability, was the Argon Retrofit system, as the expected throughput in pigs per hour was higher than for the helium system, and significantly lower than the Optimized CAS-process and Improved Electrical Stunning system. Additionally, the availability in terms of suppliers, supply safety, and cost was found to be more advantageous for argon compared with helium. However, the high recovery rate of 90% with a Helium system can mitigate some of the differences with the Argon Retrofit System.

Social Impact

The responses from the experts on each alternative were summarized and included in Table 7. The parameters analysed for the four alternatives, were risk of work accidents, toxic levels of gas, noise level, and labour time. It is important to note that the results from the Optimised CAS process are based on the use of carbon dioxide. Other gases can be used in the Optimised CAS process system, and the use of alternative gases would likely give different results. Furthermore, unless otherwise specified, the results for the Optimized CAS-system apply to both the backloader system and the tunnel system.

Table 7: Comparison of the social impact of the four alternatives for stunning.

Alternative	Optimized CAS process (using CO ₂)	Helium stunning system	Argon Retrofit System	Improved Electrical stunning
Risk of work accidents compared to carbon dioxide	Backloader: Same risk as a traditional CO ₂ stunner Tunnel system: lower than traditional CO ₂ stunners	Same risk as CO ₂ stunners.	Not expected any higher risk compared with CO ₂ stunners.	No additional risk compared with the traditional electrical system. Probably reduced due to lower throughput
Toxic levels of the gas compared to carbon dioxide	Backloader: Same risk as a traditional CO ₂ stunner Tunnel system: lower than traditional CO ₂ stunners	Very low risk	Lower risk compared to the traditional CO ₂ stunners.	Not relevant
Noise level compared to carbon dioxide	Backloader: Same risk as a traditional CO ₂ stunner Tunnel system: very uncertain	Same level as traditional CO ₂ stunners	No change compared with traditional CO ₂ stunners	Reduced compared to the traditional electrical stunning system.
Labour time compared to carbon dioxide	Unchanged compared to the traditional CO ₂ stunner	Longer stunning time - reduced number of pigs or a second person is needed.	May change - depends on the handling of longer stunning time.	No change in labor time, but more workers are required at the same time.

The risk for work accidents and changes in noise levels were not estimated to change when using helium and argon compared with the conventional carbon dioxide system. In relation to risks of toxic levels of gas, it was estimated to be a very low risk using helium. Helium is beneficial if leakage occurs, as it will accumulate at the ceiling and not the floor like CO₂ and argon. For argon, the risk of toxic levels was estimated to be lower compared with the traditional CO₂-stunners. An advantage of the inert gasses helium and argon is that they will only pose a risk when present in high concentrations and O₂ is lower than 19,5%. Conversely carbon dioxide poses health risks at much lower concentrations. The backloader system in the Optimized CAS process was expected to have the same risk of work accidents, toxic carbon dioxide levels, and noise levels compared to the conventional carbon dioxide system. When using the tunnel system, the risk of work accidents and toxic carbon dioxide levels is expected to be lower than in the conventional carbon dioxide system. There was very high uncertainty about the change of noise level in the tunnel system, as it is not fully developed yet. The labour time was unchanged in the Optimized CAS-system and the Improved electrical stunning system compared to the conventional carbon dioxide system. The longer stunning time for argon and helium may cause a reduced number of pigs going through the system, which could mean that fewer workers will be needed. However, if the current stunners are extended with larger gondolas, deeper pits, and longer slaughter days, this could compensate for the longer stunning time. Nevertheless, adding additional shifts would not increase the number of hours a single person needs to work.

In general stunning with gas requires less human contact with the pigs, than with electrical stunning. More contact with the pigs could increase the incidence of work accidents in electrical stunning. Even though the Improved electrical stunning system is reducing the stress for both pigs and workers, this would probably still be the case. The advantage of electrical stunning is, that there is no risk of toxic levels of gas.

One of the experts highlighted that greater societal acceptance of the slaughtering processes could positively influence the public perception which possibly could get another and better view of the slaughtering processes if the welfare is documented. This might enhance the working conditions and overall well-being of the staff in the slaughterhouses.

Conclusions on Social Impact

The alternatives with gas are expected to present a lower risk of workplace accidents compared with the Improved electrical stunning. This is primarily due to more human interaction with the pigs. Among the gas alternatives, the tunnel system seemed to be the best choice as there was a reduced risk of work accidents and toxic levels of CO₂. The Helium system ranks as the second-best choice in terms of work accidents and toxic helium levels. This is due to the risk of toxic helium levels being lower in comparison to traditional CO₂ stunners, as well as helium leaks accumulating at the ceiling. Subsequently, the Argon Retrofit system, which presents a lower risk of toxic levels of gas compared to traditional CO₂ stunners emerges as the best choice. The backloader system, which exhibits no significant changes from traditional CO₂ stunners regarding work accidents, toxic gas levels, and noise levels, would be considered the least favourable choice among the gas systems.

Ease of conversion

Expanding or rebuilding a stunning system involves strategic planning, financial assessment, operational evaluation, regulatory compliance, human resources management and infrastructure development. For a slaughterhouse, additional considerations include adhering to stringent animal welfare standards, implementing robust food safety and hygiene protocols, and managing environmental impact through effective waste disposal and emission controls. Community relations are crucial, requiring engagement with local stakeholders to address public concerns.

Given the complexity and the huge dependency on location and on the exact details on the specific construction plan, choice of materials etc., the task of estimating ease of conversion involves knowledge on parameters that are currently not available for the alternative stunning methods involved in this project. The resulting analysis is primarily descriptive of the switch from an existing high throughput CO₂ system to one of the alternative methods assessed.

Legal requirements

Animal welfare

According to the Council Regulation (EC) No 1099/2009 of 24 September 2009 on the protection of animals at the time of killing, animals shall only be killed after stunning in accordance with the methods and specific requirements related to the application of those methods set out in Annex I (List of stunning methods and related specifications).

The alternative methods are all included in Annex I.

Since new stunning methods are regularly developed and proposed for commercialisation, the Commission can approve new stunning methods, while keeping a harmonised and high level of protection for animals.

The European Food Safety Authority (EFSA) has developed a guide called Guidance on the assessment criteria for applications for new or modified stunning methods regarding animal protection at the time of killing². An application to get a new method approved must be submitted to EFSA and shall include all necessary scientific data and protocols showing the method's effectiveness and associated animal welfare outcomes. Based on EFSA's opinion, the European Commission can amend Annex I of the Regulation to include the new stunning method. This involves a formal decision-making process within the Commission and consultation with the Standing Committee on Plants, Animals, Food and Feed. Depending on whether scientific documentation already exists, it can be an extensive and costly process to obtain approval for a new stunning method.

When changing from one method to another, the specific requirements and key parameters of each method need to be taken into consideration. Key parameters are set out for each stunning method and specified in a way ensuring proper stunning of all animals submitted to the process. This includes specific technical and operational requirements. Since there are still no commercial plans for the new alternatives, it is not possible to estimate what exact significance this will have in relation to ease of conversion.

Building permit

If the conversion from one method to another involves a need to expand, a building permit will be necessary. Building permits are primarily regulated by national and local authorities, and regulations can vary significantly from country to country and even from region to region within the same country. If the expansion does not comply with local plans, this will prolong the approval process. Each Member State has its own procedures and rules for building permits, which can mean big differences in processing times. Some countries may offer a "light procedure" for less complex projects, which can speed up the process. Therefore, it is not possible to calculate the timeframe for this.

Environmental approval

Environmental impact assessment (EIA) is a process regulated by the EU's EIA directive (Directive 2011/92/EU of the European parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (codification), which was later amended

² <https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/j.efsa.2018.5343>

by Directive 2014/52/EU). The purpose of the EIA Directive is to ensure that environmental considerations are addressed before permission is granted for projects that may have a significant impact on the environment.

The ease of conversion in relation to obtaining environmental approval depends on several factors, including the classification of the project (Annex I or II), the national thresholds and criteria, and the local administrative practice.

Technical aspects

Each alternative system has strengths and weaknesses regarding ease of conversion. Inert gas is feasible to fit in existing CO₂ systems with some modification. Both the Argon Retrofit, and the Helium system will have throughput challenges unless additional expansion is done (Helium will need more extensive modification than the Inert Gas). Converting from CO₂ to the Improved Electrical System requires extensive modifications. However, changing from an existing electrical system could be done with fewer modifications. The strengths, weaknesses and feasibility of the Optimised CAS systems are based on knowledge provided by the manufacturer in addition to the D3 deliverable. The systems described in D3 do not directly correspond to the tested Box system, making the ease of conversion evaluation based on the untested, but proposed systems rather than the tested Box system, which was deemed infeasible at high throughput scale.

The feasibility of converting from high throughput CO₂ Stunning to an alternative stunning system involves balancing high conversion costs and infrastructure changes against potential long-term benefits in animal welfare and operational efficiency and require different physical alterations (Table 8) and financial costs (Table 9).

Table 8: An overview of the physical alterations required.

Physical alterations required when going from current high throughput CO ₂ to a high throughput alternative stunning system						
	Arrival	Driveway to lairage	Lairage	Driveway to stunner	Stunner	Sticking area
Argon Retrofit system	None	None	None	None/all ¹	Some	None
Helium System	None	None	None	All ²	All	None
Optimised CAS 'backloader' ³	None	None	None	All	Some	None
Optimised CAS tunnel ^{2,3}	None	None	None	All	All	All
Improved Electrical Stunning ⁴	None/None	None/None	Some/None	Some/All	Most/All	Most/All

¹If a second stunner is needed to maintain throughput it must be redone.

²A slope towards the stunner is required as the stunner is not on ground level.

³Based on what was described in D3, as the systems have not been tested and are only proposed.

⁴Changes depending on if the old system is traditional electrical/ CO₂

Table 9: Financial costs of building an entirely new slaughterhouse with the proposed Alternative Stunning Systems and Old CO₂ for reference.

Financial costs associated with the proposed Alternative Stunning Systems and high throughput CO ₂						
	Throughput per stunner	Stunners needed ¹	Throughput scaled	Cost per stunner	Cost of stunners	Total costs

Argon Retrofit system	420 pigs/hr	2	840 pigs/hr	30 k€	1,360 k€ ³	1,360 k€
Helium system	90 pigs/hr	7	630 pigs/hr	1,300 k€	9,100 k€	9,100 k€
Optimised CAS retrofit	650 pigs/hr	1	650 pigs/hr	1,200 k€	1,200 k€	1,200 k€ ⁴
Optimised CAS tunnel	650 pigs/hr	1	650 pigs/hr	2,800 k€	2,800 k€	2,800 k€ ⁵
Improved Electrical Stunning	170 pigs/hr	4	680 pigs/hr	540 k€	2,160 k€	2,200 k€
Old CO ₂	700 pigs/hr	1	700 pigs/hr	1,300 k€	1,300 k€	1,300 k€

¹When scaling to 600 pigs/hr.

²Varies wildly from slaughterhouse to slaughterhouse. These estimates were given by the manufacturer for their pilot test.

³It is assumed that the slaughterhouse only has a single existing backloader and requires another (1,200k€) in addition to the cost of two retrofit.

⁴This estimate is based on the system in D3, not the tested system and carries uncertainties.

⁵This value is based on the system in D3 and at a capacity corresponding to the possibility when using CO₂. It does not include modifications required to the slaughterhouse floorplan to accommodate the tunnel. The system has not been tested and carries uncertainties.

Conclusions

The conclusions on the feasibility of the different alternatives are summarised in Table 10.

Table 10: An overview of the feasibility of the Alternative Stunning Methods ¹The strengths, weaknesses and feasibility of the Optimised CAS systems is based of knowledge provided by the manufacturer in addition to the D3 deliverable. The systems described in D3 do not directly correspond to the tested 'Box system', making the ease of conversion evaluation based on the untested, but proposed systems.

How feasible are the Alternative Stunning Systems?				Estimated feasibility
	Main strengths	Main weaknesses	Impact of cost	
Argon Retrofit system	<ul style="list-style-type: none"> -Existing infrastructure can be retrofitted with relative ease -Modifications can be completed within a few days -Argon is easily available, similar CO₂ -The system can be fitted to use other heavy gasses as well -Argon stunning is already legal 	<ul style="list-style-type: none"> -Increased exposure time lowers throughput per stunner -Retrofitting could be complex depending on the design of the existing stunner, especially incompatibility between manufacturers could prove difficult -Only technical tests are performed in a paternoster system 	The relative low cost of converting to an Inert gas based stunning system, if an existing paternoster CO ₂ stunner is in place, positively impacts the feasibility.	Moderate to high – depending on existing CO ₂ stunner compatibility
Helium system	<ul style="list-style-type: none"> -Can offset the cost of helium by using a recapture system -Could be used with nitrogen in cases of helium scarcity 	<ul style="list-style-type: none"> -Helium currently operates at a low throughput, necessitating more stunners -Requires an entirely new stunner and helium recapture system 	The feasibility of converting to a helium-based stunning system is heavily influenced by its cost and requirement of entirely new	Low – for high throughput slaughter

	<ul style="list-style-type: none"> -Could reuse the existing area of a CO₂ stunner with minor modifications -Helium stunning is already legal 	<ul style="list-style-type: none"> -Unknowns in high throughput transition from CO₂ to Helium -Helium is unable to use paternoster designs <p>The price of helium is volatile</p>	stunners and recapture-systems.	
Optimised CAS retrofit ¹	<ul style="list-style-type: none"> -Existing infrastructure can be retrofitted with relative ease -Modifications can be completed relatively quickly -The system is gas agnostic -Stunning with some alternative gasses, like Argon, is already legal 	<ul style="list-style-type: none"> -Retrofitting could be complex depending on the design of the existing stunner, especially incompatibility between manufacturers could prove difficult -Other gases could have wildly different requirements regarding storage and usage. -System has not been tested, leaving multiple unknowns. Including knowledge about the effect on animal welfare 	The relative low cost of converting to the Optimised CAS retrofit system, if an existing paternoster CO ₂ stunner is in place, positively impacts the feasibility.	Verification remains
Optimised CAS tunnel ¹	<p>The envisioned system reduces pre-handling stress-The system is gas agnostic</p> <ul style="list-style-type: none"> -Stunning with some alternative gasses, like Argon, is already legal 	<ul style="list-style-type: none"> -Requires a major redesign of the slaughterhouse floor plan -Other gases could have wildly different requirements regarding storage and usage. -System has not been tested, leaving multiple unknowns. Including knowledge about the effect on animal welfare 	The cost of converting to an Optimised CAS tunnel system and requirement of redesigned slaughterhouse floorplan has a moderate to high impact on the feasibility, depending on required floorplan changes.	Verification remains
Improved Electrical Stunning	<ul style="list-style-type: none"> -Uses a commercially available electrical stunner -Modifications can be completed within a few weeks from existing electrical system -The new raceway design is relatively easy to build if there is sufficient space -Electrical stunning is already legal 	<ul style="list-style-type: none"> -Low throughput per stunner -Requires a much larger area -Multiple stunners drive up cost -Requires an extensive redesign of the slaughterhouse to change from high-throughput CO₂ system 	The cost of converting to the Improved Electrical Stunning system and requirement of entirely new stunners and raceways has a low to moderate impact on the feasibility.	Moderate

Insights from stakeholders

Stakeholder interviews

Introduction

Insights from stakeholders was gathered through interviews with representatives from select slaughterhouses, as well as comments obtained during a Workshop where the preliminary results were presented to interested stakeholders. The method for conducting the interviews can be found in the section in the appendix under Methods for the Interviews with Slaughterhouse Representatives.

Due to the preliminary nature of the results and the fact that certain details were not ready at the interview stage, specific recommendations, regarding, for example, logistical issues related to line speeds, likely transition period needed, estimated conversion timelines, as stated in the PigStun Full Work Programme document could not be provided at this stage. Nevertheless, the interviews highlight key points that play a central role in decisions to convert and areas where further research is needed.

Considerations that influence conversion

Satisfaction with current systems

For those utilising a high-concentration CO₂ stunning system, they were satisfied with the capacity of this system to stun effectively. Indeed, it was noted by one participant that the fact that the majority of pigs were in fact killed by the time they are released from the stunning chamber indicates a highly effective system. The efficiency of CO₂ was noted by another participant as an important reason why there must be more research on pre-stunning handling and lairage design. Despite one participant noting that they were experiencing blood spotting problems with their high concentration CO₂ system, they deemed that this system was the most efficient and had no reason to convert.

Furthermore, one participant cited that high-concentration CO₂ provided an unrivalled level of Meat Quality. They consulted a specialist in Meat Quality on the preliminary results and were informed that the blood spotting levels using Ar in the Box System would mean that those products would not sell. Participants were also uncertain of the disparity between Meat Quality between Ar in the Box System and the Argon Retrofit system and would like further information.

Group stunning with high-concentration CO₂ was noted as dealing with high throughput and also providing better working conditions for workers and calmer movement of the animals. Unlike the single-file stunning, group stunning eliminates the need for electric prods which was noted as benefitting both the workers and the animals by reducing stress.

However, whilst high concentration CO₂ was noted as working well, they all recognised the significant negative impacts on welfare that could not be overlooked. However, due to the unparalleled effectiveness of CO₂ across the other parameters, such as stunning efficiency, meat quality, and sourcing and supply, one participant recommended that more research should be conducted into the space allowance of the high-concentration CO₂ system, including the lairage, raceways, and gondolas. Indeed, the pre-stunning management of pigs was noted as a key parameter that affects how pigs react to CO₂ in the stunning apparatus. Therefore, another participant explained how their pre-stunning treatment of pigs, which included a rest period and housing animals from the same herd together, often led to the pigs falling asleep in the lairage.

Costs, regulation and animal welfare influence their choice of stunning

As our previous focus groups have indicated (D1), slaughter companies will choose the best option considering animal welfare, meat quality, environment and sustainability. Additionally, the health and work environment play a key role in determining the suitability of stunning systems. As one participant noted, 'Everything has to be considered.'

One participant explained that decisions are made based on cost, regulation, and then welfare. All the participants described how the challenging and uncertain economic landscape of slaughtering in Europe meant that conversion of stunning systems was not on the priority list, especially considering that all participants were primarily satisfied with their system.

Initial Reactions to the preliminary results

Argon Retrofit System

Argon Retrofit was cited as the best alternative on a number of key points. The relative ease of retrofit and the benefits to animal welfare appeared to outweigh the problem of a longer exposure time. Indeed, the longer exposure time may require more stunners, which was noted as a significant challenge to feasibility. Yet, one participant noted that operating a single stunner with a lower throughput may actually be a preferable situation in the current climate and potentially into the future, when pig numbers across Europe are falling. However, there remained a question as to how Argon would affect Meat Quality and operate in a high-throughput system. The results on Meat Quality show differing results, where in one system (Argon Retrofit system) Ar did not have negative impacts compared to CO₂, but in another (Box System for the Optimised CAS process) Ar negatively impacted on Meat Quality.

One participant noted that the tests for Argon were limited to the Dip-Lift which is a slower system than the paternoster. Therefore, they pointed out that not only was it 'disappointing' that no tests were conducted at a paternoster system but that this could be an area for future research.

Helium System

The interviewees saw a lot of potential in the Helium system but the unreliable sourcing of helium along with the high cost was cited as a major challenge for considering this as a viable alternative. Despite noting that there is a high recoverability of helium, the uncertain nature of supply and the initial cost of sourcing remained as major obstacles to the viability of this alternative. Additionally, the competition with the medical industry was noted as too significant a factor for this to be a viable option.

Box System for the Optimized CAS Process

The pre-stunning findings of the tests run in the Box system were not especially enlightening for one participant. In the Box system, animals rested for 45 minutes in the box while exposed to green light and music. To varying degrees, they had experience of these practices and felt uncertain as to their capacity to meaningfully impact on welfare. They noted that lowering the light level may be as effective, for example. Furthermore, managing the climate of the cage in terms of heat and drinkers for the pigs was noted as something they would like to better understand. Whilst another participant felt that the system offered some potential insights into improving pre-stunning but also highlighted that further research was needed, with additional points on space provision to be included.

Improved Electrical Stunning

The viability of the Improved Electrical Stunning alternative is directly related to the slaughter plants' experience with and use of electrical stunning. Whilst it was dismissed as not viable by some, participants with experience of electrical stunning viewed that this option was the most viable. They cited that the use

of several stunners meant that production throughput could be guaranteed in the event of technical failures or breakdowns.

However, the occurrence of blood spots in the hams of animals stunned in the electric stunners was cited as a serious problem, as hams with blood spots will not sell. Thus, for one participant, this was immediately a sign that Improved Electrical stunning was not an option for conversion. This view was reinforced by the specific background of this slaughter company who had converted from electrical stunning in the past. Thus, the view that electrical stunning was 'a step back' was reinforced by the lived experience of progressing from electrical stunning to high concentration CO₂ which is viewed as a more successful system across all parameters.

Opinions

System-specific opinions

Argon Retrofit system

Argon was cited by two participants as the most viable alternative and by the third participant as most likely after Improved electrical stunning. However, in comparison to high-concentration CO₂ stunning, there are questions remaining as to the capacity of Argon to deliver on Meat Quality and on an economic basis. Therefore, it was recommended that studies should now be directed towards providing more consistent evidence. This requires more data and practice, more data on Meat Quality and some interviewees perceived that Argon had potential to be better than the preliminary results indicate. Finally, it was indicated that Argon must be tested on a high-throughput system to adequately assess the viability of this alternative. Further research should also test Argon on a paternoster system which generally operates faster than the Dip-Lift. If this was to happen, the testing should be incorporated into the operations of a slaughter plant to reduce the burden on the company and make the testing more easily implementable. This would increase the likelihood of the test being possible in a commercial setting. Additionally, more data is needed on the supply and sourcing of Argon, especially if all slaughter plants are directed to replace CO₂ with Argon.

Helium System

There was a shared view that, whilst the animal welfare benefits are positive, this option is not viable due to cost and availability.

Box System for the Optimized CAS Process

The benefits of the pre-stunning management measures in the Box system were questioned by some participants. How effective is the green light alone or must it be in combination with the music and the resting period. Therefore, it is recommended that further research is conducted or more evidence provided as to the correlation between these factors and better welfare. One of the participants mentioned that the space allowance was a significant point of pre-stunning handling and management that needed further elaboration in relation to the Box system, both in terms of efficiency but also to ensure comfortable climatic conditions.

Improved Electrical Stunning

Due to the view of some of the participants that electrical stunning is seen as not being able to eliminate all welfare risks, more research on securing accurate stunning would be beneficial. Also, more information related to costs of adaptation for slaughter plants using electrical stunning was asked for by some.

General opinions

Communication of welfare at slaughter by Retailers

One participant pointed out how retailers are not communicating animal welfare at slaughter to consumers successfully. At the moment, welfare is associated with husbandry whilst the point of slaughter is overlooked. If there was better communication by retailers on welfare at slaughter, it would make it much

easier to move towards conversion in slaughter plants. They highlighted how the increased cost of Argon was not very significant when extended along the value chain.

However, one participant felt that this part of the slaughter process was obscured from welfare strategies with good reason, as attention on this aspect of the process may negatively impact on meat consumption.

Interviews with retailers

The centrality of retailers in the viability of alternatives cannot be overlooked. Perhaps just as crucial as regulation, the role of retailers in communicating to consumers and securing markets was mentioned by one participant as an important part of these issues. Therefore, it would be beneficial to interview retailers on these issues and communicate more effectively on the importance and potential of these alternatives.

More Research on Current Pre-Stunning Handling

Due to the widespread use of high concentration CO₂ stunning, one participant highlighted a need for further research on the pre-stunning phase as a mitigation factor for the negative welfare consequences of CO₂. This would be a compromise between the need for better conditions for animals and the prevalence of high concentration CO₂ stunning in slaughter plants. This research should also include handling of intact males which appear to be more aggressive in the lairage than the previously typically castrated male pigs.

Communication on the Nature of Aversiveness of CO₂

Appropriate pre-stunning management of pigs is vitally important. However, there is a need for more communication on the aversive nature of CO₂, so that the importance of these alternatives is reinforced. Whilst pre-stunning management can reduce stress and fear, the aversiveness of CO₂ is not negated and therefore, slaughter companies using high-concentration CO₂ should be informed about the nature of the aversiveness, including the degrees of pain, fear, and stress that pigs experience.

Mixed Gas Studies

One participant recommended studies into the use of nitrogen along with mixtures of gases to address issues of Meat Quality and cost as well as problems of supply.

Induction System

One participant suggested that CO₂ might be used in a second phase after the animals are induced with a non-aversive gas.

Requests for additional information

There were several aspects, where interviewees requested more information or suggested additional research:

- Stunning Efficiency Rate across the alternatives
- Efficiency of the systems – pigs per hour
- Paternoster alternative for Argon testing
- How to evaluate stress – more information on how this was done across the systems
- Use of AI in evaluating results
- Benchmarks from a better CO₂ system – an optimal system with better handling and more space so that the alternatives can be compared both with less optimal and optimal situations.
- More information on the raceways and how they can be constructed
- Sourcing of the gases – more details on the locations (countries) of suppliers and the demand for the gas if this is imposed in all slaughter plants in the EU.
- The cost of conversion in detail – adaptation
- Demo for how a system will run for a number of months – with reference to the meat quality concerns in the Improved Electrical Stunning alternative and how blood spots may affect sales.

Discussion

The EFSA report detailing the aversive nature of high concentration CO₂ stunning explicitly states the severe negative welfare experienced by pigs in this stunning system. However, the presence of a welfare issue is not sufficient to transform a production sector, where cost is paramount, and regulations drive change. Even where slaughter plants have recently, or will in the near future, upgrade their stunning systems, none of the proposed alternatives are judged by the participants to be viable due to the current uncertainty regarding their cost, supply, and efficiency and crucially, because current high concentration CO₂ stunning systems are in line with regulation. Thus, whilst the following discussions and associated recommendations point out areas for further research and development, the interviews with the slaughter plant representatives demonstrate how conversion will not be undertaken without a legislative instrument demanding conversion within a given timeframe. At the moment, the point of slaughter is a welfare issue, but this is not sufficient to drive conversion to non-aversive stunning methods.

All the participants noted that decisions about conversion of stunning systems include a team of professionals in the company, many of whom include production directors, vice directors, as well as animal welfare and financial specialists. Thus, their reflections shared in interview were provided in the understanding that viability of alternatives and the feasibility of conversion are a group decision. Interestingly, two of the participants described either a recent conversion of their slaughter plants or plans to renovate one of the slaughter plants. Whilst there is simply not enough evidence here to support a conversion to one of these alternatives within the coming months, this project is providing invaluable evidence for alternatives that can be implemented once more data is available. However, in order to present the viability of conversion to slaughter companies, many of whom are undergoing significant reorganisation and job cuts, the data and costings of conversion needs to be rigorously examined and detailed. To put it simply, one participant stated that before they can implement a new stunning system, 'we need to know that it works.' Thus, these alternatives are not viable in the foreseeable future, but they are interested in the research being carried out with a view to the long-term future.

A major barrier to alternatives appears to be the fact that high concentration CO₂ stunning performs well in important areas, related to meat quality and cost and supply. Whilst the animal welfare issues are recognised by the slaughter companies, their pre-stunning management of the animals and the guaranteed complete stunning of the pigs outweighs the viability of these alternatives, especially at this stage of their development where their performance in high-throughput systems is not known and many of their associated costs, from retrofitting where possible to sourcing and supply are uncertain.

The aversive nature of CO₂ was noted by one participant as being experienced differentially by the pigs, depending on the pre-stunning treatment of the pigs. This suggests that the negative welfare experienced by pigs in CO₂ stunning can be mitigated by pre-stunning measures. However, according to EFSA (2020 p.102), "Exposure to CO₂ at high concentration (defined in this opinion as higher than 80% by volume) should be replaced by exposure to other gas mixtures that are less aversive. More research and development on the composition of non-aversive gas mixtures is needed to eliminate pain, fear and respiratory distress during the induction to unconsciousness." Whilst pre-stunning is identified as a phase where animal welfare risks arise, minimizing all these hazards does not diminish the aversiveness of CO₂ on pigs.

One participant described the interest of their company to centre the animal, stating "How can we work with the pig to move it in the best way other than getting the pig to fit into a system and maybe have a system that fits the pig better if you understand. Because I think [...] if we ask the people that we usually ask, the ones that make the systems and all this, they'll give us the answer that we usually get. If we ask someone who doesn't work with the slaughter industry as much [...], they might have a new way of looking at it, then we might get some new answers and some better answers. So that's what we are trying to do. So, we certainly have an interest in doing this in the best way for the pigs." (In interview, 2024). When considering alternatives to stunning, this willingness to develop is an opportunity to advance better stunning systems in large slaughter plants, however, the viability of these alternatives must be demonstrated as better than

CO₂. This requires more research, more data, and legislation that motivates these powerful companies to invest in alternative systems. Whilst animal welfare is high on the agenda of the large customers that all of these meat production companies supply, decisions about conversion take a holistic approach, with issues of meat quality and economy being weighed up with animal welfare and sustainability.

As noted in the results, all participants shared how the meat sector is navigating a difficult landscape in terms of lower slaughter numbers, tariffs, and uncertain export markets. As a result, conversion will not be willingly undertaken due to the economic uncertainty. Therefore, the move towards non-aversive stunning systems must be led by legislation as there is no incentive to make such an investment in the current economic landscape. This is underscored by the fact that all the participants recognised the negative welfare of high concentration CO₂ stunning and yet, if they needed to convince their companies to convert to a non-aversive form, they would not only need more data and evidence of benefits, more information related to cost of conversion and secure supply, but also legislation would make it much more likely in terms of investment.

Interestingly, the reduced capacity of Argon did not automatically rule this alternative out as viable. One participant reflected on the wider landscape of slaughter in Europe, both in terms of pigs and cattle, and shared how if numbers continue to decrease and slaughter plants continue to consolidate, we will end up in a situation where animals are travelling great distances to slaughter. Thus, a reduced throughput as a result of longer exposure time is an opportunity to maintain slaughter plants in number but demands a redefinition of efficiency. Rather than striving to run at full utility, if we retained slaughter plants in these numbers but they ran on lowered output with more animal welfare friendly methods, how might these costs be distributed to the retailers. This requires more research and data, but it is interesting to consider how these alternatives fit into an alternative meat production system where the concept of efficiency itself is reimagined.

Feedback during PigStun workshop

Introduction

During a hybrid PigStun workshop on 19 November 2024 the alternative systems and results from the different fields of interest were presented to the PigStun consortium (onsite, 29 participants) and all interested stakeholders (online, 135 participants).

Messages by 28 participants in the Chat that included feedback were evaluated as well as responses to a short survey provided at the end of the Workshop by 24 participants. There is likely an overlap in the people who provided feedback in the chat and those who filled out the survey.

The survey included the following questions:

1. What type of organization (NGO, research institute, etc.) do you belong to?
2. Which stunning systems for pigs do you have prior experience on or in-depth knowledge about
3. Name three factors that you think would positively influence slaughterhouses to voluntarily switch from high concentration CO₂ stunning to an alternative system.
4. If slaughterhouses were, for any reason, transitioning away from high concentration CO₂ stunning, which systems would you prefer?
5. Is there specific information or research missing that you would need to answer these questions?
6. Do you have any specific feedback for
 - d) Argon Retrofit System,
 - d) Helium System,
 - d) Box system for the Optimized CAS process and
 - d) Improved Electrical Stunning?

Feedback

Most participants stated prior experience or knowledge about either high concentration CO₂ or automatic electrical stunning system.

Participants associated with the slaughter industry showed a reluctance to move away from a system that they believe to work well. Other stakeholder groups shared this assumption of a likely unwillingness to voluntarily change away from high concentration CO₂ stunning. Responses from the slaughter industry further highlighted the importance of economically and commercially viable systems and to adopt them with a focus on product quality where alternatives will show no discernible differences in meat quality when compared with CO₂ stunning. This view was shared by researchers and animal welfare NGOs.

Respondents associated with research organizations, animal welfare NGOs and legislative or executive bodies further stressed the need for government regulative or legislative measures or incentives/funding to offset the operational costs to facilitate the transition from high CO₂ to less aversive stunning alternatives. Other incentives like public awareness, adoption of the stunning method into welfare labels and customer's demand for adopting humane methods were also noted. Animal welfare NGOs further highlighted the importance of considering occupational safety, including improved worker satisfaction and mental health as potential benefits of the alternative systems and also recommended proper training of the staff to follow the animal welfare standards.

When asked which of the presented alternative systems they would prefer, if slaughterhouses, for any reason, had to transition away from high concentration CO₂ stunning, no clear preference emerged among respondents from the slaughter or meat industry. Among those from animal welfare NGOs and legislative bodies, the Argon Retrofit system was listed most often, followed by Improved Electrical. Also, studies into whether alternative gases could be used for the induction phase and followed up by CO₂ to ensure that pigs were killed or kept unconscious for an appropriate time after stunning were asked for.

Additional data would also be appreciated on the differences in the emissions involved in producing electricity, CO₂, argon and helium. Detailed information for this could provide a better idea of the overall sustainability of alternative stunning systems. Participants also suggested studies on further animal welfare parameters, including factors like noise and smell.

One of the promising features of Argon Retrofit system -as noted by participants- is its feasibility for retrofitting into existing slaughterhouses. However, one needs to consider the cost, sustainability of argon sourcing and reduced throughput. If these drawbacks are overcome and further studies about its scaling up in industrial scale is available, participants consider it as a viable alternative to high concentration CO₂ stunning.

Concerns about the Helium system were similar, with scarcity of helium as a limited resource and the larger required changes to the slaughterhouse mentioned as further drawbacks. Regarding the Optimised CAS process participants would like more information about for the whole concept, its readiness for commercial use, and the potential for using CO₂ in combination with other gases. For the Improved electrical stunning, the continued need for, even lower-voltage, electric prods was mentioned as hindering adoption by slaughterhouses currently using CO₂ stunning but was seen as a potential improvement for slaughterhouses already using electrical stunning. Some participants suggested further research into electrical stunning in groups.

Summary

In summary, based on the feedback during the PigStun workshop, a voluntary adoption of the alternative systems by the slaughterhouse industry is seen as unlikely and regulatory or other incentives would be needed to facilitate a change away from high concentration CO₂ stunning. In addition to this, the alternative systems should be tested in full high-throughput situations to verify the results on animal welfare and meat

quality under these conditions and collect practical data on economic and social parameters, such as gas usage, worker safety and worker satisfaction.

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Appendix A: Detailed results

Introduction

This section shows detailed results for each of the investigated alternatives in separate sections as well as for the benchmark CO₂ data. Please see Appendix B: Analysis Methods for more details about the performed analyses. Each section for an alternative starts with a subsection “Animal collective and stunning parameters” followed by the subsections “Animal welfare”, “Meat quality”, “Economic, environmental and social impact” and “Ease of conversion”.

In the first three subsections, results are reported in a sequence of tables. Unless otherwise stated, lists of behaviours considered for animal welfare analysis were collected for three phases; Entering, Initial reaction and Stunning Progress (see Table - B 2 in the Appendix B: Analysis Methods).

The tables show the mean, standard deviation (σ), the minimum and maximum data (Min, Max) as well as 95% confidence (95% CI; see analysis methods for details) along with the number of samples (N) of the parameter stated in the section header separately for the different measurement conditions. For some behavioural parameters the time of occurrence was analysed relative to the Start of motion that brings the animal into the atmosphere (“Start descend”) and/or relative to the time the loss of Posture of the animal (“Loss of posture”). For these parameters, data is displayed in seconds (except N), with negative values indicating that the described parameter (e.g. first agitation) occurred before the referenced time (e.g. loss of posture). In addition, the proportion of animals showing the behaviour (“Proportion”) is shown in percent. For these, no standard deviation, minimum and maximum values are reported. Results of statistical tests are indicated in the column (*) in compact letter display, where conditions that are statistically different are assigned different letters. Note that this test is always only for within this system and only for that specific parameter and reference. When no letter is shown, no statistical test was performed.

The tables describing data that was scored on an ordinal score system (Entering Overview, Initial Reaction Overview, Blood spots), the additional column “Level” indicated the scoring level of the parameter. The first row for each measurement condition (e.g. “Local CO₂ Control”) described the mean of the level occurrences, while the following rows show the percentages of occurrence for each level. The display is otherwise analogous to the one described above.

Tables for the other meat quality parameters are shown similarly to the behavioural parameters. Here multiple parameters are shown in a single table as indicated by the “Parameter” column. Temperatures in shown in °C, Drip loss is percent, while the other parameters do not have units. The proportion of samples with a pH45 below 6.1 (pH45<6.1) or 5.8 (pH45<5.8) is shown and for some parameters (e.g. T / Temperature), the values for the subset of samples where the pH45 was below a certain threshold is also shown (e.g. T(pH45<6.1)).

Due to their more qualitative nature, information in the sections “Economic, environmental and social impact” and “Ease of conversion” are described in continuous text along with tables where appropriate.

Argon Retrofit System

Please see the Introduction to this appendix and Appendix B: Analysis Methods or details on the display format and methods.

Animal collective and stunning parameters

Animal Genetics

Table - A 1: Number of animals for the different meat quality analyses separated by animal genetics. DanL = Danish Landrace, DanY = Danish Yorkshire, Du = Duroc, PI = Pietrain, DE = Deutsches Edelschwein, DL = German Landrace, NL = Dutch Landrace, LW = Large White.

Condition	Genetics	pH45, T45	pH24, T24	Colour, Drip Loss	Blood Spots
Argon	[DanL x DanY] x Du	1	1	1	1
	[DanL x DanY] x Pi	199	67	57	101
	[DL x DE] x Du	8	0	0	0
	[DL x DE] x Pi	10	0	0	20
	[NL x LW] x Pi	6	0	0	0
	DL x Pi	20	9	2	2
Local CO ₂ Control	[DanL x DanY] x Du	12	12	12	12
	[DanL x DanY] x Pi	188	54	45	84
	[DL x DE] x Du	6	0	0	0
	[DL x DE] x Pi	10	0	0	24
	[NL x LW] x Pi	4	0	0	0
	DL x Pi	26	13	6	6

Animal sex and average weight

Table - A 2: Animal sex and average slaughter weight of the animals stunned under different conditions (Argon and Local CO₂ control)

Condition	Female [%]	Castrated male [%]	Weight [kg]
Argon	52.7	47.3	98.0
Local CO ₂ Control	56.7	43.3	98.1

Gas Concentrations

Table - A 3: Residual oxygen content (percent) for two sensors. The mean gas concentration during the stunning sequence was calculated for each gondola. From these mean concentrations per gondola, the mean, minimum (min), maximum (max) and standard deviation (σ) of the means were calculated over all stunning sequences.

Condition	Sensor A [%]	Sensor B [%]

	Mean	σ	Min	Max	Mean	σ	Min	Max
Ar	0.62	0.14	0.47	0.76	0.49	0.14	0.40	0.58
Local CO ₂ Control	1.00	0.31	0.91	1.09	0.91	0.31	0.81	0.99

Animal Welfare

Pre-Stunning Handling

The handling and behaviour of the animals during the pre-stunning phase (arrival, moving to lairage, lairage, moving to stunner) were not recorded, but handling procedures remained unchanged between argon and CO₂ conditions. To avoid confounding effects, argon and CO₂ conditions were alternated between and across recording days. Handling and behaviour during entrance into the stunner was assessed as part of the video analysis.

Video Analysis

Entering

Entering Overview

Table - A 4: Distribution of the maximum (strongest) scored level per animal for entering the stunning device. The levels were scored as 0 = none, 1 = reluctance to move, 2 = aversive physical contact, 3 = painful physical contact, 4 = lasting painful physical contact. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the strongest (maximum) scored level for entering of the stunner and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and the number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	*	Min	Max	95% CI		N
Max Score	Argon		1.5	a	0	4	1.3	1.6	298
		0 [%]	34.2				28.9	39.9	102
		1 [%]	0.7				0.1	2.4	2
		2 [%]	50.0				44.2	55.8	149
		3 [%]	14.8				10.9	19.3	44
		4 [%]	0.3				0.0	1.9	1
	Local CO ₂ Control		1.6	a	0	4	1.5	1.7	300
		0 [%]	29.3				24.2	34.8	88
		1 [%]	1.0				0.2	2.9	3
		2 [%]	52.3				46.5	58.1	157
		3 [%]	16.7				12.6	21.4	50
		4 [%]	0.7				0.1	2.4	2

First reluctance to move

Table - A 5: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first reluctance to move relative to the start of the descend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first reluctance to move occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend[s]	Argon	-11.6	7.6	b	-31.5	-4.1	-15.5	-7.7	17
	Local CO ₂ Control	-27.2	29.5	a	-158.2	-4.2	-37.5	-16.9	34
Proportion [%]	Argon	5.7		a			3.4	9.0	298
	Local CO ₂ Control	11.3		b			8.0	15.5	300

First aversive physical contact

Table - A 6: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first aversive physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first aversive physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	-5.2	3.9	b	-28.6	-1.7	-5.9	-4.6	151
	Local CO ₂ Control	-8.7	10.2	a	-68.0	0.0	-10.3	-7.1	165
Proportion [%]	Argon	50.7		a			44.8	56.5	298
	Local CO ₂ Control	55.0		a			49.2	60.7	300

First painful physical contact

Table - A 7: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first painful physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first painful physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	-5.9	3.9	b	-18.4	-2.3	-7.0	-4.7	45
	Local CO ₂ Control	-16.1	32.7	a	-170.5	-1.5	-25.2	-7.0	52
	Argon	15.1		a			11.2	19.7	298

Proportion [%]	Local CO ₂ Control	17.3		a			13.2	22.1	300
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First lasting painful physical contact

Table - A 8: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first lasting painful physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the lasting painful physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	-10.5		a	-10.5	-10.5			1
	Local CO ₂ Control	-19.0	6.8	a	-23.8	-14.2			2
Proportion [%]	Argon	0.3		a			0.0	1.9	298
	Local CO ₂ Control	0.7		a			0.1	2.4	300

Initial reaction

Initial Reaction Overview

Table - A 9: Distribution of the maximum (strongest) scored level per animal for the reaction to the gas atmosphere in the induction phase. The levels were scored as 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of these strongest (maximum) scored initial reaction and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	*	Min	Max	95% CI		N
Max Score	Argon		0.9	a	0	3	0.8	1.0	298
		0	51.3				45.5	57.1	153
		1	13.8				10.1	18.2	41
		2	32.6				27.3	38.2	97
		3	2.3				0.9	4.8	7
	Local CO ₂ Control		2.3	b	0	3	2.2	2.4	300
		0	11.0				7.7	15.1	33
		1	7.0				4.4	10.5	21
		2	22.0				17.4	27.1	66
		3	60.0				54.2	65.6	180

First response to atmosphere

Table - A 10: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first response to the atmosphere, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first response to the atmosphere occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	7.9	3.7	a	2.2	16.9	6.9	9.0	51
	Local Control CO ₂	6.9	3.0	a	2.5	13.8	6.2	7.7	69
Loss of posture [s]	Argon	-13.0	6.4	a	-25.8	-1.5	-14.8	-11.1	51
	Local Control CO ₂	-13.3	5.0	a	-28.1	-3.1	-14.5	-12.1	69
Proportion [%]	Argon	17.1		a			13.0	21.9	298
	Local Control CO ₂	23.0		a			18.4	28.2	300

First agitation

Table - A 11: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first agitation, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown in percent. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	8.6	4.3	a	3.2	25.0	7.8	9.5	99
	Local Control CO ₂	8.2	4.4	a	2.6	23.5	7.5	8.9	148
Loss of posture [s]	Argon	-13.6	6.5	a	-28.7	3.3	-14.9	-12.3	99
	Local Control CO ₂	-13.3	5.8	a	-26.6	3.8	-14.2	-12.3	148
Proportion [%]	Argon	33.2		a			27.9	38.9	298
	Local Control CO ₂	49.3		b			43.5	55.1	300

First strong agitation

Table - A 12: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first strong agitation relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first strong agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form,

where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	23.0	5.2	b	16.3	28.4	18.2	27.8	7
	Local CO ₂ Control	15.1	5.2	a	3.9	29.5	14.3	15.9	180
Loss of posture [s]	Argon	-3.2	2.1	b	-6.8	-1.1	-5.1	-1.3	7
	Local CO ₂ Control	-6.8	4.7	a	-30.5	8.4	-7.5	-6.1	180
Proportion [%]	Argon	2.3		a			0.9	4.8	298
	Local CO ₂ Control	60.0		b			54.2	65.6	300

First abnormal breathing

Table - A 13: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first abnormal breathing, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first abnormal breathing occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon								0
	Local CO ₂ Control	12.3	3.7		4.3	25.6	11.7	12.8	177
Loss of posture [s]	Argon								0
	Local CO ₂ Control	-9.1	4.8		-32.1	-0.6	-9.8	-8.4	177
Proportion [%]	Argon	0.0		a			0.0	1.2	298
	Local CO ₂ Control	59.0		b			53.2	64.6	300

Stunning progress

Loss of posture

Table - A 14: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the loss of posture relative to the start of the descend of the gondola, calculated from the results of each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
	Argon	21.3	4.4	a	10.0	34.3	20.8	21.9	298

Start descend [s]	Local Control	CO ₂	20.8	4.0	a	10.1	39.0	20.4	21.3	300
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Lying

Table - A 15: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until lying, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom) , calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	50.1	11.2	b	32.9	110.6	48.8	51.4	282
	Local Control	CO ₂	44.9	8.4	a	28.9	83.1	44.0	45.9
Loss of posture [s]	Argon	28.8	12.1	b	7.4	89.6	27.4	30.2	282
	Local Control	CO ₂	24.0	8.3	a	4.6	58.7	23.1	25.0

Last movement

Table - A 16: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the last movement, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom) , calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	173.1	30.3	b	79.7	266.7	169.6	176.5	298
	Local Control	CO ₂	143.2	21.9	a	71.7	199.2	140.7	145.7
Loss of posture [s]	Argon	151.7	29.8	b	62.1	244.9	148.4	155.1	298
	Local Control	CO ₂	122.4	21.6	a	53.9	183.6	119.9	124.8

Cycle duration

Table - A 17: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence (95% CI) of the cycle duration relative to the start of the descend of the gondola. Note that this is an operational parameter reflective of the set stunning times. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend [s]	Argon	269.8	21.2	b	213.3	333.5	267.3	272.2	298
	Local Control	CO ₂	198.0	36.0	a	123.4	333.8	193.9	202.1

Stunning Effectiveness

Table - A 18: Stunning effectiveness for the dwell time with the most data points. Re-stun rate and 95% CI are given in percent. Confidence intervals are for one sided tests.

Condition	Dwell Time [s]	N	Re-stun rate [%]	95% CI
Argon	250	142	0	2.1
Local CO ₂ Control	180	106	0	2.8

Meat Quality

Carcass

After 45 min

Table - A 19: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 45 minutes postmortem for animals stunned under different conditions (argon and local CO₂) as well as the number of samples (N). The proportion of samples with a pH₄₅ below 6.1 (pH₄₅<6.1) or 5.8 (pH₄₅<5.8) and the temperature for the subset of samples where the pH₄₅ was below 6.1 (T(pH₄₅<6.1)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	pH	6.5	0.2	a	6.0	7.1	6.5	6.6	244
Local CO ₂ Control		6.6	0.2	b	6.1	7.1	6.6	6.7	246
Argon	T [°C]	36.6	1.4	a	29.8	40.2	36.4	36.8	244
Local CO ₂ Control		36.8	1.4	a	32.5	39.4	36.6	37.0	246
Argon	T(pH ₄₅ <6.1) [°C]	34.3	2.6	a	29.8	37.3	32.0	36.7	7
Local CO ₂ Control		34.6	0.4	a	34.3	34.9			2
Argon	pH<6.1 [%]	2.9		a			1.2	5.8	244
Local CO ₂ Control		0.8		a			0.1	2.9	246
Argon	pH<5.8 [%]	0.0		a			0.0	1.5	244
Local CO ₂ Control		0.0		a			0.0	1.5	246

After 24 h

Table - A 20: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 24 hours post-mortem for animals stunned under different conditions (argon and local CO₂) as well as the number of samples (N). The pH (24h) of the subset of samples with a pH₄₅ below 6.1 (pH₄₅<6.1) is shown as well. Results from statistical tests are indicated in the column * in compact

letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	pH	5.5	0.1	a	5.3	5.8	5.5	5.5	77
Local CO ₂ Control		5.5	0.1	a	5.3	5.9	5.5	5.5	79
Argon	pH(pH45<6.1)	5.5	0.2	a	5.3	5.7	5.3	5.7	6
Local CO ₂ Control		5.4	0.0	a	5.4	5.4			2
Argon	T [°C]	6.0	2.9	a	1.0	10.7	5.3	6.6	77
Local CO ₂ Control		6.3	3.0	a	0.9	10.4	5.7	7.0	79

Cut

Colour

Table - A 21: Mean, standard deviation (σ), minimum (Min). maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (L, L(pH45 < 6.1), a, b) measured for animals stunned under different conditions (argon and local CO₂) as well as the number of samples (N). The L value of the subset of samples with a pH below 6.1 L(pH45<6.1) is shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	L	53.9	3.5	a	46.0	65.8	53.0	54.8	60
Local CO ₂ Control		53.8	2.1	a	49.6	59.1	53.3	54.4	63
Argon	L(pH45<6.1)	53.3	5.1	a	46.0	59.8	46.9	59.6	5
Local CO ₂ Control		53.5	0.9	a	52.8	54.1			2
Argon	a	8.1	1.6	a	5.0	12.7	7.7	8.6	60
Local CO ₂ Control		8.6	1.4	a	4.7	11.5	8.2	8.9	63
Argon	b	11.6	1.0	a	8.9	13.9	11.4	11.9	60
Local CO ₂ Control		12.0	1.0	a	9.8	13.8	11.7	12.2	63

Drip Loss

Table - A 22: Mean, standard deviation (σ), minimum (Min). maximum (Max), 95% confidence interval (95% CI) of Drip Loss (%) measured for animals stunned under different conditions (argon and local CO₂) as well as the number of samples (N). Additionally, the drip loss of subset of samples with a pH45 below 6.1 Drip Loss(pH45<6.1) is shown.

Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	Drip Loss [%]	4.7	1.8	a	2.1	16.4	4.2	5.1	60
Local CO ₂ Control		4.5	0.9	a	2.6	7.2	4.2	4.7	63
Argon	Drip Loss (pH45<6.1) [%]	3.7	0.3	a	3.4	4.1	3.4	4.1	5
Local CO ₂ Control		4.0	0.1	a	4.0	4.1			2

Blood Spots

Table - A 23: Distribution of scored level of blood spots. Blood spots were scored as 0 = no blood spots, 1 = less than 5 blood spots, 2 = less than 30 blood spots, 3 = more than 30 blood spots. Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Blood Spots measured for animals stunned under different conditions (argon and local CO₂) and the number of samples (N). The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the blood spots levels and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters.

Condition	Level	Mean	σ	*	Min	Max	95% CI		N
Argon		0.4		a	0	3	0.3	0.6	124
Local CO ₂ Control		0.5		a	0	3	0.3	0.6	126
Argon	0 [%]	77.4					69.0	84.4	96
Local CO ₂ Control		74.6					66.1	81.9	94
Argon	1:<5 [%]	8.1					3.9	14.3	10
Local CO ₂ Control		11.1					6.2	17.9	14
Argon	2:<30 [%]	8.9					4.5	15.3	11
Local CO ₂ Control		8.7					4.4	15.1	
Argon	3:>30 [%]	5.6					2.3	11.3	7
Local CO ₂ Control		5.6					2.3	11.1	

Economic, environmental and social impact

Economic impact

The technical parameters for the Argon Retrofit system using dip-lift and paternoster system are reported in Table - A 24 and Table - A 25. Labour, and number of pigs slaughtered per hour was reported to be lower than the respective conventional CO₂ system. This resulted from the increase in exposure time as compared to the conventional system reported in D1. The dwell time (i.e. exposure time without travel time) for dip-lift at a stunning effectiveness of 99.5% was estimated at 250 s and travel time is 20 s. This represents an increase in 40% of the dwell/exposure time as compared to the conventional dip-lift system with CO₂.

The longer exposure time results in a reduction of both throughput and labour. The decrease in throughput was estimated to be around 40%. It must be noted that the increase in 40% of exposure time does not necessarily result in a reduction of throughput at the same rate. Additionally, the Argon Retrofit system with a paternoster system may have shorter exposure time than a dip-lift system. This is because O₂ levels might be lower at the lower stops as the pit would be deeper. This may result in slightly higher throughput for paternoster as compared to dip-lift systems. However, for simplicity, number of pigs per hour was estimated by reducing the throughput reported for the case study by 40%. In the case of the number of people, this was evaluated case by case.

Price estimation for argon is based on the availability of the gases themselves and the relative use as compared to other industries as well as the availability of other gases in the same country. The price for argon was estimated to be between 4 and 6 times more expensive than CO₂; here we use 5 times more. The higher cost is because it is relatively less accessible and extraction from the atmosphere is more complex than CO₂. The process is also very energy intensive.

When implementing the Argon Retrofit system in a conventional CO₂ stunning system, we explored two options. Option 1 (Table - A 24) reuses the available stunners and additional lines are included when appropriate. This means that the installation investment includes the adaptation for use with argon for all stunners and new stunners for the added lines. The cost for the added stunners was taken from the cost of installation investment reported by each case study. The cost for the adaptation of the stunners i.e. retrofit system was estimated to be 30. to 50. k€ by the relevant expert; we use 30 k€ as it would not be necessary to install a gas tank. Current cost for a new paternoster and dip-lift system was not possible to obtain. The experts estimated that the cost of a new paternoster system would be 1.200 k€. We chose to use the cost of installation investment reported by the study cases as these represent what was paid in a commercial setting. It has to be noted that the cost reported by CO₂-3 is low as the stunner is old i.e. 650.k€. When estimating later the cost per pig, the cost of installation investment and maintenance reported by the relevant case study in D1 was added i.e. the cost for the stunners already in place at the slaughterhouse.

In Table - A 24, two lines were added to the conventional dip-lift CO₂ system to reach their production level. The number of slaughter hours could be reduced from 17 to 15.86 hours. For the paternoster systems one additional line was added to reach the production level. Slaughter hours were reduced by 4.8 and 3.72 hours for CO₂-3 and CO₂-4. This was not possible for CO₂-1 were the working hour had to be increased by 1.86 h.

Table - A 24: Technical and cost parameters of the alternative being implemented in the relevant study cases. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system; and CO₂-2: using dip-lift system. Cells in red show values that are from the alternative system itself.

Technical and cost parameters	Argon retrofit system (Dip-lift) *	Argon retrofit system (paternoster)*		
	CO ₂ -2**	CO ₂ -1***	CO ₂ -3***	CO ₂ -4***

Labor used in the pre-stunning and stunning process, per day	126.9	156.8	56	52.1
Water for cleaning (m ³ /day)	12	195	6	130
Electricity for stunning (kWatt/day)	171.9	247.5	424	1,282.9
Gas for stunning (tonnes argon/day)	11.205	5.865	7.2	4.24
Pigs per hour ¹	723	921	821	621
Hours of slaughter per day	15.8	13.1	11.2	8.68
Days with slaughter per year	240	250	254	252
Proportion of pigs discarded due to meat quality	0	0	5	0
Number of people	8	12	5	6
Number of lines per system	6	3	2	2
Number of gondolas/stunners per line		6	6	6
Depreciation period yr	10	10	10	10
Maintenance - % of installation costs	12.86	8	11	7.6
Labour cost/hour €	30	38	35	20
Gas price (€ per Tonnes) ²	931.97	1,750.00	680	1,350
Electricity price (€ per kWatt)	0.125	0.183	0.1129	0.24
Water costs (€/m ³)	4.5	4.5	1.25	4.46
Cost per pig discarded due to meat quality	100	100	100	100
Installation investment ³	1,160,000	530,000	710,000	1,760,000
Maintenance - % of installation costs	12.9	8	11	7.6

**The alternative system is implemented in a conventional CO2 dip-lift and paternoster system. It is possible to adapt current stunners to the new system. Hence, it is not necessary to invest in new stunners unless more lines are needed. The installation investment and maintenance cost of the old system is obtained from D1 and therefore not calculated here again. This will later be added to the cost per pig.*

***A better solution may be to replace the dip-lift system by a paternoster system*

****A better solution may be to install a paternoster system with more gondolas that will compensate the reduced throughput (see Table - A 25)*

1The assumption is that an increase in 40% of exposure time for the Argon Retrofit system as compared to the conventional CO2 systems results in a reduction in throughput at the same rate. Values are based on numbers reported for the study cases.

2The price for argon was estimated to be 4 to 6 times the price for CO2 by an expert. Here we use 5 times more.

3Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. In this case, this includes the cost of stunners for the added lines and cost of the retrofit system for each line. The cost of stunners used here are obtained from the study cases.

Option 2 (Table - A 25) is the installation of a new paternoster system that will compensate for the loss in throughput. The system lead suggested that the cost of the stunner would increase by 40% as compared to

the conventional paternoster system installed in the study case. It has to be noted that the amount of resources used e.g. water, gas and electricity were maintained same as for Table - A 24. System lead advised that there should be an increase in the amount of resources used, however, this may be low.

Table - A 25: Technical and cost parameters of the alternative being implemented in the relevant study cases when using a new paternoster system that will compensate for the loss in throughput. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system. Cells in red show values that are from the alternative system itself.

Technical and cost parameters	Argon Retrofit system (paternoster)*		
	CO ₂ -1	CO ₂ -3	CO ₂ -4
Labor used in the pre-stunning and stunning process, per day	140	64	62
Water for cleaning (m ³ /day)	130	3	65
Electricity for stunning (kWatt/day)	165	212	641.4
Gas for stunning (tonnes argon/day)	3.91	3.6	2.11
Pigs per hour ¹	860	575	435
Hours of slaughter per day	14	16	12.4
Days with slaughter per year	250	254	252
Proportion of pigs discarded due to meat quality	0	5	0
Number of people	10	4	5
Number of lines per system	2	1	1
Number of gondolas/stunners per line	6	6	6
Depreciation period yr	8	11	7.6
Maintenance - % of installation costs	38	35	20
Labour cost/hour €	1,400	544	1,080
Gas price (€ per Tonnes)	0.18	0.11	0.24
Electricity price (€ per kWatt)	4.5	1.25	4.46
Water costs (€/m ³)	100	100	9.2
Cost per pig discarded due to meat quality	100	100	9.2
Installation investment ²	3,056,000	940,000	2,410,000
Maintenance - % of installation costs	8	11	7.6

*The alternative system is implemented in a conventional CO₂ paternoster system.

¹ The assumption is that an increase in 40% of exposure time for the Argon Retrofit system as compared to the conventional system results in a reduction in throughput at the same rate. Values are based on numbers reported for the study cases.

² Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. In this case, this includes the cost of the new stunners (that will compensate for the reduced throughput) and the retrofit

system per line. The cost of stunners used here is the cost of installation investment reported for the study cases in D1 increased by 40%.

Environmental impact

Efficiency and resource use

According to the representative of the Argon Retrofit System, it was estimated that there would be no change in water resources, amount of wastewater, energy use (electricity, diesel, gas, etc.), or disinfectant compared with the Carbon dioxide stunner. The gas for stunning was predicted to be similar to the carbon dioxide stunner as well. Additionally, the dwell time for 99,5 % stunning effectiveness was estimated by the representative of the Argon Retrofit system to be about 270 seconds for the argon Dip-lift. The dwell time was approximately 40% longer than required for stunning with CO₂. The numbers were determined by using a systematic optimization routine, where the dwell time was altered depending on the previous stun results, and a statistical model was used to determine the necessary exposure time. For the paternoster system, the exposure time will likely be a little shorter and stunning efficiency a little higher, caused by lower levels of residual oxygen that can be reached in this system. The stun-to-stick time is unchanged compared to the CO₂ systems. Argon is heavier than air. Therefore, systems that currently use where CO₂, do not need to be redesigned substantially as long as the system can cope with the reduced capacity.

Availability of Argon

The information on the availability of argon was collected by sending emails to a contact person from Air Liquide (company selling gas).

Argon makes up 0.93% of the earth's atmosphere and thus is more abundant than helium in the atmosphere. It is relatively easy to obtain and is typically produced as a byproduct in air separation plants, which are widespread and use well-established processes (Air Liquide). Argon is used for several purposes such as welding, lighting, preservation of historical documents, and more. The supply is stable and consistent, making argon relatively easy and affordable. Argon is not, like helium, prioritized to the medical industry, and the safety of the supply is therefore higher. There are 5-10 companies worldwide that operate internationally and have sufficient supply of argon. In some cases, local companies can supply argon as well.

In terms of economics, argon is currently estimated to be 4-5 times more expensive than carbon dioxide, when purchased in Europe. The price can differ greatly from country to country and is also highly affected by energy and transportation cost. Recovery systems for argon would be theoretically possible, however, when stunning with argon, very high purities are needed, and can only be achieved with cryogenic treatment (production in very low temperatures). Therefore, recovery of argon seems more complex and expensive than recovery systems for CO₂. Also, recovery might not be economically viable due to the relatively low price of argon (under current circumstances).

Social impact

In terms of the risk of work accidents and toxic levels of argon, it is not expected to make any change when using argon compared to carbon dioxide. It was stated that argon should be at least as safe as carbon dioxide. Another advantage of the inert gas argon is that it will only pose a risk when present in high concentrations and O₂ is lower than 19.5% (EU-OSHA, 2016). The amount of potential hazardous actions, such as shackling, sticking, and standing close to the stunner will potentially be spread over a longer time, as the exposure time is longer for argon. However, the risk per animal going through the stunner will be the same. The noise level between the Argon Retrofit system and the conventional carbon dioxide system is not expected to change. Whether the labour time in the Argon Retrofit system is changed compared with the conventional carbon dioxide system, will depend on how the longer exposure time will be handled. It can be handled in several ways such as longer slaughter days or an extension of the current stunner system

so that the capacity of the animals becomes higher, for example larger gondolas and deeper pits. However, when adding additional shifts, the increase in hours a single person works has not been estimated.

Ease of conversion

An existing CO₂ Dip-Lift or paternoster CO₂ stunner can be modified to use argon instead of CO₂. If the gas is replaced one to one in the system, there will be no need to alter the lairage or the driveway towards the stunner or the sticking area after. For slaughterhouses with a Dip-Lift or Paternoster System to switch to this method, the Argon Retrofit System must be installed inside the pit of the stunner. This can likely be achieved in a single day. Additionally, the control unit (alarms for inadequate gas atmospheres and regulation of gas flow) for the Dip-Lift System may have to be adjusted for the use of Argon and control by residual oxygen content. For the easiest user experience with only limited necessary changes, cooperation from the manufacturer of the Dip-Lift System would be highly beneficial. This would also ensure storage of relevant data in a single system. Without this cooperation, the controls for the gas atmosphere (based on CO₂-sensors) would either have to be disabled in the old Dip-Lift System and replaced by a separate solution, or the sensor input to the existing Dip-Lift control would have to be reverse engineered to allow handling of residual oxygen sensors. Again, these changes should be possible to implement in a single day and could be implemented to allow easily switching back to unchanged CO₂ stunning if desired. After these changes, the stunner is ready to be used with Argon or other inert gas mixtures. If installing the systems takes more than one day, the old system can still be used. As such, no downtime should occur for the installation of the system. In addition, the CO₂ tank will have to be replaced or supplemented by an Argon tank.

However, this approach will result in a loss in capacity due to the increased necessary exposure time in the gas using argon instead of CO₂. Keeping high capacity then creates a need to expand, depending on how you choose to handle this capacity loss. As is the case for helium as well. One way to compensate for some of the lost capacity could be to extend working hours. In case of an existing Dip-Lift, it is assumed that the preferred way of expanding would be by adding a second stunner. For a paternoster system, two viable options exist. It is possible to either add an additional retrofitted CO₂ stunner or replace the entire stunner with a larger model to make up for the decreased capacity. Adding a new stunner enables the old one to perform at virtually zero downtime during installation, while replacing the existing stunner with a larger one might not require a building permit.

Estimated cost of a high throughput system

The Argon Retrofit System offers a throughput of 420 pigs per hour with a paternoster system, which translates to the need for two stunners to achieve a throughput of 840 pigs per hour. Each stunner is estimated to be retrofitted at around 30 k€, resulting in a total equipment estimated cost of 60 k€ for the necessary retrofitting to two existing paternoster stunners to perform high throughput at >600 pigs/hour. Though if the slaughterhouse uses an incompatible stunner or previously only used a single paternoster stunner, an additional paternoster stunner is needed, which is estimated at 1,200k€. There is a high likelihood the Argon Retrofit system will take up more space, but these costs were not possible to estimate by the manufacturer. The total cost of around 1,260k€ in total for retrofitting two paternoster stunners highlights the potential of converting at a relatively low expense, though with additional complexity depending on the throughput of the slaughterhouse.

Strengths, weaknesses and feasibility

Main Strengths

- Existing infrastructure can be retrofitted with relative ease
- Modifications can be completed within a few days
- Argon is easily available, similar CO₂

- The system can be fitted to use other heavy gasses as well
- Argon stunning is already legal

Main Weaknesses

- Increased exposure time lowers throughput per stunner
- To achieve similar capacity an additional or a larger stunner is most likely needed
- Retrofitting could be complex depending on the design of the existing stunner, especially incompatibility between manufacturers could prove to be difficult
- Argon is 4-5 times more expensive than CO₂

How does the Cost of Conversion Make the Alternative More or Less Feasible

The relative low cost of 1,200k€ for converting to an inert gas based stunning system impacts the feasibility to the better. The main drawback is the lower capacity per stunner leading to the requirement of some facilities to invest in a second stunner or a deeper pit for paternoster systems. The high throughput retrofit system offers the potential to convert without requiring new stunners.

Helium

Please see the Introduction to this appendix and the Appendix B: Analysis Methods section for details on the display format and methods.

Animal collective and stunning parameters

Animal Genetics

Animals had one of the following genetics: DL x Pi, DE x DL, [DL x DE] x Pi, DL or DE x Du for animals stunned with Helium and DL x Pi, [DL x DE] x Pi or DL for animals stunned with CO₂.

Animal sex and average weight

Table - A 26: Average sex and slaughter weight from five days of data collection.

Condition	Female [%]	Castrated male [%]	Weight [kg]
Helium	48	52	108.0
Local CO ₂ Control	55	45	93.3

Gas Concentrations

Table - A 27: Residual oxygen content for two sensors when the gondola reached its top position (start) and when the gondola began to move down again (end). The mean oxygen concentration and standard deviation (σ) was calculated across all gondolas. Information about the mean concentration while the gondola is at the top position is not available. Data for the CO₂ control condition is not available

Condition	Time	Sensor A [%]		Sensor B [%]	
		Mean	σ	Mean	σ
Helium	Start	0.63	0.21	0.78	0.13
	End	0.71	0.19	0.80	0.06

Animal welfare

Pre-Stunning Handling

Arrival & Moving to Lairage

Table - A 28: Proportion of animals that were slipping and falling or showing high pitched vocalisation during arrival and moving to lairage. The extent of human stimulation was recorded as gentle, moderate (moderate sound or occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

	Arrival			Moving to Lairage		
Animals [N]	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation
28	0.04	0.00	gentle	0	0.04	gentle

Lairage

Table - A 29: Proportion of animals that were standing sitting or lying. Additionally, the proportion of fighting and mounting animals was recorded. Recordings were done every 10 minutes for 2 minutes.

		Body Position			Aversive Interactions	
Time of Observation [min]	Animals [N]	Standing [%]	Sitting [%]	Lying [%]	Fighting [%]	Mounting [%]
10	22	0.18	0.05	0.77	0	NA
20	22	0.36	0.18	0.45	0	NA
30	22	0.36	0.23	0.41	0	NA
40	22	0.41	0.18	0.41	0	NA
50	22	0.73	0.00	0.27	0	NA
60	22	0.59	0.09	0.32	0	NA

Moving and Entrance to Stunner

The behaviour of the pigs during the moving to the stunner and the entrance into the stunner was not recorded.

Video Analysis

Entering

Video analysis from the Helium System was limited to one or two selected animals per gondola. Additionally, in the Helium system, for behaviours relating to the Entering phase, only the first pig showing a given behaviour was taken into consideration. For cases where two animals were coded in a gondola, it was

assumed for analysis that both animals coded for that gondola exhibited the behaviour observed in the first pig.

Entering Overview

Table - A 30: Distribution of the maximum (strongest) scored level per animal for entering the stunning device. The levels were scored as 0 = none, 1 = reluctance to move, 2 = aversive physical contact, 3 = painful physical contact, 4 = lasting painful physical contact. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the strongest (maximum) scored level for entering of the stunner and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and the number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	*	Min	Max	95% CI		N
Max Score	Local CO ₂ Control		1.8	a	0	3	1.4	2.1	35
		0	11.4				3.2	26.7	4
		1	31.4				16.9	49.3	11
		2	25.7				12.5	43.3	9
		3	31.4				16.9	49.3	11
		4	0.0				0.0	10.0	0
	Helium		1.4	a	0	4	1.2	1.7	169
		0	56.2				48.4	63.8	95
		1	0.0				0.0	2.2	0
		2	0.0				0.0	2.2	0
		3	34.3				27.2	42.0	58
		4	9.5				5.5	14.9	16

First reluctance to move

Table - A 31: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence (95% CI) of the observed time until the first reluctance to move relative to the start of the ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first reluctance to move occurred before the start of the ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	-77.0	22.4		-101.4	-53.9	-92.1	-61.9	11
	Helium								0
Proportion [%]	Local CO ₂ Control	31.4		b			16.9	49.3	35
	Helium	0.0		a			0.0	2.2	169

First aversive physical contact

Table - A 32: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first aversive physical contact relative to the start of the ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first aversive physical contact occurred before the start of the ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	-43.2	29.2		-66.9	-4.6	-65.6	-20.8	9
	Helium								0
Proportion [%]	Local CO ₂ Control	25.7		b			12.5	43.3	35
	Helium	0.0		a			0.0	2.2	169

First painful physical contact

Table - A 33: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first painful physical contact relative to the start of the ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first painful physical contact occurred before the start of the ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	-48.4	41.3	a	-88.1	-2.1	-76.1	-20.6	11
	Helium	-29.0	42.0	a	-218.3	-0.5	-40.0	-18.0	58
Proportion [%]	Local CO ₂ Control	31.4		a			16.9	49.3	35
	Helium	34.3		a			27.2	42.0	169

First lasting painful physical contact

Table - A 34: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first lasting painful physical contact relative to the start of the ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the lasting painful physical contact occurred before the start of the ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control								0

	Helium	-36.9	42.6		-145.8	-1.2	-59.6	-14.2	16
Proportion [%]	Local CO ₂ Control	0.0		a			0.0	10.0	35
	Helium	9.5		a			5.5	14.9	169

Initial reaction

Initial Reaction Overview

Table - A 35: Distribution of the maximum (strongest) scored level per animal for the reaction to the gas atmosphere in the induction phase. The levels were scored as 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of these strongest (maximum) scored initial reaction and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level.

	Condition	Level	Mean	σ	Min	Max	95% CI		N
Max Score	Local CO ₂ Control		1.9		1	3	1.6	2.1	35
		0 [%]	0.0				0.0	10.0	0
		1 [%]	20.0				8.4	36.9	7
		2 [%]	71.4				53.7	85.4	25
		3 [%]	8.6				1.8	23.1	3
	Helium		0.4		0	1	0.3	0.5	169
		0 [%]	58.6				50.8	66.1	99
		1 [%]	41.4				33.9	49.2	70
		2 [%]	0.0				0.0	2.2	0
		3 [%]	0.0				0.0	2.2	0

First response to atmosphere

Table - A 36: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first response to the atmosphere, relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first response to the atmosphere occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	21.2	0.2	a	21.1	21.4	21.1	21.4	7
	Helium	40.2	0.9	b	37.7	42.4	40.0	40.5	70
Loss of posture [s]	Local CO ₂ Control	-2.7	3.7	a	-10.5	0.7	-6.1	0.7	7

	Helium	-6.1	5.9	a	-19.1	6.8	-7.5	-4.6	70
Proportion [%]	Local CO ₂ Control	20.0		a			8.4	36.9	35
	Helium	41.4		b			33.9	49.2	169

First agitation

Table - A 37: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first agitation, relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal, either relative to the start of the ascend of the gondola (top) and the relative to the time of loss of postures (bottom). Negative values indicate that the first agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown in percent. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	21.5	0.8		20.1	22.8	21.2	21.9	25
	Helium								0
Loss of posture [s]	Local CO ₂ Control	-3.5	4.3		-9.9	3.8	-5.2	-1.7	25
	Helium								0
Proportion [%]	Local CO ₂ Control	71.4		b			53.7	85.4	35
	Helium	0.0		a			0.0	2.2	169

First strong agitation

Table - A 38: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first strong agitation relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first strong agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	26.7	0.0		26.7	26.7			3
	Helium								0
Loss of posture [s]	Local CO ₂ Control	4.4	3.3		0.6	6.5	-3.9	12.7	3
	Helium								0

Proportion [%]	Local CO ₂ Control	8.6		b			1.8	23.1	35
	Helium	0.0		a			0.0	2.2	169

First abnormal breathing

Table - A 39: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first abnormal breathing, relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first abnormal breathing occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	22.5			22.5	22.5			1
	Helium								0
Loss of posture [s]	Local CO ₂ Control	-4.4			-4.4	-4.4			1
	Helium								0
Proportion [%]	Local CO ₂ Control	2.9		a			0.1	14.9	35
	Helium	0.0		a			0.0	2.2	169

Stunning progress

Loss of posture

Table - A 40: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the loss of posture relative to the start of the ascend of the gondola, calculated from the results of each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	24.5	4.4	a	17.2	31.6	23.0	26.0	35
	Helium	49.4	6.6	b	32.3	68.1	48.3	50.4	169

Lying

Table - A 41: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until lying, relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
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Start ascend	Local CO ₂ Control	75.4	37.0	a	31.5	146.7	62.7	88.1	35
	Helium	74.7	7.2	a	51.1	99.6	73.6	75.8	169
Loss posture of	Local CO ₂ Control	50.9	37.8	b	4.6	118.2	37.9	63.9	35
	Helium	25.3	6.5	a	10.3	42.5	24.3	26.3	169

Last movement

Table - A 42: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the last movement, relative either to the start of the ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	137.1	8.9	a	106.0	148.3	134.0	140.2	35
	Helium	182.3	27.0	b	80.0	259.4	178.2	186.4	169
Loss posture of [s]	Local CO ₂ Control	112.6	9.3	a	85.0	128.8	109.4	115.8	35
	Helium	132.9	26.5	b	44.5	209.1	128.9	137.0	169

Cycle duration

Table - A 43: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the cycle duration relative to the start of the ascend of the gondola. Note that this is an operational parameter reflective of the set stunning times. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start ascend [s]	Local CO ₂ Control	148.2	0.8	a	146.7	149.7	147.9	148.4	35
	Helium	262.5	5.5	b	255.0	304.8	261.7	263.3	169

Stunning Effectiveness

Table - A 44: Stunning effectiveness the Helium system and a local CO₂ control. Dwell time (s) for CO₂ is estimated based on the video analysis. Re-stun rate and 95% CI are given in percent. Confidence intervals are for one sided tests.

Condition	Dwell Time [s]	N	Re-stun rate [%]	95% CI
Local CO ₂ Control	120	35	0.0	8.2
Helium	200	167	1.2	3.8

Meat Quality

Carcass

After 45 min

Table - A 45: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 45 minutes post mortem for animals stunned under different conditions (helium and local CO₂) as well as the number of samples (N). The proportion of samples with a pH₄₅ below 6.1 (pH₄₅<6.1) or 5.8 (pH₄₅<5.8) and the temperature for the subset of samples where the pH₄₅ was below 6.1 (T(pH₄₅<6.1)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Local CO ₂ Control	pH	6.5	0.2	b	5.9	6.9	6.4	6.5	35
Helium		6.3	0.2	a	5.9	6.8	6.2	6.4	50
Local CO ₂ Control	T [°C]	40.0	0.6	b	38.6	41.7	39.7	40.2	35
Helium		39.4	0.5	a	38.2	40.3	39.3	39.6	50
Local CO ₂ Control	T(pH ₄₅ <6.1) [°C]	41.0	0.8	b	40.2	41.7	39.1	42.8	3
Helium		39.5	0.5	a	38.9	40.2	39.2	39.9	11
Local CO ₂ Control	pH<6.1 [%]	8.6		a			1.8	23.1	35
Helium		22.0		a			11.5	36.0	50
Local CO ₂ Control	pH<5.8 [%]	0.0		a			0.0	10.0	35
Helium		0.0		a			0.0	7.1	50

After 24 h

Table - A 46: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 24 hours post mortem for animals stunned under different conditions (helium and local CO₂) as well as the number of samples (N). The pH (24h) of the subset of samples with a pH₄₅ below 6.1 (pH₄₅<6.1) is shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
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Local CO ₂ Control	pH	5.5	0.2	a	5.3	6.1	5.5	5.6	35
Helium		5.5	0.1	a	5.3	5.8	5.5	5.5	50
Local CO ₂ Control	pH(pH45<6.1)	5.5	0.1	a	5.3	5.6	5.1	5.9	3
Helium		5.5	0.1	a	5.4	5.8	5.4	5.6	11
Local CO ₂ Control	T [°C]	4.2	0.6	a	2.9	5.3	4.0	4.4	35
Helium		5.5	1.2	b	3.8	8.0	5.2	5.9	50

Cut

Colour

Table - A 47: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (L, L(pH45 < 6.1), a, b) measured for animals stunned under different conditions (helium and local CO₂) as well as the number of samples (N). The L value of the subset of samples with a pH below 6.1 (L(pH45<6.1)) is shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Local CO ₂ Control	L	47.3	3.5	a	31.4	51.1	46.1	48.5	35
Helium		58.6	3.1	b	50.8	66.8	57.7	59.4	50
Local CO ₂ Control	L(pH45<6.1)	47.9	0.8	a	47.2	48.8	45.9	49.9	3
Helium		60.2	3.1	b	56.9	66.8	58.1	62.2	11
Local CO ₂ Control	a	12.6	2.0	b	9.5	18.4	11.9	13.3	35
Helium		1.3	1.3	a	-0.9	4.5	0.9	1.7	50
Local CO ₂ Control	b	5.7	1.0	a	3.5	8.0	5.3	6.0	35
Helium		12.3	1.2	b	10.2	15.0	12.0	12.7	50

Drip Loss

Table - A 48: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Drip Loss (%) measured for animals stunned under different conditions (helium and local CO₂) as well as the number of samples (N). Additionally, the drip loss of the subset of samples with a pH45 below 6.1 (Drip Loss(pH45<6.1)) is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Local CO ₂ Control	Drip Loss [%]	2.6	1.4	a	0.4	7.8	2.1	3.1	35
Helium		3.7	2.8	b	0.0	10.0	2.9	4.5	50
Local CO ₂ Control	Drip Loss (pH45<6.1) [%]	4.0	0.4	a	3.6	4.4	3.0	4.9	3
Helium		4.6	2.6	a	0.8	8.9	2.9	6.4	11

Blood Spots

Table - A 49: Distribution of scored level of blood spots. Blood spots were scored as 0 = no blood spots, 1 = less than 5 blood spots, 2 = less than 30 blood spots, 3 = more than 30 blood spots. Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Blood Spots measured for animals stunned under different conditions (helium and local CO₂) and the number of samples (N). The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the blood spots levels and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence (95% CI) interval and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters.

Condition	Level	Mean	σ	*	Min	Max	95% CI		N
Local CO ₂ Control		0.0		b	0	0	0.0	0.2	35
Helium		0.5		a	0	3	0.3	0.8	50
Local CO ₂ Control	0 [%]	100.0					90.0	100.0	35
Helium		68.0					53.3	80.5	34
Local CO ₂ Control	1:<5 [%]	0.0					0.0	10.0	0
Helium		16.0					7.2	29.1	8
Local CO ₂ Control	2:<30 [%]	0.0					0.0	10.0	0
Helium		14.0					5.8	26.7	7

Local CO ₂ Control	3:>30 [%]	0.0					0.0	10.0	0
Helium		2.0					0.1	10.6	1

Economic, environmental and social impact

Economic impact

The technical and cost parameters for the Helium Stunning system implemented in the relevant study case are reported in Table - A 50 and Table - A 51. Price estimation for helium is based on the availability of the gas itself and the relative use as compared to other industries as well as the availability of other gases in the same country. The price for helium was estimated to be between 80 to 100 times more expensive than CO₂. This is because of its low availability and very few companies/countries currently extracting the gas. This results in its actual availability and price be highly influenced by political crisis. Here we use 90 times more.

The amount of helium used daily is not available at the moment. The estimation reported in Table - A 50 and Table - A 51 is calculated on the basis of the total capacity of the tower and the percentage of helium recovered daily. The tower has the capacity for 9m³ of helium and recovers 90%. At a temperature of 15 °C the weight of this volume is 1.49 x 10⁻⁴ tonnes. The initial fill of the system would use 0.00015 tonnes per stunner and the system would use 1.49 x 10⁻⁵ tonnes per day per stunner. The calculation of cost per pig includes the cost of the initial fill once and the cost of gas used daily. It was assumed that each tower/line would need to be filled initially. The cost of maintenance is unknown.

The current pilot system can slaughter 50 pigs per hour per stunner (5 pigs/gondola). The lower rate is due to the longer exposure time as compared to CO₂ systems (200 s vs 100 s). Additionally, the lower rate is explained by the low speed of transport of the gondola and the robot leading the pigs into the stunner. Experts are confident that this process could be optimized and potentially achieve 90 pigs per hour per stunner. Additionally, the capacity of the system may be possible to increase even more by doubling the size of the gondola. Therefore, the estimation of the technical and cost parameters is calculated for a throughput of 90 and 180 pigs per hour (Table - A 50 and Table - A 51, respectively). However, it has to be noted that the doubling the size of the gondola to increase the capacity has not yet been tested.

This system is comparable to functioning of a conventional dip-lift system i.e. uses a single gondola that goes up instead of down to a pit ('reversed dip-lift' hereafter). The experts recommended that this system is thought not to be feasible with a system comparable to a paternoster arrangement with multiple gondolas going up and down and replacing the paternoster stunner with reversed helium dip-lift system is diffculted by space limitations. With the possible space limitations in mind, here the technical and cost parameters when replacing the paternoster system by a reversed dip-lift system (for case studies with current paternoster system) are reported.

For the helium stunning system to be installed in a functioning slaughterhouse it has to be installed from scratch. Therefore, the installation investment corresponds to the cost of the helium equipment and none of the current equipment can be re-used. The cost estimated by the system leads is 1,300k€ which is the cost for the whole project for one line. The cost for extra lines will be lower as some of the items are not a function of the number of lines. The difference is unknown at the moment. Hence, here we multiplied this cost by the number of lines for both Table - A 50 and Table - A 51. The cost for a larger gondola is likely to be higher but this is unknown.

Table - A 50 reports the technical and cost parameters for the helium stunning system considering a regular gondola size with a capacity for 5 pigs. The throughput under these circumstances is 90 pig per hour per stunner. This is a more conservative scenario than the one presented in Table - A 51. To reach the target production level of the old system, the number of lines had to be increased. Study cases with a conventional CO₂ stunning system using paternoster system (CO₂-1, 3 and 4) would need to increase the number of lines by four times. Conventional CO₂ stunning system with dip-lift system (CO₂-2) would need to double the amount of current lines. To reach the same target production, a reduction of slaughter hours was needed for CO₂-1, 2 and 3 (0.62, 1.06 and 3.22 slaughter hours less per day, respectively) and 2.58 hours would have to be added daily for CO₂-4.

Table - A 50: Technical and cost parameters of the alternative being implemented in the relevant study cases. This considers a more conservative throughput of 90 pigs per hour per stunner. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system; and CO₂-2: using dip-lift system. Cells in red show values that are from the alternative system itself.

Technical and cost parameters	Helium stunning system			
	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4
Labor used in the pre-stunning and stunning process, per day	428.096	414.388	332.228	209.762
Water for cleaning (m ³ /day)	108.33	16	4	43.33
Electricity for stunning (kWatt/day)	137.5	229.2	282.67	427.62
Gas for stunning (tonnes helium/day)	0.00015	0.00012	0.00012	5.98E-05
Gas for initial fill (tonnes CO ₂ /day)	0.0015	0.0012	0.0012	0.0006
Pigs per hour	900	720	720	360
Hours of slaughter per day**	13.38	15.94	12.78	14.98
Days with slaughter per year**	250	240	254	252
Proportion of pigs discarded due to meat quality	0	0	5	0
Number of people	32	26	26	14
Number of lines per system	10	8	8	4
Number of gondolas/stunners per line				
Depreciation period yr	10	10	10	10
Maintenance - % of installation costs	8	12.86	11	7.65
Labour cost/hour €	38	30	35	20
Gas price (€ per Tonnes) ¹	31,500	16,775	12,240	24,300
Electricity price (€ per kWatt)	0.183	0.125	0.113	0.24
Water costs (€/m ³)	4.5	4.5	1.25	4.46
Cost per pig discarded due to meat quality	100	100	100	9.2

Installation investment ²	1,300,000	10,400,000	10,400,000	5,200,000
Maintenance - % of installation costs	Unknown	Unknown	Unknown	Unknown

**The alternative system is implemented in all conventional CO₂ systems. For this alternative it is not possible to adapt the current stunners and needs to be installed from the scratch. This means that the cost per pig does not include the installation investment of the study cases.*

***Experts have suggested that the helium stunning system might most likely not be able to be implemented in a paternoster system because it is not possible to build a reversed paternoster system i.e. multiple gondolas going up instead of down into a pit, and therefore too many lines would be needed, and space limitations might be a problem.*

¹ *The price for helium was estimated to be 80 to 100 times the price for CO₂ by an expert. Here we use 90 times more.*

² *Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. The project cost for one line is 1300k€ including alarms, sensors, screens and stunners among other things. The cost of the project considering a bigger gondola is likely to be higher, as well as the cost for additional lines might be lower since some of the items included in the total are not a function of the number of lines. Here we use 1300k€ per line since the actual cost is unknown.*

Table - A 51 reports the technical and cost parameters considering a throughput of 180 pigs per pig per stunner. The dip-lift system (CO₂-2) was able to cope with the same number of lines as compared to the previous stunning system in place. Number of slaughter hours were reduced from 17 to 15.94 h. For the paternoster system more lines had to be added in all study cases (CO₂-1 and CO₂-3: +3 lines; and CO₂-4: +1 line). However, labour time was reduced for CO₂-1 and CO₂-3 by 0.62 and 3.22 hours. CO₂-4 would need to increase labour hours by 2.58 h.

Table - A 51: Technical and cost parameters of the alternative being implemented in the relevant study cases. This calculation considers a less conservative throughput of 180 pigs per hour per stunner. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with conventional CO₂ stunning system using a paternoster system; and CO₂-2: using a dip-lift system. Cells in red show values that are from the alternative system itself.

Technical and cost parameters	Helium stunning system*			
	CO ₂ -1**	CO ₂ -2	CO ₂ -3**	CO ₂ -4**
Labor used in the pre-stunning and stunning process, per day	227.43	223.13	178.89	119.87
Water for cleaning (m ³ /day)	54.17	8	2	21.6
Electricity for stunning (kWatt/day)	68.75	114.6	141.33	213.81
Gas for stunning (tonnes helium/day)	0.00007479	0.000059832	0.00005983	0.00002991
Gas for initial fill (tonnes helium/day)	0.000748	0.000598	0.000598	0.000299
Pigs per hour	900	720	720	360
Hours of slaughter per day	13.38	15.94	12.78	14.98
Days with slaughter per year	250	240	254	252
Proportion of pigs discarded due to meat quality	0	0	5	0
Number of people ^{1,2}	17	14	14	8
Number of lines per system	5	4	4	2
Number of gondolas/stunners per line				
Depreciation period yr	10	10	10	10

Maintenance - % of installation costs	8	12.86	11	7.65
Labour cost/hour €	38	30	35	20
Gas price (€ per Tonnes) ¹	31,500	16,775	12,240	24,300
Electricity price (€ per kWatt)	0.183	0.125	0.1129	0.24
Water costs (€/m ³)	4.5	4.5	1.25	4.46
Cost per pig discarded due to meat quality	100	100	100	100
Installation investment ²	6,500,000	5,200,000	5,200,000	2,600,000
Maintenance - % of installation costs	Unknown	Unknown	Unknown	Unknown

**The alternative system is implemented in all conventional CO₂ systems. For this alternative it is not possible to adapt the current stunners and needs to be installed from the scratch. This means that the cost per pig does not include the installation investment of the study cases.*

***Experts have suggested that the helium stunning system might most likely not be able to be implemented in a paternoster system because it is not possible to build a reversed paternoster system and therefore too many lines would be needed, and space limitations might be a problem.*

¹The price for helium was estimated to be 80 to 100 times the price for CO₂ by an expert. Here we use 90 times more.

²Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. The project cost for one line is 1,300k€ including alarms, sensors, screens, software development to operate the system, robot with software implementation, and stunners among other things. The cost for additional lines might be lower since some of the items included in the total are not a function of the number of lines. Since this is unknown, here we multiple the cost by the number of lines.

Environmental impact

Efficiency and resource use

According to the representative for the Helium System, information on disinfectant use, wastewater treatment, and energy consumption, could not be obtained. This was due to other stunning methods running simultaneously, making it impossible to isolate and attribute these factors to one single method. The water use was estimated to be higher in the current helium system compared to a high-concentration CO₂ system. This was caused by the setting using the bleeding belt. The water use is estimated to be the same if the pigs are bled in a hanging position.

The gas for stunning per day and the calculated amount per pig, differed each day and could vary between 633 L/pig to 794 L/pig. The first time the tower was filled, 9,00 ccm of helium was needed for the first filling of the gas chamber. During the day, a refill with helium will happen automatically when the residual oxygen level in the lowest sensor becomes higher than 0,7 %. The supply during the day will be affected by different factors such as the weather etc. At the end of the day, 90% of the helium in the tower is recovered and stored in big tanks and will be used for the first filling the next time.

The dwell time were 200 seconds, which is longer than stunning with CO₂. The pigs per hour being led through the system was on average 50 pigs per hour, but a maximum of 90 pigs per hour seems feasible according to the representative of the alternative. In Deliverable 3 it is stated that this is a reduction in throughput and will be an option for small and medium slaughterhouses. Nevertheless, some actions can be done to counteract the slower throughput, which is described in Deliverable 3. The stun-to-stick time differed, but the average time for 5 animals was 25 s. This is lower than the 45-95 seconds observed in the high-concentration CO₂ slaughterhouses described in PigStun deliverable 2.

Availability of Helium

The information on the availability of helium was collected by sending emails to a contact person from Air Liquide. Helium is a scarce resource, making up only 0,00052 % of the atmosphere, and helium production is limited to only a few regions (Siddhantakar et al., 2023). These include The United States, Qatar, and Algeria. The most common way to obtain Helium is by extraction from natural gas using cryogenic distillation. Therefore, acquiring helium can be challenging due to the complexity of the extraction and purification process, as well as the limited resources. The demand for helium is high due to use for several purposes, such as Magnetic resonance imaging machines used for medical images, welding, and more. The high demand for helium and the limited supply makes it highly susceptible to shortages or supply bottlenecks, which can lead to higher prices and reduced availability. Additionally, prices can be influenced by the political landscape, as sources are only in a few countries. Another aspect is that the supply to the medical industry and other selected customers is prioritized, and therefore industrial customers may experience insufficient supply during certain periods. There are 5-10 companies worldwide that operate internationally and have a sufficient supply of helium. In some cases, local companies can purchase helium from large international companies and act as intermediaries, if there is sufficient helium available.

In terms of economics, helium is currently estimated to be 80-100 times more expensive than CO₂, when purchased in Europe. The delivery form, whether as a liquid or a gas, also impacts the price. Additionally, the price can differ greatly from country to country and is also highly affected by energy and transportation costs. An advantage of helium is that it is relatively easy to recover after use and has been shown to have a recovery rate of around 98% in experimental settings.

Social impact

In terms of risks concerning work accidents, there was a possible risk of sticking pigs on the belt compared with after shackling. However, it was estimated that it probably was not higher than in the conventional carbon dioxide system. Nevertheless, the risk was only based on a one-site observation and is therefore not confirmed. Another advantage of the inert gas helium is that, it will only pose an indirect risk when the presence of the gas causes O₂ to be lower than 19,5% (EU-OSHA, 2016), while CO₂ poses a direct health risk.

Due to the properties of helium and room setup, a very low risk of toxic levels of Helium compared to the carbon dioxide, system was estimated.

The noise level was estimated to be mostly the same for the use of helium compared with the carbon dioxide system.

In terms of labor time, the stunning time for helium is longer than for the conventional carbon dioxide system. However, it depends on the number of pigs per gondola and is reduced by a second person sticking and shackling.

Ease of conversion

The Helium stunner involved in this project is the first helium stunner worldwide and is running at low capacity. No effort has yet been made to develop practical applications of the method as a standard solution at commercial high throughput slaughterhouse. Consequently, there are multiple unknown factors about what it would take to go from a high throughput CO₂ stunning to use Helium.

Given the nature of the Helium gas there is a need to use a tower approach rather than a pit as used in high concentration CO₂ stunners commercially. In the existing helium system one box corresponding to a Dip-Lift is used and raised in the tower. Another way to go could be a tunnel system, but this has not been tested using helium. It is estimated that a “reverse” paternoster system (in which the elevator moves up) to be able to increase the number of gondolas in one system is not feasible for helium given the volatile nature of helium. The possibility of reusing would then be too low.

It is estimated that a helium stunner does not require more area than that of a CO₂ Dip-Lift or Backloader. Conversion from an existing CO₂ system to a Helium system could thus in principle be done by removing the original CO₂ stunner and using the area where the original stunner was placed, one to one, to build a tower using helium. Additionally, some space is needed as a “recovery room” for the reuse of helium. When replacing the CO₂ stunner with a helium stunner it will not be possible to reuse any material parts from the CO₂ stunner. If the new stunner is placed in the area of the original stunner, the old raceway can be used with only minor modifications. A slope in the raceway is necessary, since the entrance of the helium stunner is not on the ground level. By this approach the sticking area could also be used without modification. However, the approach will lead to a capacity reduction.

The extent of the required expansion will depend on how the original slaughterhouse is structured. If there is no extra space in the near area of the original stunner, it may be necessary to change or extend the holding area. This is especially true since more helium stunners are necessary to reach the same capacity. The manufacturer indicated that there was no technical limit to increasing the number of pigs in the gondola from 6 to 10. This increase would enable a higher throughput for the system, though it is unknown whether the increase in gondola size would negate the animal welfare benefits of using Helium.

Based on the experience of implementing the existing helium system it is estimated that if the right permits are available and a CO₂ stunner will be replaced with a Helium system (accepting the capacity reduction) it can be done within a period without slaughtering of 1-2 weeks. The period for an expansion to high throughput will depend on whether extra space in the slaughterhouse is already existing. If not getting building permit and environmental approval could prolong the process vastly.

Helium's high cost is offset by a recovery system that purifies and stores it for reuse. While the recovery rate is expected to be 98% it is currently closer to 90-95% recoverability. Though delivery is currently stable, the system could be adapted for other gases like nitrogen if needed. Helium is costlier and less available than CO₂ due to limited extraction sites, reducing its large-scale viability. Yet, technology allows for helium reuse, easing cost issues. An important aspect regarding helium is its critical uses, such as cooling medical imaging equipment, and which may leave it prioritised if demand exceeds supply.

Estimated cost of a high throughput system

The current helium system implemented by MRI runs at 50 pigs/hour, but it is estimated that 90 pigs/hour would be possible by increasing speed without further changes to the system. The throughput increase is partly possible by increasing gondola size.

To achieve the target of 600 pigs/hour, seven stunners are required with a throughput of 90 pigs/hour. However, no price estimates have been made for a commercial Helium-based stunning system. The estimate is therefore based on the price estimated in table 9 of D1, which puts a CO₂ stunner between 700k€ and 1,700k€. The highest price estimate is likely to be a paternoster system that is not compatible with Helium. Therefore, 900k€ per stunner is used as that is slightly more expensive than the cheapest CO₂ stunner. The additional cost above the lowest CO₂ price is due to the expenses related to the complex system required to reuse Helium, a necessity due to the higher price of the gas. No information was provided regarding the cost to rebuild the slaughterhouse to accommodate this new system, though a similar area-requirement to CO₂ is expected. Despite price similarity between CO₂ and Helium stunners, the need for seven Helium stunners due to long exposure times puts the price estimate of scaling a helium 6,300k€ excluding floor plan changes required. The cost of above 6 million euros in total of both the stunners and the necessary infrastructure modifications highlights the importance of evaluating the long-term benefits to animal welfare of the alternative.

Strengths, weaknesses and feasibility

Main Strengths in ease of conversion

- Can offset the cost of helium by using a recapture system
- Can reuse the existing area of a CO₂ stunner with minor modifications
- Helium stunning is already legal
- Might be possible to adapt to nitrogen in cases of helium scarcity

Main Weaknesses in ease of conversion

- Helium currently operates at a low throughput
- Requires an entirely new stunner
- Requires a Helium recapture system
- Many unknowns in the transition from CO₂ to Helium in high throughput
- Helium is unable to use paternoster designs due to gas attributes
- Helium has potential limited availability and 80-100 times more expensive compared to CO₂

How does the Cost of Conversion Make the Alternative More or Less Feasible

The feasibility of converting to a helium-based stunning system is heavily influenced by its cost and requirement of entirely new stunners and recapture-systems. Each helium stunner costs approximately 900k€, resulting in a total of 6,300k€ for the seven stunners needed to reach high throughput, due to longer exposure times compared to CO₂ systems. While a recovery system helps mitigate helium's high cost by allowing reuse, overall expenses remain significant. The extensive infrastructure modifications and multiple stunners required make it a costly alternative. Thus, it's essential to weigh these substantial costs against the potential long-term benefits to animal welfare.

Box System for the Optimised CAS process

Please see the Introduction to this appendix and Appendix B: Analysis Methods section for details on the display format and methods.

Animal collective and stunning parameters

Animal Genetics

Table - A 52: Number of animals for the different stunning conditions (Argon, CO₂, Helium) separated by animal genetics. For Argon information for 3 gondolas is missing. DanL = Danish Landrace, DanY = Danish Yorkshire, Du = Duroc

Condition	Genetics	N
Argon	[DanL x DanY] x Du	45
CO ₂	[DanL x DanY] x Du	54
Helium	[DanL x DanY] x Du	54

Animal sex and average weight

Table - A 53: Animal sex and estimated average weight of the animals stunned under different conditions (Argon, CO₂, Helium).

Condition	Female [%]	Castrated male [%]	Weight [kg]
Argon	51.1	48.9	110
CO ₂	44.4	55.6	110
Helium	38.9	61.1	110

Gas Concentrations

Table - A 54: Residual oxygen content (percent) for two sensors. The mean gas concentration during the stunning sequence was calculated for each gondola. From these mean concentrations per gondola, the mean, minimum (min), maximum (max) and standard deviation (σ) of the means were calculated over all stunning sequences.

Condition	Sensor A [%]				Sensor B [%]			
	Mean	σ	Min	Max	Mean	σ	Min	Max
Argon	1.50	0.09	1.09	1.92	1.42	0.06	1.07	1.78
CO ₂	86.59	0.28	85.15	88.03	86.89	0.24	85.69	88.09
Helium	1.93	0.12	1.73	2.13	1.65	0.04	1.60	1.69

Animal welfare

Pre-Stunning Handling

Arrival & Moving to Lairage

Table - A 55: Proportion of animals that were slipping and falling or showing high pitched vocalisation during arrival and moving to lairage. The extent of human stimulation was recorded as gentle, moderate (moderate sound or occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

	Animals	Arrival			Moving to Lairage		
		Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation
CO ₂	54	0.02	0.00	gentle & moderate	NA	NA	NA
Argon	54	0.33	0.04	gentle & moderate	NA	NA	NA
Helium	36	0.08	0.03	gentle & moderate	NA	NA	NA

Lairage

Table - A 56: Proportion of animals that were standing, sitting or lying. Additionally, the proportion of fighting and mounting animals was recorded. Recordings were done every 10 minutes for 2 minutes.

Gas	Time of Observation [min]	Animals	Body Position [%]			Aversive Interactions [%]	
			Standing	Sitting	Lying	Fighting	Mounting
CO ₂	10	54	0.30	0.02	0.69	0.04	0.00
	20	54	0.24	0.15	0.61	0.00	0.00
	30	54	0.13	0.04	0.83	0.00	0.00
	40	54	0.20	0.07	0.72	0.00	0.00
	50	54	0.24	0.09	0.67	0.04	0.00
	60	45	0.33	0.09	0.58	0.00	0.00
Argon	10	54	0.48	0.02	0.50	0.02	0.02
	20	54	0.20	0.02	0.78	0.00	0.00
	30	54	0.09	0.06	0.85	0.00	0.00
	40	54	0.06	0.07	0.87	0.02	0.00
	50	54	0.13	0.06	0.81	0.02	0.00
	60	54	0.15	0.06	0.80	0.02	0.00
Helium	10	54	0.43	0.06	0.52	0.00	0.00
	20	54	0.24	0.04	0.72	0.00	0.00
	30	54	0.15	0.00	0.85	0.02	0.00
	40	54	0.20	0.04	0.76	0.00	0.00
	50	54	0.20	0.02	0.78	0.00	0.00
	60	45	0.16	0.02	0.82	0.00	0.00

Moving and Entrance to Stunner

Table - A 57: Proportion of animals that were slipping and falling or showing high pitched vocalisation during the moving of the pigs to the stunner or the entrance of the pigs into the stunner/raceway. The extent of human stimulation was recorded as gentle (no sounds, gentle use of paddles), moderate (some sounds and moderate use of paddles), intense (loud sound and/or physical stimulation).

		Time of Observation [min]	Animals	Slipping & Falling [%]	Vocalisation [%]	Human Stimulation	Automatic Stimulation

Moving to Stunner	CO ₂	1	15	0	0	gentle	NA
Moving to Stunner	CO ₂	2	12	0	0	gentle	NA
Moving to Stunner	CO ₂	3	12	0	0	gentle	NA
Entrance Stunner	CO ₂	1	9	0	0	gentle	NA
Entrance Stunner	CO ₂	2	9	0	0	gentle	NA
Entrance Stunner	CO ₂	3	9	0	0	gentle	NA
Moving to Stunner	Argon	1	3	0.67	NA	NA	NA
Entrance Stunner	Argon	NA	NA	NA	NA	NA	NA
Moving to Stunner	Helium	NA	NA	NA	NA	NA	NA
Entrance Stunner	Helium	NA	NA	NA	NA	NA	NA

Video Analysis

Entering

Entering Overview

Table - A 58: Distribution of the maximum (strongest) scored level per animal for entering the stunning device. The levels were scored as 0 = none, 1 = reluctance to move, 2 = aversive physical contact, 3 = painful physical contact, 4 = lasting painful physical contact. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the strongest (maximum) scored level for entering of the stunner and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and the number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	*	Min	Max	95% CI		N
Max Score	Argon		0	a	0	0	0.0	0.2	54
		0 [%]	100				93.4	100.0	54
		1 [%]	0				0.0	6.6	0
		2 [%]	0				0.0	6.6	0
		3 [%]	0				0.0	6.6	0
		4 [%]	0				0.0	6.6	0

	CO ₂		0	a	0	0	0.0	0.2	54
		0 [%]	100				93.4	100.0	54
		1 [%]	0				0.0	6.6	0
		2 [%]	0				0.0	6.6	0
		3 [%]	0				0.0	6.6	0
		4 [%]	0				0.0	6.6	0
	Helium		0	a	0	0	0.0	0.2	52
		0 [%]	100				93.2	100.0	52
		1 [%]	0				0.0	6.8	0
		2 [%]	0				0.0	6.8	0
		3 [%]	0				0.0	6.8	0
		4 [%]	0				0.0	6.8	0

First reluctance to move

Table - A 59: Mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first reluctance to move relative to the start of the descend/ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first reluctance to move occurred before the start of the descend/ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon							0
	CO ₂							0
	Helium							0
Proportion [%]	Argon	0	a			0	6.6	54
	CO ₂	0	a			0	6.6	54
	Helium	0	a			0	6.8	52

First aversive physical contact

Table - A 60: Mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first aversive physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first aversive physical contact occurred before the start of the descend/ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon							0
	CO ₂							0

	Helium							0
Proportion [%]	Argon	0	a			0	6.6	54
	CO ₂	0	a			0	6.6	54
	Helium	0	a			0	6.8	52

First painful physical contact

Table - A 61: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence (95% CI) of the time until the first painful physical contact relative to the start of the descend/ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the first painful physical contact occurred before the start of the descend/ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon							0
	CO ₂							0
	Helium							0
Proportion [%]	Argon	0	a			0	6.6	54
	CO ₂	0	a			0	6.6	54
	Helium	0	a			0	6.8	52

First lasting painful physical contact

Table - A 62: Mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first lasting painful physical contact relative to the start of the descend/ascend of the gondola, calculated from the values recorded for each animal. Negative values indicate that the lasting painful physical contact occurred before the start of the descend/ascend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon							0
	CO ₂							0
	Helium							0
Proportion [%]	Argon	0	a			0	6.6	54
	CO ₂	0	a			0	6.6	54
	Helium	0	a			0	6.8	52

Initial reaction

Initial Reaction Overview

Table - A 63: Distribution of the maximum (strongest) scored level per animal for the reaction to the gas atmosphere in the induction phase. The levels were scored as 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95%

confidence interval (95% CI) of these strongest (maximum) scored initial reaction and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	*	Min	Max	95% CI		N
Max Score	Argon		0.9	a	0	3	0.7	1.2	54
		0 [%]	48.1				34.3	62.2	26
		1 [%]	22.2				12.0	35.6	12
		2 [%]	22.2				12.0	35.6	12
		3 [%]	7.4				2.1	17.9	4
	CO ₂		1.5	b	0	3	1.3	1.7	54
		0 [%]	3.7				0.5	12.7	2
		1 [%]	61.1				46.9	74.1	33
		2 [%]	18.5				9.3	31.4	10
		3 [%]	16.7				7.9	29.3	9
	Helium		0.7	a	0	2	0.5	1.0	52
		0 [%]	53.8				39.5	67.8	28
		1 [%]	19.2				9.6	32.5	10
		2 [%]	26.9				15.6	41.0	14
		3 [%]	0.0				0.0	6.8	0

First response to atmosphere

Table - A 64: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first response to the atmosphere, relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first response to the atmosphere occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ ascend [s]	Argon	42.8	12.7	c	9.2	60.6	37.5	48.0	25
	CO ₂	22.0	5.6	a	10.3	37.4	20.3	23.6	48
	Helium	30.5	14.0	b	9.8	73.8	24.1	36.8	21
Loss of posture [s]	Argon	-24.3	10.3	b	-53.1	-8.8	-28.5	-20.0	25
	CO ₂	-18.1	6.0	c	-38.4	-3.8	-19.9	-16.4	48
	Helium	-49.5	15.4	a	-67.8	-16.0	-56.5	-42.5	21

Proportion [%]	Argon	46.3		a			32.6	60.4	54
	CO ₂	88.9		b			77.4	95.8	54
	Helium	40.4		a			27.0	54.9	52

First agitation

Table - A 65: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first agitation, relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown in percent. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ ascend [s]	Argon	62.0	6.9	b	48.9	75.7	58.0	65.9	14
	CO ₂	24.4	4.1	a	19.3	34.7	22.3	26.6	17
	Helium	81.8	7.7	c	65.2	91.2	77.4	86.2	14
Loss of posture [s]	Argon	-6.7	4.7	b	-15.6	-2.0	-9.4	-4.0	14
	CO ₂	-12.5	5.2	a	-19.6	-0.1	-15.2	-9.9	17
	Helium	-4.5	5.4	b	-13.1	5.4	-7.6	-1.3	14
Proportion [%]	Argon	25.9		a			15.0	39.7	54
	CO ₂	31.5		a			19.5	45.6	54
	Helium	26.9		a			15.6	41.0	52

First strong agitation

Table - A 66: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first strong agitation relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first strong agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ ascend [s]	Argon	70.6	4.6	b	64.0	74.7	63.2	78.0	4
	CO ₂	36.2	2.8	a	32.0	39.4	34.0	38.3	9
	Helium								0
Loss posture [s]	Argon	-8.2	4.7	a	-13.0	-3.5	-15.7	-0.7	4
	CO ₂	-2.6	4.1	a	-6.5	7.2	-5.8	0.6	9
	Helium								0
Proportion [%]	Argon	7.4		a			2.1	17.9	54

	CO ₂	16.7		a		7.9	29.3	54
	Helium	0.0		a		0.0	6.8	52

First abnormal breathing

Table - A 67: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first abnormal breathing, relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Negative values indicate that the first abnormal breathing occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ ascend [s]	Argon	45.8	6.3	b	36.6	54.8	40.5	51.1	8
	CO ₂	30.3	6.5	a	13.8	43.0	28.2	32.4	39
	Helium	50.9	16.9	b	19.4	77.0	42.2	59.6	17
Loss posture [s] of	Argon	-19.9	4.9	b	-24.1	-8.2	-24.0	-15.8	8
	CO ₂	-10.2	5.6	c	-32.6	-2.6	-12.0	-8.3	39
	Helium	-33.3	11.6	a	-54.1	-10.8	-39.2	-27.4	17
Proportion [%]	Argon	14.8		a			6.6	27.1	54
	CO ₂	72.2		b			58.4	83.5	54
	Helium	32.7		a			20.3	47.1	52

Stunning progress

Loss of posture

Table - A 68: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the loss of posture relative to the start of the descend/ascend of the gondola, calculated from the results of each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ ascend [s]	Argon	64.4	7.0	b	54.0	86.2	62.5	66.3	54
	CO ₂	40.2	6.1	a	30.2	67.3	38.5	41.9	54
	Helium	80.4	10.6	c	46.0	97.5	77.5	83.4	52

Lying

Table - A 69: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until lying, relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
	Argon	87.4	12.5	b	62.1	114.4	83.9	90.8	54

Start descend/ascend [s]	CO ₂	55.7	11.6	a	35.0	86.8	52.5	58.9	53
	Helium	100.6	16.2	c	51.4	126.2	96.1	105.1	52
Loss of posture [s]	Argon	22.9	14.2	b	1.4	51.7	19.1	26.8	54
	CO ₂	15.4	10.0	a	1.4	44.4	12.6	18.2	53
	Helium	20.2	13.8	ab	2.2	44.0	16.3	24.0	52

Last movement

Table - A 70: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the last movement, relative either to the start of the descend/ascend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each animal. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter). Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon	247.7	30.9	c	150.8	320.3	239.3	256.2	54
	CO ₂	186.8	42.1	a	111.2	329.9	175.3	198.3	54
	Helium	229.7	22.0	b	181.1	284.5	223.6	235.8	52
Loss of posture [s]	Argon	183.3	29.7	b	92.4	251.7	175.2	191.4	54
	CO ₂	146.6	39.4	a	71.6	279.2	135.9	157.4	54
	Helium	149.3	20.3	a	100.7	195.0	143.7	155.0	52

Cycle duration

Table - A 71: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the cycle duration relative to the start of the descend/ascend of the gondola. Note that this is an operational parameter reflective of the set stunning times. Number of samples = N

	Condition	Mean	σ	*	Min	Max	95% CI		N
Start descend/ascend [s]	Argon	578.4	26.9	b	564.5	683.5	571.1	585.8	54
	CO ₂	452.1	8.2	a	442.7	464.0	449.9	454.4	54
	Helium	582.8	24.7	b	559.7	672.4	575.9	589.6	52

Stunning Effectiveness

Table - A 72: Stunning effectiveness for the dwell times, which were not chosen to be optimal but to ensure stunning-to-death for all animals. Re-stun rate and 95% confidence interval (95% CI) are given in percent. Confidence intervals are for one sided tests.

Condition	Dwell Time	N	Re-stun rate [%]	95% CI
Argon	480	54	0	5.4
CO ₂	360	54	0	5.4
Helium	480	54	0	5.4

Meat Quality

Carcass

After 45 min

Table - A 73: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 45 minutes post mortem for animals stunned under different conditions (argon, helium and CO₂) as well as the number of samples (N). The proportion of samples with a pH₄₅ below 6.1 (pH₄₅<6.1) or 5.8 (pH₄₅<5.8) and the temperature for the subset of samples where the pH₄₅ was below 6.1 (T(pH₄₅<6.1) or 5.8 (T(pH₄₅<5.8)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	pH	5.9	0.3	a	5.3	6.6	5.8	6.0	54
CO ₂		6.4	0.2	c	6.1	6.7	6.4	6.5	
Helium		6.1	0.3	b	5.4	6.9	6.1	6.2	
Argon	T [°C]	37.6	1.3	b	32.6	39.7	37.2	37.9	
CO ₂		35.0	2.6	a	28.2	38.8	34.3	35.7	
Helium		37.6	0.7	b	35.9	39.0	37.4	37.8	
Argon	T(pH ₄₅ <6.1) [°C]	37.7	1.4	a	32.6	39.7	37.3	38.1	43
Helium		37.8	0.7	a	36.4	38.7	37.4	38.1	20
Argon	T(pH ₄₅ <5.8) [°C]	37.8	1.7	a	32.6	39.7	36.9	38.7	16
Helium		37.9	0.8	a	36.5	38.7	37.2	38.6	7
Argon	pH<6.1 [%]	79.6		c			66.5	89.4	54
CO ₂		0.0		a			0.0	6.6	
Helium		37.0		b			24.3	51.3	
Argon	pH<5.8 [%]	29.6		b			18.0	43.6	
CO ₂		0.0		a			0.0	6.6	
Helium		13.0		ab			5.4	24.9	

After 24 h

Table - A 74: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 24 hours post mortem for animals stunned under different conditions (argon, helium and CO₂) as well as the number of samples (N). The pH (24h) of the subset of samples with a pH₄₅ below 6.1 (pH(pH₄₅<6.1)) and below 5.8 (pH(pH₄₅<5.8)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
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Argon	pH	5.5	0.1	a	5.4	5.7	5.5	5.5	54
CO ₂		5.5	0.1	a	5.3	5.8	5.5	5.5	
Helium		5.5	0.1	a	5.3	5.9	5.4	5.5	
Argon	pH(pH45<6.1)	5.5	0.1	a	5.4	5.7	5.5	5.5	43
Helium		5.5	0.1	a	5.4	5.9	5.4	5.5	20
Argon	pH(pH45<5.8)	5.5	0.1	a	5.4	5.6	5.4	5.5	16
Helium		5.5	0.0	a	5.4	5.5	5.4	5.5	7
Argon	T [°C]	2.8	0.8	a	1.2	4.4	2.5	3.0	54
CO ₂		2.9	1.1	a	1.0	4.8	2.6	3.2	
Helium		2.8	1.2	a	0.6	4.5	2.5	3.1	

Cut

Colour

Table - A 75: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (L, L(pH45 < 6.1), a, b) measured for animals stunned under different conditions (argon, helium and CO₂) as well as the number of samples (N). The L value of the subset of samples with a pH below 6.1 (L(pH45<6.1)) and below 5.8 (L(pH45<5.8)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	L	51.5	2.4	a	45.3	56.5	50.9	52.2	54
CO ₂		52.3	3.2	a	44.3	60.5	51.5	53.2	
Helium		52.2	2.0	a	46.8	56.2	51.7	52.7	
Argon	L(pH45<6.1)	51.5	2.4	a	45.3	56.5	50.7	52.2	43
Helium		52.0	2.2	a	46.8	56.2	51.0	53.1	20
Argon	L(pH45<5.8)	51.1	2.0	a	46.0	53.9	50.0	52.1	16
Helium		53.1	2.1	b	50.8	56.2	51.2	55.0	7
Argon	a	5.1	0.6	a	3.1	6.6	4.9	5.2	54
CO ₂		5.1	0.7	a	3.6	7.0	4.9	5.3	
Helium		5.6	0.7	b	3.6	7.0	5.4	5.8	
Argon	b	10.1	0.5	a	9.1	11.4	10.0	10.2	54
CO ₂		10.5	0.8	b	8.7	12.2	10.3	10.8	
Helium		10.4	0.4	b	9.3	11.4	10.3	10.5	

Drip Loss

Table - A 76: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Drip Loss (%) measured for animals stunned under different conditions (argon, helium and CO₂) as well as the number of samples (N). Additionally, the drip loss of the subset of samples with a pH45 below 6.1 (Drip Loss(pH45<6.1)) and below 5.8 (Drip Loss(pH45<5.8)) are shown. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
Argon	Drip Loss [%]	7.7	2.9	c	0.6	12.6	6.9	8.5	54
CO ₂		2.7	1.6	a	0.7	6.8	2.3	3.1	
Helium		5.3	3.1	b	1.5	12.4	4.5	6.2	
Argon	Drip Loss (pH45<6.1) [%]	8.6	2.2	a	1.4	12.6	7.9	9.3	43
Helium		7.9	2.9	a	3.2	12.4	6.5	9.2	20
Argon	Drip Loss (pH45<5.8) [%]	9.5	1.5	a	6.9	12.6	8.7	10.3	16
Helium		10.4	1.4	a	8.3	12.4	9.1	11.7	7

Blood Spots

Table - A 77: Distribution of scored level of blood spots. Blood spots were scored as 0 = no blood spots, 1 = less than 5 blood spots, 2 = less than 30 blood spots, 3 = more than 30 blood spots. Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Blood Spots measured for animals stunned under different conditions (argon, helium and CO₂) and the number of samples (N). The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the blood spots levels and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters.

Condition	Level	Mean	σ	*	Min	Max	95% CI		N
Argon		0.6		b	1	3	0.5	0.9	54
CO ₂		0.1		a	1	2	0.1	0.3	
Helium		0.4		ab	1	3	0.3	0.6	
Argon	0 [%]	59.3					45.0	72.4	32
CO ₂		87.0					75.1	94.6	47
Helium		68.5					54.4	80.5	37
Argon	1: < 5 [%]	18.5					9.3	31.4	10
CO ₂		13.0					5.4	24.9	7
Helium		25.9					15.0	39.7	14
Argon	2: < 30 [%]	22.2					12.0	35.6	12

CO ₂		0.0					0.0	6.6	0
Helium		5.6					1.2	15.4	3
Argon	3: > 30[%]	0.0					0.0	6.6	0
CO ₂		0.0					0.0	6.6	
Helium		0.0					0.0	6.6	

Economic, environmental and social impact

Economic impact

The experts of the box system suggested two options for upscaling to a high throughput: A Backloader system and The Tunnel solution. Technical and cost parameters for the Backloader system with CO₂ are reported in Table - A 78, and parameters for The Tunnel solution is in Table - A 79. Most of the technical parameters reported are estimated by the experts to be similar to CO₂-2 study cases reported in D1. The cost of maintenance was not provided by the expert.

To calculate the cost per pig when using the Backloader system technical and cost parameters were estimated using as an example the study cases reported in D1 i.e. the study case implementing the new alternative system. The main assumption was that the study case should reach their previous number of pigs slaughtered per day. The Backloader system includes a backloader stunner i.e. commercial name for a type of paternoster system, and a retrofit system that includes a climate and an automatic driveway. The retrofit system can only be directly implemented with a backloader. Here we assume that the study case has a paternoster stunner different than a backloader to consider the worst-case scenario. The cost of a retrofit system is 1,200k€ (Climate = 0.5 k€; automatic driveway = 0.7 k€). The cost for a new standard backloader is 1,300k€.

To reach the number of slaughtered pigs per day the number of lines was adjusted first, and then the number of slaughter hours per day. Only one conventional paternoster study case had to be adjusted for the number of lines by adding one extra line (CO₂-1). All study cases ended up with a surplus of pigs which was adjusted by decreasing the number of slaughter hours per day (CO₂-1, 3 and 4 would have to work 4.74, 12.59, 1.85 and 4.10 hours less, respectively). The number of people was reported to be similar to study case CO₂-2 when using a Backloader system which was estimated to be eight people for four lines. However, number of people by stage was not reported in this study case. It was assumed that CO₂-2 would have 1 person for lairage, 2 people to check technical parameters of the stunner and 5 people for bleeding and shackling in total. Number of people needed for the Backloader system was estimated accordingly. The installation investment included a new stunner and one retrofit system per line.

The direct adaptation of a dip-lift system i.e. installation of retrofit system, is limited by space availability. In theory, it should be possible to install the automatic driveway in front of the dip-lift however this would be difficult to organize. Instead, it is suggested to change the current dip-lift system to a new backloader. However, the expert advises that this is only economically feasible in slaughterhouses with a current throughput of 600 to 650 pigs/h. Here we report technical and cost parameters using the second scenario.

Similarly, as with study cases with a paternoster system, the study case with a dip-lift system (CO₂-2) the number of lines and working hours were adjusted to reach the same production level as the study case. When implementing only one new retrofitted backloader there was a negative difference of 425 slaughtered pigs per day between the old and the new system while maintaining the same slaughter hours per day. To

follow the same method as with the other alternatives, a second line was added. The surplus of slaughtered pigs was adjusted by reducing slaughter hours from 17 to 8.83 hours a day.

Table - A 78: Technical and cost parameters of the Backloader system being implemented in the relevant study cases. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using a paternoster system; and CO₂-2 using a dip-lift system. Cells in red show values that are from the alternative system itself; cells in black correspond to values that could not be provided by the expert.

Technical and cost parameters	Backloader system*			
	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4
Labor used in the pre-stunning and stunning process, per day	46.31	44.13	56.62	33.19
Water for cleaning (m ³ /day) ¹	24	24	12	12
Electricity for stunning (kWatt/day) ¹	343.80	343.8	171.9	171.90
Gas for stunning (tonnes CO ₂ /day) ¹	22.41	22.41	11.21	11.21
Pigs per hour	1300	1300	650	650
Hours of slaughter per day	9.26	8.83	14.15	8.29
Days with slaughter per year	250	240	254	252
Proportion of pigs discarded due to meat quality	0	0	0	0
Number of people ¹	5	5	4	4
Number of lines per system	2	2	1	1
Number of gondolas/stunners per line	6	6	6	6
Depreciation period yr	10	10	10	10
Maintenance - % of installation costs				
Labour cost/hour €2	38	30	35	20
Gas price (€ per Tonnes) ²	350	186.39	136	270
Electricity price (€ per kWatt) ²	0.183	0.125	0.1129	0.24
Water costs (€/m ³) ²	4.5	4.5	1.25	4.46
Cost per pig discarded due to meat quality	100	100	100	100
Installation investment ³	5,000,000	5,000,000	2,500,000	2,500,000

*The alternative system is implemented in a conventional CO₂ paternoster and dip-lift system.

¹ Technical parameters taken from study case CO₂-2 as estimated by the expert.

² Cost per unit obtained from each study case, respectively.

³ Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. This includes the cost of one new backloader and one retrofit system per line. In the case that the slaughterhouse already has a backloader this can be retrofitted (1200 k€). This option is not explored here.

Similar calculation was done for the Tunnel solution as with the installation of the backloader system in a previous paternoster and dip-lift system. The throughput of this alternative is the same as the backloader

solution i.e. 650 pig per hour per stunner. The implementation of this system requires installing the system from scratch, therefore the installation investment include the cost of the tunnel i.e. 2800 k€. This includes the tunnel and the automatic driveway. Unfortunately, most of the parameters are not available yet and therefore the cost per pig is not calculated.

Table - A 79: Technical and cost parameters of the Tunnel solution being implemented in the relevant study cases. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using a paternoster system; and CO₂-2 using a dip-lift system. Cells in red show values that are from the alternative system itself; cells in grey means not applicable; and cells in black correspond to values that could not be provided by the expert.

Technical and cost parameters	The Tunnel solution*			
	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4
Labor used in the pre-stunning and stunning process, per day	46.3	44.1	56.6	33.2
Water for cleaning (m ³ /day) ¹	unknown	unknown	unknown	unknown
Electricity for stunning (kWatt/day) ¹	unknown	unknown	unknown	unknown
Gas for stunning (tonnes CO ₂ /day) ¹	unknown	unknown	unknown	unknown
Pigs per hour	1300	1300	650	650
Hours of slaughter per day	9.2	8.8	14.2	8.3
Days with slaughter per year	250	240	254	252
Proportion of pigs discarded due to meat quality	0	0	0	0
Number of people ¹	5	5	4	4
Number of lines per system	2	2	1	1
Number of gondolas/stunners per line				
Depreciation period yr	10	10	10	10
Maintenance - % of installation costs				
Labour cost/hour € ²	38	30	35	20
Gas price (€ per Tonnes) ²	350	186.39	136	270
Electricity price (€ per kWatt) ²	0.183	0.125	0.1129	0.24
Water costs (€/m ³) ²	4.5	4.5	1.25	4.46
Cost per pig discarded due to meat quality	100	100	100	9.2
Installation investment ³	3,600,000	3,600,000	1,800,000	1,800,000

* The alternative system is implemented in conventional CO₂ system with paternoster and dip-lift system.

¹ Technical parameters cannot be estimated yet.

² Cost per unit obtained from each study case, respectively.

³ Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. This includes the cost of one tunnel and one automatic driveway per line. For this alternative it is not possible to adapt the current stunners.

Environmental impact

Efficiency and resource use

It was not possible to get exact figures of the resource used in the back loader system. However, the gas, water, and detergent use in the back loader system were expected to be the same as in the conventional high-concentration system. The electricity use was expected to be higher as extra electricity is needed for the automatic railway installed.

For the tunnel system, the expert was not able to estimate the resource amount, as it was not fully developed yet.

The expected throughput of the backloader system and the tunnel system is 700 pigs per hour. The exposure time was expected to be the same or slightly reduced in both the backloader system and the tunnel system. This was caused by the loss of posture being reduced, as a consequence of the controlled and stable stunning environment in the new systems. The stun-to-stick time was not expected to change on individual animal levels. According to deliverable 3, the lairage time varies between 30-240 minutes. Another advantage of this system is that different kinds of gasses can be used and adjusted to the system.

Availability of carbon dioxide

The information on the availability of carbon dioxide was collected by sending emails to a contact person from Air Liquide. CO₂ is the easiest gas to obtain compared to helium and argon. It is abundantly produced from various natural and industrial processes including combustion of fossil fuels, fermentation, and as a byproduct from various industries. There are numerous methods to capture and purify it, and it can among others be captured from industrial emissions. The most common source of CO₂ production is the manufacturing processes for hydrogen or ammonia, where CO₂ is generated as a byproduct. CO₂ has a high demand on the market, which is caused by being used for various purposes such as carbonation in beverages, fire extinguishers, dry ice, refrigeration, and more.

There are between 5-10 large international companies, and various local companies that can supply CO₂. However, if large producers reduce their production of hydrogen and ammonia, which is the most common source of CO₂ production, there may be supply shortages. This typically occurs during the summer period, when there is high demand from the beverage industry. During this period, supply to slaughterhouses will be prioritized, ensuring high security of supply.

Social impact

For the backloader system in the optimized CAS process, the risk of work accidents and toxic levels of carbon dioxide was expected to be the same as for the traditional carbon dioxide system. For the tunnel system, the risk of work accidents and toxic carbon dioxide levels was expected to be lower than the conventional carbon dioxide system. Regarding the noise level in the backloader system, there was confidence that it would be lower than in conventional carbon dioxide systems. For the tunnel system, there was a high uncertainty on the expected noise level. This was due to the system not being fully developed yet, making it impossible to provide reliable information. The amount of working hours was expected to be the same as for the traditional carbon dioxide system for both the backloader system and tunnel system.

Ease of conversion

The Optimised CAS systems describes a generalised approach rather than a specific system. The approach has been theorised into two possible alternatives. (1) The Optimised CAS for retrofitting an existing backloading stunner. (2) The Optimised CAS in a tunnel system. The stunning method tested in this alternative is most akin to the Optimised CAS tunnel system rather than the Optimised CAS retrofit, though neither optimised CAS system is directly comparable to the tested Box system.

Both systems are, according to the manufacturer, agnostic of which gas is used and can thus be applied with both current and future gasses available for stunning courtesy of the CAS equipment. The CAS system is developed to enhance the accuracy and reliability of the gas concentrations, including CO₂, O₂ and other relevant gasses. To refine the control of gas level a regulation system will be implemented. The tunnel system differs from the conventional backloader by using tunnel system instead of a pit either below or above floor-level. The tunnel system has been proposed using automated walkways, which does not require manual or automatic pushing of the pigs. Regardless of whether it's a retrofit-CAS or a Tunnel-CAS, it is important to figure out supply chains and requirements regarding the chosen gas, as both availability, price and handling of the gasses can differ wildly.

The retrofittable CAS system should not require many changes to the slaughterhouse floorplan or building, as it was designed especially for retrofitting on existing backloading paternoster stunners, whereas the tunnel system will require a major redesign of the slaughterhouse.

Estimated cost of a high throughput system

The manufacturer theorises that either of the Optimised CAS systems achieves a throughput of approx. 650 pigs per hour, which translates to a single stunner for high throughput of 600 pigs. The Optimised CAS retrofit of a paternoster is estimated at 1,200 k€ with little to no changes required to the slaughterhouse. Though if the slaughterhouse uses an incompatible stunner, the retrofitting might be more expensive or outright impossible. Additional capacity above 650 pigs per hour requires an additional stunner. The tunnel system is estimated to cost 2,800 k€ without including the changes required to the floorplan of the slaughterhouse. Depending on which of the Optimised CAS systems is chosen the total cost is between 1,200 k€ and 2,800 k€ in total without modifications required to the slaughterhouse or other required costs.

Strengths, weaknesses and feasibility

The strengths, weaknesses and feasibility of the Optimised CAS systems is based on knowledge provided by the manufacturer in addition to the D3 deliverable. The systems described in D3 do not directly correspond to the tested Box system, making the ease of conversion evaluation based on the untested, but proposed systems rather than the tested Box system, which was deemed infeasible at high throughput scale.

Main Strengths of the Optimised CAS Retrofit

- Existing infrastructure can be retrofitted with relative ease
- Modifications can be completed relatively quickly
- The system is gas agnostic
- Automated walkways before stunning should lessen stress related to the moving of animals
- Stunning with some alternative gasses, such as Argon, is already legal

Main Weaknesses of the Optimised CAS Retrofit

- Does not necessitate a change away from CO₂ stunning, limiting benefits for animal welfare
- Limited knowledge regarding animal welfare improvements
- Retrofitting could be complex depending on the design of the existing stunner, especially incompatibility between manufacturers could prove difficult
- Other gases could have wildly different requirements regarding storage and usage.
- System is not tested in current state with high throughput, leaving multiple unknowns.

How does the Cost of Conversion Make the Optimised CAS Retrofit More or Less Feasible

The relative low cost of retrofitting an existing stunner with an Optimised CAS system positively impacts the feasibility. Retrofitting an Optimised CAS system is estimated at 1,200 k€ with a throughput of 650 pigs per hour using a single existing stunner. If the proposed Optimised CAS system for retrofitting delivers on

all specifications, there are few economic drawbacks and enables conversion without requiring new stunners. However, it is not addressed in the current description, how the high throughput can be maintained when gasses with different properties, requiring increased exposure time, are used.

Main Strengths of the Optimised CAS Tunnel

- Automated walkways before stunning should lessen stress related to the moving of animals
- Stunning pigs directly on the walkway could improve animal welfare related to the stunning itself
- The system is gas agnostic
- Stunning with some alternative gasses, such as Argon, is already legal

Main Weaknesses of the Optimised CAS Tunnel

- Requires a major redesign of the slaughterhouse floor plan
- Other gases could have wildly different requirements regarding storage and usage.
- System is not tested in current state with high throughput, leaving multiple unknowns.

How does the Cost of Conversion Make the Optimised CAS Tunnel More or Less Feasible

The feasibility of converting to the Optimised CAS Tunnel system is heavily influenced by its cost and requirement of entirely new stunners and conveyors. The system is estimated at 2,800 k€ without installation and changes required to the slaughterhouse floorplan and will thusly be more expensive than the 2,800 k€. The costs associated to converting is believed to be similar regardless of which stunning method is currently in use, due to its novelty. Thus, it's essential to weigh these costs against the potential long-term benefits to animal welfare.

Improved Electrical Stunning

Please see the Introduction to this appendix and Appendix B: Analysis Methods section for details on the display format and methods.

Animal collective and stunning parameters

Animal sex and average weight

Table - A 80: Average slaughter weight (kg) from two days of data collection. Genetic information is currently not available.

Condition	Weight [kg]
Four Stunners	101.1

Animal welfare

Pre-Stunning Handling

Arrival & Moving to Lairage

Table - A 81: Proportion of animals that were slipping and falling or showing high pitched vocalisation during arrival and moving to lairage. The extent of human stimulation was recorded as gentle, moderate (moderate sound or

occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

	Arrival			Moving to Lairage		
Animals	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation
1274	0.02	0.02	gentle & moderate	0	0	gentle

Lairage

Table - A 82: Proportion of animals that were standing sitting or lying. Additionally, the proportion of fighting and mounting animals was recorded. Recordings were done every 10 minutes for 2 minutes.

Time of Observation	Animals	Body Position [%]			Aversive Interactions [%]	
		Standing	Sitting	Lying	Fighting	Mounting
10	288	0.92	0.06	0.02	0.0	0.01
20	288	0.85	0.09	0.07	0.0	0.02
30	288	0.75	0.13	0.11	0.0	0.03
40	288	0.55	0.15	0.27	0.0	0.01
50	288	0.45	0.22	0.34	0.0	0.02
60	288	0.36	0.12	0.52	0.0	0.01

Moving & Entrance to Stunner

Table - A 83: Proportion of animals that were slipping and falling or showing high pitched vocalisation during the moving of the pigs to the stunner or the entrance of the pigs into the stunner/raceway as well as the proportion of automatic stimulation. The extent of human stimulation was recorded as gentle, moderate (moderate sound or occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

Location	Time of Observation	Animals	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Stimulation with peddle [%]	Stimulator [%]	Automatic Stimulation
Moving to stunner	10	160	0.03	0.05	gentle & moderate	NA	NA	no stimulation
entrance raceway	10	160	NA	0.08	NA	0.36	0.07	NA
entrance raceway	20	160	NA	0.04	NA	0.47	0.02	NA

Video Analysis

Entering

Reluctance to move in the raceway

Table - A 84: Mean and 95% confidence interval (95% CI) of the proportion of animals that were reluctant to move into the raceway. No statistical tests could be performed as data from only one condition is available. Number of samples = N

	Condition	Mean	95% CI		N
Proportion [%]	Four Stunners	31.7	24.9	39	180

Reluctance to enter the stunner

Table - A 85: Mean and 95% confidence interval (95% CI) of the proportion of animals that were reluctant to enter the stunner. No statistical tests could be performed as data from only one condition is available. Number of samples = N

	Condition	Mean	95% CI		N
Proportion [%]	Four Stunners	62.8	55.3	69.9	180

Use of brush

Table - A 86: Mean and 95% confidence interval (95% CI) of the proportion of the use of the brush. No statistical tests could be performed as data from only one condition is available. Number of samples = N

	Condition	Mean	95% CI		N
Proportion [%]	Four Stunners	93.9	89.3	96.9	180

Use of electric prod

Table - A 87: Mean and 95% confidence interval (95% CI) of the proportion of the use of the electric prod. No statistical tests could be performed as data from only one condition is available. Number of samples = N

	Condition	Mean	95% CI		N
Proportion [%]	Four Stunners	18.3	13	24.8	180

Initial reaction

Incorrect electrode placement

Table - A 88: Mean and 95% confidence interval (95% CI) of the proportion of incorrect electrode placement. No statistical tests could be performed as data from only one condition is available. Number of samples = N

	Condition	Mean	95% CI		N
Proportion [%]	Four Stunners	0.6	0	3.1	180

Stunning Effectiveness

Table - A 89: Stunning effectiveness of the four stunners. Re-stun rate and 95% CI are given in percent. Confidence intervals are for one sided tests. Data was collected during benchmark measurements in WP2 after sticking and before bleeding. No information was made available about re-stuns after bleeding.

Condition	N	Re-stun rate [%]	95% CI
Four stunners	180	0.6	2.6

Meat Quality

Carcass

After 45 min

Table - A 90: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 45 minutes post-mortem for animals stunned in the four electrical stunners as well as the number of samples (N). The proportion of samples with a pH45 below 6.1 (pH45<6.1) or 5.8 (pH45<5.8) and the temperature for the subset of samples where the pH45 was below 6.1 (T(pH45<6.1)) or 5.8 (T(pH45<5.8)) are shown as well. No statistical tests could be performed as data from only one condition is available.

Condition	Parameter	Mean	σ	Min	Max	95% CI		N
Four Stunners	pH	6.3	0.2	5.7	6.9	6.3	6.4	60
	T [°C]	33.1	4.1	23.5	38.7	32.0	34.1	
	T(pH45<6.1) [°C]	30.2	4.4	23.5	36.4	27.3	33.2	11
	T(pH45<5.8) [°C]	29.3		29.3	29.3			1
	pH<6.1 [%]	18.3				9.5	30.4	60
	pH<5.8 [%]	1.7				0.0	8.9	

After 24 h

Table - A 91: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 24 hours post-mortem for animals stunned in the four electrical stunners as well as the number of samples (N). The pH (24h) of the subset of samples with a pH45 below 6.1 pH(pH45<6.1) or 5.8 (T(pH45<5.8)) are shown as well. No statistical tests could be performed as data from only one condition is available.

Condition	Parameter	Mean	σ	Min	Max	95% CI		N
Four Stunners	pH	5.4	0.1	5.3	5.6	5.4	5.4	60
	pH(pH45<6.1)	5.4	0.0	5.3	5.4	5.4	5.4	11
	pH(pH45<5.8)	5.4		5.4	5.4			1
	T [°C]	2.6	0.4	1.4	3.8	2.5	2.7	60

Cut

Colour

Table - A 92: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (L, L(pH45 < 6.1), a, b) as well as the number of samples (N). The L value of the subset of samples with a pH below 6.1 (L(pH45<6.1)) or 5.8 (L(pH45<5.8)) are shown as well. No statistical tests could be performed as data from only one condition is available.

Condition	Parameter	Mean	σ	Min	Max	95% CI		N
Four Stunners	L	53.8	2.3	48.9	59.3	53.2	54.3	60
	L(pH45<6.1)	53.3	2.3	49.5	56.4	51.7	54.8	11
	L(pH45<5.8)	52.0		52.0	52.0			1
	a	6.1	0.8	4.1	8.2	5.9	6.3	60
	b	10.9	0.4	9.9	11.6	10.8	11.0	

Drip Loss

Table - A 93: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Drip Loss (%) measured for animals stunned in the four electric stunners as well as the number of samples (N). Additionally, the drip loss of the subset of samples with a pH45 below 6.1 (Drip Loss(pH45<6.1)) or 5.8 (Drip Loss(pH45<5.8)) are shown. No statistical tests could be performed as data from only one condition is available.

Condition	Parameter	Mean	σ	Min	Max	95% CI		N
Four Stunners	Drip Loss [%]	5.5	2.9	0.6	14.2	4.8	6.3	60
	Drip Loss (pH45<6.1)	7.3	3.9	1.3	14.2	4.7	9.9	11
	Drip Loss (pH45<5.8)	7.8		7.8	7.8			1

Blood Spots

Table - A 94: Distribution of scored level of blood spots. Blood spots were scored as 0 = no blood spots, 1 = less than 5 blood spots, 2 = less than 30 blood spots, 3 = more than 30 blood spots. Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Blood Spots measured for animals stunned in the four electric stunners and the number of samples (N). The first row for shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the blood spots levels and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. No statistical tests could be performed as data from only one condition is available.

Condition	Level	Mean	σ	Min	Max	95% CI		N
Four Stunners		0.9		0	3	0.7	1.2	60
	0 [%]	43.3				30.6	56.8	26
	1:<5 [%]	30.0				18.8	43.2	18

	2:<30 [%]	20.0				10.8	32.3	12
	3:>30 [%]	6.7				1.8	16.2	4

Economic, environmental and social impact

Economic impact

The technical and cost parameters for the Improved Electrical stunning process implemented in a conventional electrical stunning system and conventional CO₂ stunning system are reported in Table - A 95. The approach for equipment installation for both conventional electrical and conventional CO₂ stunning system is similar. The current stunners are advised not to or cannot be reused, respectively. A conventional electrical stunning system could potentially re-use their current stunners, however, for the new system to work efficiently restructuring of the floor plan needs to be done. Experts also advise that the number of lines should be a multiple of four as otherwise peoplepower is not used efficiently. Multiple of four lines were considered for the study cases and then slaughter hours were adjusted to reach the throughput of the old system accordingly.

The amount of water used per day was estimated from the system. The amount of electricity is an estimation based on the amount of electricity used in Electrical-1 study case. Electrical-1 reports 144 kWatt/day for one line. Experts agree that the amount of electricity used in an Improved electrical system could be estimated as a function of the number of lines installed. For the proportion of pig discarded due to meat quality issues, the experts reported that this would be less than in the conventional electrical stunning system (i.e. less than 0.15 %). However, they inform that the proportion of pig discarded due to the stunning method is unknown (i.e. they refer to the proportion discarded due to other factors). It is suggested to use a 0.02%.

The Improved electrical stunning system needs to be installed from scratch. Hence, the installation investment corresponds to the cost of the new stunners. This did not include any costs regarding changes in the pre-stunning area as the design of and materials available from the study case was not available at the moment. These changes include an S-curve design, high side walls and a two-choice system at the raceway entrance.

Table - A 95: Technical and cost parameters of the alternative being implemented in the relevant study cases. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system; and CO₂-2: using dip-lift system. E-1: study case, Electrical-1, reported in D1 with a conventional electrical stunning system. Cells in red show values that are from the alternative system itself, cells in grey parameter not relevant for the alternative system.

Technical and cost parameters	Improved electrical stunning process*				
	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4	E-1
Labour used in the pre-stunning and stunning process, per day	283.29	270	216.46	126.91	152.94
Water for cleaning (m ³ /day)	6	3	3	3	3
Electricity for stunning (kWatt/day)	1152	576	576	576	576
Gas for stunning (tonnes CO ₂ /day)					
Pigs per hour	1360	680	680	680	680
Hours of slaughter per day	8.9	16.9	13.5	7.9	9.6

Days with slaughter per year	250	240	254	252	281
Proportion of pigs discarded due to meat quality ¹	0.02	0.02	0.02	0.02	0.02
Number of people	32	16	16	16	16
Number of lines per system	8	4	4	4	4
Number of gondolas/stunners per line					
Depreciation period yr	10	10	10	10	10
Maintenance - % of installation costs	1.8	1.8	1.8	1.8	1.8
Labour cost/hour €	38	30	35	20	30
Gas price (€ per Tonnes)					
Electricity price (€ per kWatt)	0.183	0.125	0.11	0.24	0.205
Water costs (€/m ³)	4.5	4.5	1.25	4.46	4.5
Cost per pig discarded due to meat quality	100	100	100	100	219
Installation investment ²	4,514,400	2,257,200	2,257,200	2,257,200	2,257,200

** The alternative system is implemented in the conventional electrical stunning and conventional CO₂ stunning system. For this alternative, installing the system from the scratch results in a more efficient system. This means that the new cost per pig does not include the installation investment of the study case.*

¹ The proportion of pig discarded was reported to be less than in the conventional electrical stunning which is 0.15%. However, experts inform that the proportion of pig discarded due to the stunning method is unknown i.e. they refer to the proportion discarded due to other issues. It is suggested to use 0.02%.

² Installation investment is the price the slaughterhouse has to pay to implement the alternative stunning system. This includes the cost of four electrical stunners (or multiple of four) and their conveyor. It does not include changes to the pre-stunning area.

Environmental impact

Efficiency and resource use

The amount of water used in the Improved electrical stunning system has increased substantially from 200-300 L/day to 3000 L/day. The increase was not only due to the additional stunners but also changes in the cleaning procedures. The change in cleaning procedures and more square meters also caused the disinfectant use to increase 5-6 times. The energy consumption in the Improved electrical system is four times higher than in the traditional system, due to the installation of four new stunners.

The exposure time for the Improved electrical stunning was between 2.8-3 seconds, and the stun-to-stick time was 2-5 seconds. The exposure time is very low compared with high-concentration carbon dioxide stunners. Conversely, the stun-to-stick time is significantly shorter. The estimated number of pigs per hour going through the system is 650 and 170 for each stunner.

Availability of electricity

In terms of availability, electricity is highly available and can be accessed from almost everywhere in Europe connected to an electricity network. It can be produced in several ways, and there are a lot of suppliers, which causes a high security of supply. The price of electricity can differ between countries but is generally a cheap alternative compared with CO₂.

Social impact

For the Improved electrical stunning system, there was no increased risk compared with the traditional electrical stunning system. Since the throughput rate is lower, it will presumably be easier for the workers as both the pigs and the workers are less stressed.

The noise level is lower with the Improved electrical stunning system compared with the traditional one, as the pigs are less stressed.

There was no change in labour time per staff member in the Improved electrical stunning compared traditional one. However, the Improved electrical stunning requires more workers involved at the same time.

Ease of conversion

The Improved electrical stunning system is based on the existing electrical stunning used at commercial scale in a high-throughput slaughterhouse. The change is done by increasing the number of stunners and raceway design rather than the stunning method itself.

The core of this improved system lies in using four electrical stunners in parallel, reducing throughput per stunner. Conversion to this system would require sufficient space for the four stunners and associated raceways. Existing electrical stunning systems could be adapted by adding more stunners. The existing raceway and sticking area could then potentially be adapted with modifications to accommodate the multi-stunner layout. Converting from facilities using CO₂ stunning would require a more significant restructuring.

The raceway design incorporates an S-curve approach and high side walls in the final section of the walkway before the raceway. Converting existing raceways to this design may require moderate floor plan modifications depending on the current layout. Adapting existing walkways to include high walls will furthermore require some structural adjustments. The double-door system at the raceway entrance, allowing pigs a choice of stunner entry, could be integrated into existing raceways with adjustments, again depending on original construction. In addition to the physical changes to the floorplan it is important to note that the Improved electrical stunning requires more than double the number of workers to facilitate the less stressful driving of the pigs than the original electrical Stunning Method.

Conversion time depends heavily on the existing facility. Adapting an existing electrical stunning system to the four-stunner layout with raceway modifications could potentially be completed within a timeframe of 1-2 weeks without slaughtering, assuming permits are in place. Converting from CO₂ stunning methods would require more extensive modifications and a longer downtime. Expanding an existing CO₂ facility to accommodate the Improved electrical system's layout would very likely require building permits and environmental approvals, significantly prolonging the process.

Estimated cost of a high throughput system

The Improved Electric system offers a throughput of 170 pigs per hour, which translates to the need for four stunners to achieve a throughput of 680 pigs per hour. It should be noted that due to the changes in personnel going from four to six stunners was not deemed feasible. Instead, the manufacturer suggested that for an increase in stunning capacity to make sense you would have to double from four to eight, as anything else would leave the system and personnel cost unoptimized. Each stunner is estimated to cost 540 k€, resulting in a total equipment estimated cost of 2,160 k€ for the necessary stunners to perform high throughput at >600 pigs/hour. Moreover, the estimated cost to rebuild the slaughterhouse to fit this system is estimated at 3,000 k€ due to the extra area required to fit the additional raceways, stunners and sticking lines. It was also pointed out that while a new modification was being made to the floor plan, floor-heating or water misters could be implemented to ensure better animal welfare during cold or hot weather. This financial data provides a relatively clear understanding of the investment required for the Improved Electric

system. The cost of 2-5 million euros in total of both the stunners and the necessary infrastructure modifications highlights the importance of evaluating the long-term benefits to animal welfare of the alternative.

Strengths, weaknesses and feasibility

Main Strengths

- Uses a commercially available electrical stunner
- Modifications can be completed within a few weeks from existing electrical system
- The new raceway design is relatively easy to build if there is sufficient space
- Electrical stunning is already legal

Main Weaknesses

- Low throughput per stunner
- Requires a much larger area
- Multiple stunners drive up cost
- Requires an extensive redesign of the slaughterhouse to change from high-throughput CO₂ system

How does the Cost of Conversion Make the Alternative More or Less Feasible

The feasibility of converting to the Improved electrical stunning system is heavily influenced by its cost and requirement of entirely new stunners and raceways. Each electrical stunner costs approximately 540k€, resulting in a total of 2,160 k€ for the four stunners needed to reach high throughput, if changing from high throughput CO₂ to Improved electrical. Changing from an existing electrical will only require three stunners as one is reused, putting the cost at 1,620k€. Thus, it's essential to weigh these costs against the potential long-term benefits to animal welfare.

Benchmark Measurements

Please see the Introduction to this appendix and the Appendix B: Analysis Methods section for details on the display format and methods.

Animal welfare

Pre-Stunning handling

Arrival & Moving to Lairage

Table - A 96: Proportion of animals that were slipping and falling or showing high pitched vocalisation during arrival and moving to lairage. The extent of human stimulation was recorded as gentle, moderate (moderate sound or occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

			Arrival			Moving to Lairage		
	Truck	Animals	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation
A	6	1167	0.01	0.01	gentle & moderate	0.00	NA	gentle

B	6	868	0.09	0.00	gentle & moderate	0.07	NA	gentle & moderate
C	6	840	0.01	0.02	gentle	0.00	0	gentle

Lairage

Table - A 97: Proportion of animals that were standing sitting or lying. Additionally, the proportion of fighting and mounting animals was recorded. Recordings were done every 10 minutes for 2 minutes.

	Time of Observation [min]	Animals	BODY POSITION [%]			AVERSIVE INTERACTIONS [%]	
			Standing	Sitting	Lying	Fighting	Mounting
A	10	120	0.96	0.01	0.03	0.01	0.01
	20	120	0.61	0.11	0.28	0.03	0.00
	30	120	0.34	0.13	0.53	0.03	0.00
	40	120	0.19	0.15	0.66	0.01	0.00
	50	120	0.12	0.13	0.75	0.02	0.01
	60	120	0.19	0.20	0.62	0.03	0.00
B	10	197	0.97	0.01	0.02	0.06	0.01
	20	197	0.89	0.04	0.07	0.06	0.02
	30	197	0.72	0.03	0.25	0.04	0.01
	40	197	0.56	0.14	0.29	0.05	0.01
	50	89	0.88	0.09	0.25	0.03	0.03
	60	89	0.80	0.11	0.30	0.04	0.01
C	10	192	0.74	0.13	0.13	0.01	0.01
	20	192	0.58	0.15	0.27	0.02	0.00
	30	192	0.54	0.20	0.27	0.01	0.00
	40	192	0.36	0.22	0.42	0.01	0.00
	50	192	0.24	0.21	0.55	0.00	0.00
	60	192	0.24	0.15	0.61	0.01	0.00

Moving & Entrance Stunner

Table - A 98: Proportion of animals that were slipping and falling or showing high pitched vocalisation during the moving of the pigs to the stunner or the entrance of the pigs into the stunner/raceway as well as the proportion of automatic stimulation. The extent of human stimulation was recorded as gentle, moderate (moderate sound or occasionally touching and pushing of the pig with boards paddle or by hand) and intense (loud sounds of physical stimulation to move the pig).

	Location	Time of Observation	Animals	Slipping + Falling [%]	Vocalisation [%]	Human Stimulation	Automatic Stimulation [%]
A	Moving to Stunner	10	135	0	0.02	NA	0.04
	Moving to Stunner	20	135	0	0.01	NA	0.04
	Moving to Stunner	30	120	0	0.02	NA	0.07

	Entrance Stunner	10	59	0.02	0.03	no stimulation	0.19
	Entrance Stunner	20	122	0.02	0.03	gentle	0.09
	Entrance Stunner	30	127	0	0.02	no stimulation	0.10
B	Moving to Stunner		70	0.14	0.03	intense	0.00
	Moving to Stunner		56	0.04	0.00	gentle	0.00
	Moving to Stunner		79	0.09	0.01	gentle	0.00
	Entrance Stunner		65	0.02	0.00	moderate	0.17
	Entrance Stunner		42	0.00	0.00	gentle	0.10
	Entrance Stunner		72	0.00	0.10	gentle	0.14
C	Moving to Stunner	1	96	0	0	gentle	0.00
	Entrance Raceway	1	8	0	0.00	NA	0.00
	Entrance Raceway	2	8	0	0.00	NA	0.00
	Entrance Raceway	3	8	0	0.00	NA	0.00
	Entrance Raceway	4	8	0	0.13	NA	0.125
	Entrance Raceway	5	8	0	0.00	NA	0.00
	Entrance Raceway	6	8	0	0.00	NA	0.25

Video Analysis

Video analysis for the Benchmark slaughterhouses was carried out at a per gondola group level but using the same ethogram. For parameters up to loss of posture, the time of first animal in a gondola showing the behaviour noted as well as the number of animals that showed this behaviour in total, as well as the number of animals for which this behaviour could be judged (i.e. the number of animals for which the behaviour could have been visible, had they shown it). The times of loss of posture and lying were recorded for both the first and last pig in each gondola. Time of last gasping and last movements were recorded for the last pig as one category. For all benchmark slaughterhouses, the number of animals with abnormal breathing was recorded as the number of animals showing gasping or hyperventilation until the last loss of posture in the gondola. This means that some animals recorded with abnormal breathing here, could have potentially only shown gasping after their loss of posture. The time of first abnormal breathing in a gondola was only assessed for slaughterhouse B. For benchmark slaughterhouse A, entering could not be judged, due to the angles of the video recording. For parameters pertaining the time of behaviours, the group-based analysis causes the calculated means across multiple gondolas in the analysis sections to be shifted towards either earlier (first) or later (last) times than would have been found through analysis at the individual animal level. This needs to be considered when interpreting the data.

Entering

Entering Overview

Table - A 99: Distribution of the maximum (strongest) scored level per group for entering the stunning device. The levels were scored as 0 = none, 1 = reluctance to move, 2 = aversive physical contact, 3 = painful physical contact, 4 = lasting painful physical contact. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the strongest (maximum) scored level for entering of the stunner and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and the number of samples scored with that level. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	σ	Min	Max	95% CI		N
Max Score	A								0
	B		2.6		2	4	2.5	2.7	147
		0 [%]	0.0				0.0	2.5	0
		1 [%]	0.0				0.0	2.5	0
		2 [%]	51.0				42.7	59.3	75
		3 [%]	37.4				29.6	45.8	55
		4 [%]	11.6				6.9	17.9	17
	C		0.9		0	3	0.8	1.1	90
		0 [%]	23.3				15.1	33.4	21
		1 [%]	65.6				54.8	75.3	59
		2 [%]	10.0				4.7	18.1	9
		3 [%]	1.1				0.0	6.0	1
		4 [%]	0.0				0.0	4.0	0

First reluctance to move

Table - A 100: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first reluctance to move relative to the start of the descend of the gondola, calculated from the values recorded for each group. Negative values indicate that the first reluctance to move occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A							0
	B	-17.4	13.5	-66.8	-8.7	-21.3	-13.6	50
	C	-4.3	2.9	-13.8	-1.5	-5.8	-2.7	16
Proportion [%]	A							0
	B	96.5				93.5	98.4	257
	C	50.0				42.1	57.9	162

First aversive physical contact

Table - A 101: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the observed time until the first aversive physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each group. Negative values indicate that the first aversive physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A							0
	B	-13.4	9.4	-52.4	-7.4	-16.1	-10.8	51
	C	-2.8	1.4	-4.0	-0.5	-4.6	-1.0	5
Proportion [%]	A							0
	B	95.3				91.9	97.5	255
	C	7.5				3.5	13.8	120

First painful physical contact

Table - A 102: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first painful physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each group. Negative values indicate that the first painful physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A							0
	B	-9.8	9.4	-47.4	-3.4	-13.2	-6.4	32
	C	-2.7		-2.7	-2.7			1
Proportion [%]	A							0
	B	26.0				20.7	31.8	254
	C	0.9				0.0	5.1	107

First lasting painful physical contact

Table - A 103: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first lasting painful physical contact relative to the start of the descend of the gondola, calculated from the values recorded for each group. Negative values indicate that the lasting painful physical contact occurred before the start of the descend. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A							0
	B	-14.0	12.4	-39.1	-2.1	-22.3	-5.6	11
	C							0
Proportion [%]	A							0
	B	6.7				3.9	10.5	255

	C	0.0				0.0	3.5	105
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Initial reaction

Initial Reaction Overview

The scores range from 0 (dark green) to 3 (red). 0=no reaction; 1=response to atmosphere, 2=agitation; 3=strong agitation.

Table - A 104: Distribution of the maximum (strongest) scored level per group for the reaction to the gas atmosphere in the induction phase. The levels were scored as 0= no reaction; 1= response to atmosphere, 2= agitation; 3= strong agitation. The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of these strongest (maximum) scored initial reaction and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95% confidence interval (95% CI) and number of samples scored with that level. A detailed description of these scores is provided in the ethogram in the appendix B.

	Condition	Level	Mean	Min	Max	95% CI		N
Max Score	A		2.8	2	3	2.6	2.8	124
		0 [%]	0.0			0.0	2.9	0
		1 [%]	0.0			0.0	2.9	0
		2 [%]	25.0			17.7	33.6	31
		3 [%]	75.0			66.4	82.3	93
	B		2.0	1	3	1.8	2.1	107
		0 [%]	0.0			0.0	3.4	0
		1 [%]	35.5			26.5	45.4	38
		2 [%]	33.6			24.8	43.4	36
		3 [%]	30.8			22.3	40.5	33
	C		2.2	2	3	2.2	2.3	104
		0 [%]	0.0			0.0	3.5	0
		1 [%]	0.0			0.0	3.5	0
		2 [%]	75.0			65.6	83.0	78
		3 [%]	25.0			17.0	34.4	26

First response to atmosphere

Table - A 105: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first response to the atmosphere, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each group. Negative values indicate that the first response to the atmosphere occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
	A	11.1	4.9	4.9	35.2	9.5	12.6	41

Start descend [s]	B	10.2	3.0	3.7	21.2	9.3	11.0	45
	C	11.2	1.9	6.6	14.7	10.3	12.0	21
Loss of posture [s]	A	-7.3	2.7	-12.4	-0.7	-8.1	-6.4	41
	B	-5.7	3.2	-13.0	4.9	-6.6	-4.7	45
	C	-10.3	2.8	-17.4	-4.1	-11.6	-9.0	21
Proportion [%]	A	50.0				43.6	56.4	244
	B	75.4				69.5	80.7	244
	C	83.9				77.0	89.4	149

First agitation

Table - A 106: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first agitation, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each group. Negative values indicate that the first agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown in percent. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A	15.1	4.9	8.3	37.2	13.5	16.6	40
	B	14.7	4.1	6.5	24.6	13.2	16.1	32
	C	16.6	2.9	11.9	23.2	15.3	17.9	21
Loss of posture [s]	A	-3.3	3.1	-11.1	5.7	-4.2	-2.3	40
	B	-1.3	4.1	-12.2	8.3	-2.8	0.2	32
	C	-4.8	2.7	-9.6	1.1	-6.0	-3.6	21
Proportion [%]	A	49.6				43.4	55.8	264
	B	22.1				17.3	27.6	267
	C	81.7				74.6	87.5	153

First strong agitation

Table - A 107: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first strong agitation relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each group. Negative values indicate that the first strong agitation occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A	17.3	5.0	11.3	39.5	15.5	19.1	33
	B	14.9	3.7	8.8	23.0	13.3	16.5	23
	C	17.1	1.8	15.5	20.5	15.5	18.7	7
	A	-0.9	3.4	-7.6	7.5	-2.1	0.4	33

Loss of posture [s]	B	-0.3	4.1	-8.3	7.2	-2.1	1.5	23
	C	-2.4	2.2	-5.1	1.5	-4.5	-0.4	7
Proportion [%]	A	35.2				29.5	41.3	264
	B	11.8				8.3	16.2	280
	C	18.8				12.7	26.4	138

First abnormal breathing

Table - A 108: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the first abnormal breathing, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each group. Negative values indicate that the first abnormal breathing occurred before the referenced time. In addition, the proportion of animals showing the behaviour ("Proportion") is shown. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	B	9.4	2.6	4.4	14.4	8.6	10.3	38
		Loss of posture [s]	-15.2	5.1	-30.6	-8.4	-16.9	-13.6
Proportion [%]	A	3.5				1.7	6.4	282
	B	36.7				29.8	44.0	188
	C	23.1				16.6	30.8	147

Stunning progress

Loss of posture

Table - A 109: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the loss of posture relative to the start of the descend of the gondola, calculated from the values recorded of the first and last pig losing posture in the gondola. Number of samples = N

	Condition	Level	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A	First	18.3	4.6	9.1	41.3	16.9	19.8	41
		Last	28.8	6.0	21.9	55.0	26.9	30.7	41
	B	First	15.8	1.9	11.5	20.6	15.3	16.3	51
		Last	24.3	3.6	19.4	37.3	23.3	25.3	51
	C	First	21.4	2.9	15.3	26.2	20.1	22.8	21
		Last	30.4	3.8	24.5	39.0	28.7	32.1	21

Lying

Table - A 110: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until lying, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for the first and last lying in each gondola. Number of samples = N

	Condition	Level	Mean	σ	Min	Max	95% CI		N
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Start descend [s]	A	First	29.0	7.1	10.5	47.1	26.7	31.2	41
		Last	54.7	14.6	29.8	102.0	50.1	59.3	41
	B	First	24.8	3.2	18.2	31.6	23.9	25.7	51
		Last	33.6	4.8	25.3	48.7	32.2	34.9	51
	C	First	25.7	3.4	18.5	32.2	24.2	27.3	21
		Last	38.3	5.6	27.6	46.8	35.7	40.8	21
Loss of posture [s]	A	First	10.6	5.6	1.4	24.3	8.8	12.4	41
		Last	36.4	13.7	12.5	82.2	32.0	40.7	41
	B	First	9.0	3.2	3.1	17.0	8.1	9.9	51
		Last	17.8	4.4	9.6	31.9	16.5	19.0	51
	C	First	4.3	2.2	0.7	9.7	3.3	5.3	21
		Last	16.8	4.8	8.9	24.0	14.6	19.0	21

Last movement

Table - A 111: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the time until the last movement, relative either to the start of the descend of the gondola (top) or to the time of loss of posture (bottom), calculated from the values recorded for each group. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A	162.8	22.5	101.7	212.4	155.7	169.9	41
	B	161.1	15.5	117.4	195.7	156.8	165.5	51
	C	141.6	7.4	128.3	168.2	138.2	145.0	21
Loss of posture [s]	A	134.0	22.5	77.8	182.9	126.9	141.1	41
	B	136.8	15.8	89.1	166.6	132.4	141.3	51
	C	111.2	9.1	95.3	142.0	107.1	115.3	21

Cycle duration

Table - A 112: Mean, standard deviation (σ), minimum (Min), maximum (Max) and 95% confidence interval (95% CI) of the cycle duration relative to the start of the descend of the gondola. Note that this is an operational parameter reflective of the set stunning times. Number of samples = N

	Condition	Mean	σ	Min	Max	95% CI		N
Start descend [s]	A	206.9	53.9	172.7	394.6	189.8	223.9	41
	B	195.2	40.4	158.1	337.0	183.9	206.6	51
	C	158.1	35.1	147.7	309.8	142.1	174.1	21

Stunning Effectiveness

Table - A 113: Stunning effectiveness, Re-stun rate and 95% confidence interval (95% CI). Confidence intervals are for one sided tests.

Condition	Dwell Time [s]	N	Re-stun rate [%]	95% CI
A	190	150	0.0	2.0
B	180	150	0.7	3.1
C	120	150	2.0	5.2

Meat Quality

These data consist of two benchmark sites where data were collected as part of the PigStun project (Benchmarks 1 & 2), and three studies recently published from Poland (Rybarczyk et al. 2015), Denmark (Aaslyng & Hviid 2020), and Greece (Mantis et al. 2019). The benchmark sources do not contain all the same parameters measured at the four PigStun systems and are therefore missing in some of the charts.

Carcass

After 45 min

Table - A 114: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 45 minutes post-mortem for animals stunned under different conditions (1,2, A&H, M et al., R et al.) as well as the number of samples (N). The proportion of samples with a pH45 below 6.1 (pH45<6.1) or 5.8 (pH45<5.8) and the temperature for the subset of samples where the pH45 was below 6.1 (T(pH45<6.1)) are shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
1	pH	6.5	0.2	b	5.9	6.9	6.4	6.5	50
2		6.4	0.1	a	6.2	6.6	6.3	6.4	45
A&H		6.6	0.2				6.6	6.6	246
M et al.		6.4	0.2				6.4	6.4	590
R et al.		6.3	0.2				6.2	6.4	60
1	T [°C]	38.1	1.0	b	34.1	39.2	37.7	38.4	44
2		36.2	0.8	a	34.6	38.5	35.9	36.4	45
A&H		39.5	0.7				39.4	39.6	247
M et al.		37.9	1.9				37.7	38.0	590
R et al.		39.2	1.3				38.8	39.5	60
1	T(pH45<6.1) [°C]	37.0	2.6		34.1	39.0	30.6	43.5	3

	pH<6.1 [%]	6.0		a			1.3	16.5	50
2		0.0		a			0.0	7.9	45
1	pH<5.8 [%]	0.0		a			0.0	7.1	50
2		0.0		a			0.0	7.9	45

After 24 h

Table - A 115: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (pH, T) measured 24 hours post-mortem for animals stunned under different conditions (1,2, A&H, M et al., R et al.) as well as the number of samples (N). The pH (24h) of the subset of samples with a pH45 below 6.1 (pH45<6.1) is shown as well. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
1	pH	5.5	0.1	a	5.3	5.7	5.5	5.5	45
2		5.8	0.1	b	5.6	6.0	5.8	5.8	
A&H		5.7	0.1				5.7	5.7	248
M et al.		5.5	0.1				5.5	5.5	590
R et al.		5.6	0.1				5.6	5.7	60
1	pH(pH45<6.1)	5.4	0.0		5.3	5.4	5.2	5.5	3
	T [°C]	2.5	0.1	b	2.3	2.9	2.5	2.6	44
2		1.5	0.3	a	1.0	2.4	1.4	1.6	45
A&H		4.0	0.1				3.9	4.0	248
M et al.		6.3	2.5				6.1	6.5	590
R et al.		2.3	0.7				2.1	2.5	60

Cut

Colour

Table - A 116: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of different meat quality parameters (L, L(pH45 < 6.1), a, b) measured for animals stunned under different conditions (1,2, A&H, M et al., R et al.) as well as the number of samples (N). Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
1	L								0

2									
A&H		51.9	3.1				51.5	52.3	248
M et al.		52.1	3.1				51.8	52.3	590
R et al.		55.1	3.3				54.2	55.9	60
1	a								0
2									
A&H		6.3	1.0				6.1	6.4	248
M et al.		5.7	1.3				5.6	5.8	590
R et al.		6.5	1.2				6.2	6.8	60
1	b								0
2									
A&H		3.9	1.0				3.7	4.0	248
M et al.		13.3	0.9				13.3	13.4	590
R et al.		13.6	1.1				13.4	13.9	60

Drip Loss

Table - A 117: Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Drip Loss (%) measured for animals stunned under different conditions (1,2, A&H, M et al., R et al.) as well as the number of samples (N). Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters (comparisons are valid only within the same parameter).

Condition	Parameter	Mean	σ	*	Min	Max	95% CI		N
1	Drip Loss [%]								0
2		2.7	1.3		0.3	5.2	2.3	3.1	40
A&H		2.2	1.3				2.1	2.4	248
M et al.		4.7	2.4				4.5	4.9	590
R et al.		3.0	1.6				2.6	3.4	60

Blood Spots

Table - A 118: Distribution of scored level of blood spots. Blood spots were scored as 0 = no blood spots, 1 = less than 5 blood spots, 2 = less than 30 blood spots, 3 = more than 30 blood spots. Mean, standard deviation (σ), minimum (Min), maximum (Max), 95% confidence interval (95% CI) of Blood Spots measured for animals stunned under different conditions (1,2, A&H, M et al., R et al.) and the number of samples (N). The first row for each measurement condition shows the mean, minimum (Min), maximum (Max) and 95% confidence (95% CI) of the blood spots levels and the total number of samples (N). The following rows show the percentages of occurrence for each level along with the 95%

confidence interval (95% CI) and number of samples scored with that level. Results from statistical tests are indicated in the column * in compact letter display form, where statistically different conditions are indicated by different letters.

Condition	Level	Mean	σ	*	Min	Max	95% CI		N
1									0
2		0.2			0	3	0.1	0.6	39
	0 [%]	87.2					72.6	95.7	34
	1:<5 [%]	5.1					0.6	17.3	2
	2:<30 [%]	5.1					0.6	17.3	
	3:>30 [%]	2.6					0.1	13.5	1

Economic, environmental and social parameters

Economic parameters

Alternative methods explored in this report will be compared in terms of cost per slaughtered pig to the study cases described and reported in D1 (see annex). As described before, the technical and cost parameters for the alternative systems were estimated by ‘implementing’ them in the relevant study case. The aim was to reach the same number of pigs slaughtered before implementing the alternative system. Hence rather than a direct comparison with the study cases, is a comparison between the alternative systems once they have been implemented in each of these study cases (see across system analysis). Here we report the cost per pig as reported in D1 for each of the study cases (Table - A 119).

Table - A 119: Cost per pig (cents) for each study case implementing the relevant alternative stunning system. CO₂-1, CO₂-3 and CO₂-4: study cases reported in D1 with a conventional CO₂ stunning system using paternoster system; and CO₂-2: using dip-lift system. E-1: study case, Electrical-1, reported in D1 with a conventional electrical stunning system.

Cost per pig	CO ₂ -1	CO ₂ -2	CO ₂ -3	CO ₂ -4	E-1
Instillation cost	7.11	2.54	2.78	12.51	3.01
Maintenance costs	5.69	3.27	3.06	9.56	0.54
Labour costs	44.19	33.46	24.35	22.99	27.69
Water costs	4.86	0.31	0.04	5.37	3.46
Electricity costs	0.25	0.12	0.26	2.85	0.45
Gas costs	11.37	12.13	5.32	10.61	0.00
Total	73.47	51.83	35.81	63.89	35.15

Environmental parameters

The livestock industry contributes with 14.5% of the total human-induced greenhouse gas emissions (GHG), whereas pig meat production contributes with 9% (Gerber et al., 2013).

Within pig production (cradle to slaughterhouse gate), the main environmental impact is attributed to the primary production including the feed and animal production and handling of manure. The contribution from

the slaughterhouse activities is a minor part, compared to the contribution from cradle to the slaughterhouse gate (Dorca-Preda et al., 2021; Reckmann et al., 2013). The main environmental impact at the slaughterhouse is abiotic depletion (fossil fuels) (Al-Zohairi et al., 2023; Dorca-Preda et al., 2021), which contributed with 25% of the total impact from cradle to slaughterhouse gate on Danish pig meat in 2016 (Dorca-Preda et al., 2021). The other impact factors analysed in the study by Dorca-Preda et al. (2021) include climate change, soil carbon, indirect land use change, direct land use change eutrophication potential, acidification, and land occupation. These results were consistent with a study from Germany, where the slaughterhouse process contributed with between 1-12 % of the overall environmental impact including the impact categories: Global warming potential, eutrophication, acidification, and non-renewable energy (Reckmann et al., 2013). The two studies show that the slaughterhouse process contributes to the environmental impact, but with quite different effect (Dorca-Preda et al., 2021; Reckmann et al., 2013)

In general, the environmental impact of certain animal production systems can be decreased by either reducing the input or increasing the outputs (Mogensen et al., 2016). Regarding the slaughterhouse process this could be done by higher utilization of the proportion of pig parts used for human consumption and use of by-products for pet feed, biofuel, and biogas together with increasing the share of renewable energy (Al-Zohairi et al., 2023; Dorca-Preda et al., 2021). Utilization of live-weight pigs and animal by-products can differ between slaughterhouses. The main causes of differences are export options, legislative requirements, and economic viability (Al-Zohairi et al., 2023).

The impact categories and the functional unit, used for determining the environmental impact, are important for the final result. The guidelines for FAO (2018), can be used to assess the environmental impact of the pig production system (cradle to slaughterhouse gate).

Environmental impact from current systems with CO₂ stunning

The search in Web of Science resulted in 46 papers and did not reveal any relevant publications on the environmental impact of stunning with CO₂.

For the environmental impact in terms of efficiency, data from Deliverable 1 was used as the base level for stunning with high concentration CO₂. The time of cycle (defined as the time from when the pig gets in the stunner until they are removed from the stunner) was between 145 and 250 seconds. Some variations are associated with the system (paternoster or dip-lift), the capacity of the gondola, and the variance in CO₂ concentration (88-98%). The average stun-to-stick time depends on how long the pigs are in the CO₂ and the group size (EFSA, 2004). The stun-to-stick time in the slaughterhouses presented in deliverable 1 was between 45 and 95 seconds and will be used as the base level

Environmental impact in terms of resource use was defined in deliverable 2, where the benchmark for electricity was 86 kWh per 1000 kg live weight. For water and detergent, it was 2,0 M3 and 0,8 kg, per 1000 kg live weight.

Environmental impact from current system with Electrical stunning

The search in Web of Science resulted in 46 papers and did not reveal any relevant publications on the environmental impact of stunning with electrical stunning.

For the environmental impact in terms of efficiency, data from Deliverable 1, was taken as the base level for electrical stunning. The exposure time and stun-to-stick time are to our knowledge similar between the traditional electrical stunning and the alternative. The pigs per hour were on average 680.

Social parameters

The authority from Germany answered that both stunning methods were considered safe for the employees, and to their knowledge, no relevant work-related accidents in the pig stunning process in Germany.

The Danish authority for working environment sent some data on the work accidents in Danish slaughterhouses. No data was available on the connection between stunning methods and work accidents. However, since 98% of the slaughterhouses in Denmark use carbon dioxide for stunning, it can be assumed that the work accidents mainly relate to the system with carbon dioxide. Between 2019 and 2023, the average number of work accidents was 586.

Across systems comparisons

Animal Welfare: Overview of (unique) benefits and challenges

Below a summary table with all results presented based on how each system or gas compares for each evaluated parameter.

A unique benefit or challenge is determined by whether a metric is beneficial, neutral, or detrimental for only one system. In other words, below the metrics are described for which there is a clear better or worse alternative system for the compared parameters. A system is considered beneficial when it shows a significant improvement to its CO₂ counterpart (Argon or Helium) or a substantial improvement to the CO₂ benchmarks (BM). Conversely, a challenge reflects the opposite, that is, when any system is detrimental. A system is considered neutral for a specific metric when neither significant nor substantial differences are found in at least one direction. For example, if all systems (Y & Z) improve a metric except for one (X) that shows no change, the neutrality of system X is unique because it is the worst-performing system overall (a challenge). Conversely, if all systems worsen the metric, except for one that shows no change (a benefit), its neutrality is also unique. However, unique neutrals are not evaluated as such if some of the comparisons are not available due to lack of data).

No data refers to when no quantification occurred for that metric in a system for either the alternative or its CO₂ counterpart. Uninformative refers to metrics that do not per se inform of an improved welfare condition, as they rely on other metrics to be assessed (i.e., whether abnormal breathing begins earlier or later in a system is less relevant than for how long that abnormal breathing occurs).

Since no measurements could be taken for commercial CO₂ stunning (without a 45-minute wait) in similar conditions to the Box system for the Optimised CAS process; Ar, He, and CO₂ were compared against each other within the Box system. Additionally, the Box CO₂ condition was compared to benchmark measurements to determine whether the Box system—where pigs are resting and lying down before and during gas exposure—offers advantages over standard CO₂ stunning.

Table - A 120: Summary of each system's (unique) benefits and challenges.

System(s)	Argon Retrofit	Helium System	Box System	Box System	Box System	Box vs BM	Electric vs BM
Gas(es)	Ar vs CO ₂	He vs CO ₂	Ar (BOX) vs CO ₂ (BOX)	He (BOX) vs CO ₂ (BOX)	Ar (BOX) vs He (BOX)	CO ₂ (BOX) vs CO ₂ (BM)	Electric
ENTERING							
Entering Overview Scores (%)							
Entering Overview Scores (Mean Score)							

Duration First Reluctance to Move - Start (s)							
Proportion of animals with reluctance to move (%)							*
Duration First Aversive Physical Contact - Start (s)							
Proportion of animals with aversive physical contact (%)							
Duration First Painful Physical Contact - Start (s)							
Proportion of animals with Painful Physical Contact (%)							
Duration First Lasting Physical Painful Contact - Start (s)							
Proportion of animals with Lasting Painful Physical Contact (%)							
INITIAL REACTION							
Initial Reaction Scores (%)							
Initial Reaction Scores (Mean Score)							
Duration Start - First Strong Agitation (s)							
Duration First Strong Agitation - Loss of Posture (s)							
Proportion Strong Agitation (%)							
Duration Start - First Abnormal Breathing (s)							
Duration First Abnormal Breathing - Loss of Posture (s)							

Proportion of animals with abnormal breathing (%)							
Duration Start - First Response to Atmosphere (s)							
Duration Start - First Agitation (s)							
Cycle Duration (s)							
Duration First Response to Atmosphere - Loss of Posture (s)							
Duration First Agitation - Loss of Posture (s)							
Proportion with Response to Atmosphere (%)							
Proportion Agitation (%)							
STUNNING PROGRESS							
Duration Start - Loss of Posture (s)							
Duration Start - Lying (s)							
Duration Loss of Posture - Lying (s)							
Duration Start - Last Movement (s)							
Duration Loss of Posture - Last Movement (s)							
Stunning Efficiency							

* Two proxies were used in the evaluation of the electrical system's effect on reluctance to move: the first was reluctance to move in the raceway, where a decrease was observed (beneficial); the second was reluctance to enter the stunner, where no change was noted (neutral).

Table - A 121: Key to the table above.

	Beneficial
	Neutral
	Detrimental

	No data
	Unique Beneficial
	Unique Neutral
	Unique Detrimental
	Uninformative

Economic, environmental and social impact: considerations

Table - A 122: Important aspects to consider when exploring the cost per pig reported in Table 2 and Table 3 for the alternative stunning system. Please note that where the value is not available or is unknown and no estimation is available, this has not been included in the calculation of the cost per pig.

Alternative stunning system	Aspects
Argon Retrofit system	Cost of a new stunner for dip-lift and paternoster system is unknown. Here we use the cost reported by the study cases.
	The cost of installation from CO ₂ -3 corresponds to an old stunner and therefore much cheaper than the other stunners.
	Table 3 shows an estimation of the cost of a paternoster system with more gondolas based on the assumption that a system that compensates the reduction in 40% of throughput would be 40% more expensive.
	Cost of maintenance is estimated to be similar to cost reported by study cases using CO ₂ .
	Cost for argon is an estimation relative to the price for CO ₂ estimated by a relevant expert.
	Throughput is estimated on the assumption that an increase in 40% of the dwell time would result in a reduction in 40% of the throughput.
	Amount of gas, water and electricity are estimated to be similar than CO ₂ systems
Helium stunning system	Cost of maintenance is unknown
	Cost of helium is an estimation relative to the cost of CO ₂ . Helium price is volatile.
	The installation investment reported here corresponds to the cost of the whole pilot project. Some of the items included in the cost do not depend on the number of stunners. Hence, the cost for additional lines will be lower. However, in this deliverable the cost is multiplied by the number of stunners. The cost for a stunner with a larger gondola is unknown, hence we use the same value.
	Amount of water and electricity are estimated to be similar to the study cases using CO ₂

	Amount of helium is estimated on the basis of the total volume of the tower and the estimation of the amount of gas that can be recovered daily
Backloader system for the Optimised CAS process	Cost of maintenance is unknown
	Amount of water, electricity, gas and people are estimated to be similar to study case CO ₂ -2
Improved electrical stunning process	Electricity is 4 times the amount reported in case study Electrical-1
	Cost of maintenance is estimated to be similar to cost reported by study cases using a conventional electrical stunning.

Appendix B: Analysis Methods

Statistical analyses

In order to explore the differential analysis between alternative systems by taking the parameters for animal welfare and meat-quality into consideration, the same descriptive and inferential statistics for analysing meat quality and animal welfare data collected at both the individual animal level and the gondola (group) level were used. To identify the significant pattern in the data (Table - B 1 and Table - B 2), central tendency (Mean; for continuous data, percent; for binomial data) as well as measure of dispersion (Standard deviation- SD), Min and Max; for continuous data, percentages of individual scores; for ordinal data) for each of the variables, was measured. To provide a range within the true mean of the population is likely to fall, a two-sided 95% confidence interval using t-test for respective parameters was performed. For binomial data - as part of descriptive statistics- proportions were calculated (percentages of estimates meeting a particular condition) and used as a two-sided binomial test to calculate the confidence interval for the proportion. Regarding ordinal data, frequencies and percentages for each category were calculated. Upon determining the total number of data points for ordinal variables, the frequency and percentage of each category (e.g., different levels of blood spots) was calculated. A two-sided binomial test was used to calculate the confidence interval.

Table - B 1: Data analysis plan for meat quality variables and animal welfare indicators for 'within system analysis'.

Data type	Descriptive Statistics				Inferential Statistics			
	i: # Animals	ii: Tendency	iii: Variation	iv: Confidence	i: Model	ii: Sided	iii: Effects	iv: Test
Continuous	N	Mean	SD, Min, Max	Two-sided t-test	Linear	Two-sided	Only those common for all systems	EMM
Binomial	N	Percent		Two-sided binomial	Generalized Linear			
Ordinal	N	Mean	Percent each	Two-sided binomial each	Cumulative Link			

To test hypotheses and determine whether the observed differences or relationships are statistically significant, hypothesis testing as described in Table - B 1 namely linear model (e.g., ANOVA or regression for continuous variables), generalized linear model (GLM) for binomial data and cumulative link model for ordinal parameters was applied. When conditions (> more than two) are tested, post-doc analysis with estimated marginal means (EMM) was carried out to test which of the specific conditions varies from each other. If additional information like sex, weight, genetics, age of animals were available, data was collected on group level and included in the model to analyse the confounding effects. In case of per gondola analysis, specific quantile comparisons (e.g., comparing the 20%, 50%, and 80% quantiles) were used to evaluate differences between gondolas with varying animal numbers.

Animal Welfare

Variables from behaviour inside the gas stunner were collected via video analysis either at the animal or gondola level. The Videos were analysed based on Parameters that were defined as part of WP2 (assessment protocol). The Parameters on the induction phase and stunning progress have been used in prior studies to assess animal welfare for stunning with CO₂, inert gases and inter gas mixtures with CO₂ (e.g. Dalmau et al. 2010, Llonch et al. 2012a, Llonch et al. 2012b, Atkinson et al 2020).

The ethogram (Table - B 2) containing the variables used to assess the animal welfare aspect along with their data type and the coding instructions is presented below. Due to the absence of audio from the video materials obtained from some systems/slaughterhouses or because it would not be possible to isolate the origin of specific vocalizations, it was decided to not to include vocalizations as a parameter in the analysis. To estimate the time to induction of unconsciousness, the time of loss of posture (LoP) was used as a proxy for the onset of unconsciousness. LoP is the earliest indicator of potential loss of consciousness (EFSA, 2017). While LoP should not be considered a proof of unconsciousness at that exact time, a previous study on stunning with CO₂ and nitrogen CO₂ mixtures, found LoP to correlate with an EEG based measures unconsciousness (Llonch 2013). Similarly, the parameter lying is used to mark the time deep unconsciousness is reached. It has previously been shown by Forslid that movements typically occur after loss of posture and before the animal is lying still, occur at a time after a reduction in EEG activity occurs. The exact time when an animal becomes unconscious between LoP and lying cannot be assessed here.

In the three alternative gas stunning systems, individual parameters were collected on a per-animal basis to ensure a detailed analysis of each animal's behaviour and physiological response during the stunning process, with video analysis from the Helium System being limited to one or two selected animals per gondola. Additionally, in the Helium system for behaviours relating to the Entering phase, only the first pig showing a given behaviour was taken into consideration. For cases where two animals were coded in a gondola, it was assumed for analysis that both animals coded for that gondola exhibited the behaviour observed in the first pig. The (individual) parameters were analysed independently to estimate specific behaviours during initial loading (e.g., reluctance to move, aversion or painful physical contact), first reactions, and abnormal breathing. The time of first occurrence of each behaviour was considered relative to the start of the gondola as well as relative to the loss of posture (LoP). Additionally, for behaviours related to loading and initial reactions independently, the worst/most severe behaviour observed for that animal was noted, and the proportions of animals for worst behaviours were captured. For the following parameters such as LoP, lying and last movement, the onset of behaviour after the start of the gondola and the time of first behaviour relative to LoP were assessed.

With the exception for Box system for the optimized CAS process, the partner associated with each alternative system or responsible for obtaining videos from benchmark slaughterhouses analysed these videos on their own after a shared calibration (Argon Retrofit System by FLI and Helium System by MRI, Benchmark slaughterhouse A: DTI, B: FLI, C: WLR). To analyse the videos for Box System, equal number of stunning sequences from each gas condition (i.e; CO₂, Ar and He) were shared between MRI and WLR. Videos were split so that videos for each gas condition were equally shared by two institutes. To ensure unbiased assessment in the Argon Retrofit system, the videos were shuffled in such a way that observers were unaware whether a given video was from Argon stunning or from the local CO₂ control condition in the same stunner.

All videos pertaining to video analysis were scored independently by observers using BORIS software (<https://www.boris.unito.it/>) For calibration of video analysis, a representative video of animal stunning (CO₂ stunning based) containing two video sequences sourced from a UFAW HSA conference by BSI Schwarzenbeck (von Holleben & von Wenzlawowicz, 2020) was distributed to all observers. The video served the aim of analysing videos using both group and individual animal approach. Observers independently assessed the selected welfare attributes based on the predefined criteria and subsequently scored the calibration video. Observers were further requested to score a video sequence captured from their own system using the approach they planned to implement. Following the scoring, a video conference was organized where sequences of videos were watched together, individual opinions regarding scoring along with assessment justification was received, compared and discussed, and finally adjusted to have a uniform assessment from all video observers.

Video analysis for the Benchmark slaughterhouses was carried out at a per gondola group level using the same ethogram. For parameters up to loss of posture, the time of first animal in a gondola showing the behaviour was noted as well as the number of animals that showed this behaviour in total, as well as the

number of animals for which this behaviour could be judged (i.e. the number of animals for which the behaviour could have been visible, had they shown it). The times of loss of posture and lying were recorded for both the first and last pig in each gondola. Times of last gasping and last movements were recorded for the last pig as one category. For all benchmark slaughterhouses, the number of animals with abnormal breathing was recorded as the number of animals showing gasping or hyperventilation until the last loss of posture in the gondola. This means that some animals recorded having abnormal breathing may have only exhibited gasping after their loss of posture. The time of first abnormal breathing in a gondola was only assessed for slaughterhouse B. For benchmark slaughterhouse A, entering could not be judged, due to the angles of the video recording. For parameters pertaining the time of behaviours, the group-based analysis causes the calculated means across multiple gondolas in the analysis sections to be shifted towards either earlier (first) or later (last) times than would have been found through analysis at the individual animal level. This needs to be considered when interpreting the data.

Table - B 2: Ethogram for the analyses of videos for animal welfare aspects.

Category	Indicator	Type	Definition	Coding Type	level
Entering/ loading stress	Reluctance to move	optional	A pig stopped walking, without moving its head and body	First Proportion +	animal
	Aversive physical contacts	optional	Animal is pushed directly (human or automatic gate) or indirectly (other pigs) into the stunner.		
	Painful physical contact	optional	Gate briefly closing onto a pig that results in a short but strong reaction from the pig (e.g. a squeal) or an animal being forcefully shoved or hit.		
	Lasting painful physical contact	optional	Physical contact that likely causes a more than brief painful sensation or an animal being squeezed by a gate in a situation where it cannot or does not quickly remove itself from the situation		
Process	Start movement	single	Gondola starts ascending/descending		Gondola
	Stocking density	numeric	Number of animals in the gondola		Gondola
Initial Reactions	(First) response to atmosphere	optional	A response recorded after the gondola has started the descent, that is not a direct reaction to the movement start of the gondola. The pig responds with additional alertness by starting sudden, typically small, movements, raising the head with increased sniffing or licking or standing up if were previously lying, or simple retreat attempts (a spontaneous movement forward or backing).	First Proportion +	Animal
	Agitation	optional	Increased activity prior to loss of posture. This will include rapid turning around, retreat attempts with arching of the back, or lateral head movements or trying		

			to get up again from a sitting or lying position.		
	strong Agitation	optional	Intense activity or excessive movements and escape attempts, prior to loss of posture, such as jumping and climbing.		
Abnormal Breathing	Gasping	multiple	Deep breath through a rapidly wide opening and closing mouth before loss of posture		
	Hyperventilation	optional	Breathing through a constantly open mouth or with high frequency		
Stunning Progress	Loss of posture	single	The pig lies or falls down and is no longer able to stand or sit and does not regain standing or sitting posture and does not show obviously willing attempts to regain a standing or sitting position. Alternatively, loss of posture is assumed in a situation where the pig remains a sitting posture while displaying opisthotonos (dorsiflexion of neck) indicating that the pig would not be able to regain standing posture, but side walls or other pigs support the pig preventing the pig from lying down normally.	First + Last	
	Lying	optional	The pig is in a state with mostly relaxed muscles without trying to regain posture, with no sign of coordinated or excessive (potentially involuntary) movements. Muscle jerks and gasping can still occur.	First + Last	
	Last movements	multiple	Last movements (incl. Gasping) after loss of posture	Last + Proportion	
Process	Ejection	single	First animal has fallen out of gondola		Gondola

For each parameter the event type (single, optional, multiple), the coding type (first, last, period) and the level (per gondola or per animal) are given. "Single" = event occurred for each animal when stunning was successful; "optional" = event could only occur once, but does not have to occur at all; "multiple" = event can occur multiple times; "first" = Time of the first animal showing that behaviour, "last" = Time of the last animal showing that behaviour, "proportion" = percent of animals showing behaviour per gondola (including number of animals showing that behaviour and number of animals for which behaviour can be judged)

Meat Quality

For all stunning methods pH and temperature were measured at 45 minutes and at 24h post-mortem (PM) at the left side of the carcass in the Longissimus dorsi muscle. Furthermore, carcasses were inspected for bloodspots and bleedings or bruises and samples were taken for the drip loss analyses and for colour measurements. All meat quality measurements were executed following the SOP's from the EU funded project meat quality and are also described in Deliverable 3.

Parameters measured for meat-quality along with their data type are mentioned below in Table - B 3:

Table - B 3: Parameters relevant to meat-quality measurement

1	pH	pH45: at 45-min	Continuous
		pH24: at 24-hr	
2	Temperature	T45: at 45-min	Continuous
		T24: at 24-hr	
3	Percentage (%) of carcasses with pH45 below 5,8		Binomial
4	Temperature (T45) of carcasses with pH45 below 5,8		Continuous
5	Colour		Continuous
6	Blood spot	Haemorrhages on the surface	Scoring
		None	0
		Multiple point bleeding	1
		5-30 spots on the muscle	2
		>30 spots on the muscle	3
7	Drip-loss		Continuous

Methods for the Interviews with Slaughterhouse Representatives

Representatives associated with a decision-making capacity for conversion were contacted for interviews in early October. Due to work commitments, only three out of 4 could participate within the desired timeframe. Interviews were conducted between 28.10 and 1.11 2025 on Zoom and recorded on a voice recorder.

The interviewees were provided with preliminary results and additional information regarding Animal Welfare, Meat Quality, and the Environment, Economic, and Social Impact. Due to the preliminary nature of these results, they will not be published and were produced solely for the purpose of these interviews. Additional comments were provided to the interviewees on the day of interview regarding the throughput of Argon and the throughput capacity of Helium, where relevant.

Due to insufficient information about the envisioned upscaled (high throughput) implementations regarding the Optimised CAS process system at the time of the interviews, AU decided that for this alternative only the results about meat quality and animal welfare from the Box system could be included and other aspects (e.g. economics and ease of conversion) could not be discussed.

The interview material was transcribed and coded. Taking a grounded theory analytical approach, the interviews were analysed through a system of open coding to identify common themes and ideas emerging from the perspectives of the participants. The findings have been arranged according to their satisfaction levels with their current system, their initial reflections on the alternatives, preferences for future conversion, and recommendations to assist further development of the alternatives.

The interviews lasted between 45 mins and 1 hr and were based on an interview guide based on the material shared with the interviewees. As these were semi-structured interviews, the participants were invited to share their thoughts and reflections beyond the specific questions that were posed which facilitated a broader understanding of the decision-making processes underpinning conversion. Interviewees provided their informed consent and were informed that their responses will not be correlated to their company thus, in the remainder of this document, they will not be differentiated or will be referred to as P1, P2, and P3.

Economic, environmental and social impact

Economic impact

Definitions

Data were collected through the application of questionnaires and follow-up one-on-one meetings with the relevant experts for each of the alternatives. Questions were aimed at collecting information about the estimated technical parameters and costs of their alternative stunning system to estimate the parameters used for the economic model. The parameters used are defined in Table - B 4. In the case of the Improved electrical stunning system, parameters (but for amount of electricity and proportion of pig discarded due to meat quality issues) were obtained from a commercial slaughterhouse in which it has already been implemented.

Table - B 4: Parameters used for the economic model

Cost factor	Description
Installation investment €	The costs of installing the stunner for a pig slaughterhouse. In this report, this is the cost of the alternative stunning equipment installed in the study cases (i.e. the cost from any current equipment reused is not included here but added to the cost per pig calculations (obtained from D1)).
Depreciation rate %/year	The proportion of the investment per year needed for replacing the installation
Maintenance €/year	Annual maintenance costs of the stunner. See 'installation investment'.
Labour related to pre-stunning and stunning, hours/day	Number of staff hours per day required for pre-stunning, stunning, bleeding and shackling
Throughput pigs/hour	Average number of pigs slaughtered per hour
Working hours per day	Average hours of slaughter per working day
Working days per year	Average days at work during a year
Water for stunning m ³ /day	1000 liters of water required per day for cleaning stunner and raceway
Electricity for stunning, kWatt/day	Kilowatt hours of electricity used for stunning per day (stunner and raceway)
Gas for stunning, tonnes/day	Tonnes of gas (CO ₂) required per day for stunning
Costs per discarded pig, €	Avg. price for a pig paid to the farmer
Labour €/hour	Avg. cost per hour for staff working with pre-stunning, stunning and bleeding
Gas price € per tonnes	Avg. price per tonnes of CO ₂ for stunning

Electricity €/kWatt	Avg. price per kWatt used for stunning
Water €/m ³	Avg. price per 1000 litres of water used for cleaning stunner and raceway

Questionnaire

An expert for each of the alternatives was identified. The questionnaire asked the experts to estimate the technical parameters and costs for their alternative stunning method. Some parameters were not included as they were case specific, rather than inherent values for the stunning methods (working hours per day, working days per year, costs per discarded pig, and price for resources i.e. water, electricity, gas and labour).

To estimate the additional installation costs and maintenance costs example slaughterhouses were used for each of the conventional systems as a baseline. Since slaughterhouses can vary in their configuration, infrastructure and size, the example slaughterhouses aimed to aid with this variation. In this way, experts developing gas-related alternatives were asked to estimate the costs for additional equipment needed to implement their alternative in a slaughterhouse currently using a conventional CAS system with CO₂ (dip-lift and paternoster). In the case of the expert developing the Improved electrical stunning system, they estimated the costs for a conventional CAS system with CO₂ and electrical stunning system.

For the example slaughterhouses, we used the parameters reported in D1 and selected the following case studies: CO₂-2 for dip-lift, CO₂-1 for paternoster, and Electrical-1 for conventional electrical stunning. In the case of Electrical-1, since the data were collected from the Improved electrical stunning system already in place at the time, some of the information collected was adjusted to better fit the characteristics of a conventional electrical stunning system. The relevant parameters provided for the slaughterhouse examples were parameters that describe the infrastructure of the lairage area (pen size, number of animals) and raceways, stunning process and infrastructure, bleeding and work pattern. Production level of all examples was set at 700 pigs slaughtered per hour instead of taking the production level described in D1 for these cases. This was decided to avoid confusion.

The survey was first sent out to the relevant expert for each of the alternative stunning methods. One-on-one meetings were set up with each of the experts to go through the questionnaire, answer the questions, clarify any doubts and note any observations and insights. Notes were taken and a summary of the meeting was sent out for the experts for approval.

To the date only the document sent to Argon Retrofit experts has been approved. Answers about both technical and cost parameters are still pending from the remaining alternatives.

Challenges encountered for data collection of the parameters for the alternative stunning methods explored in this project mainly arose from the lack of wide commercial experience and the inherent complicated nature of comparing costs between different stunning methods. This means that estimating the costs parameters for each system is associated with a high degree of uncertainty and is based on many assumptions. Explanation of the estimation process can be found in Table - B 7 in the Appendices.

Technical and cost parameters obtained

Only a few of the technical parameters and none of the cost parameters has been estimated in the pilot and performance testing in WP3 (see D3). Most technical and cost parameters were not measured in the alternative system itself but were compared to the values reported for the study cases in D1 instead. In these cases, experts reported their parameters not to change as compared to the values reported in D1. The value reported here corresponds to the value reported for the relevant conventional system represented by the study cases used in D1. Some general comments follow on parameters that observed difficulties in most alternatives. This is described in more detail in the Table - B 5 and Table - B 6.

Technical parameters

Working hours per day and working days per year vary between slaughterhouses and are not inherent to a certain stunning system. Most of the alternative systems have not been implemented yet in a fully commercial scale in high throughput slaughterhouse (except for Improved electrical stunning). The amount of resources used by each alternative was not measured empirically in most of the cases. For these situations, the amount was estimated relative to the values reported for study cases in D1 by the experts.

Cost parameters

Most of the cost parameters were not possible to be estimated directly from the alternative systems themselves and correspond to assumptions made by the experts. Maintenance costs and costs of resources (labour, gas, electricity and water) for most alternatives were compared by the experts to the values reported in D1. The expert for the Optimised CAS system (Backloader system and The Tunnel solution) did not want to provide maintenance cost for their systems, and cost for helium and argon is an estimation relative to the price of CO₂ provided by a relevant expert.

For the alternative stunning methods, the proportion of pig discarded due to meat quality issues and price paid to the farmer for a pig was not available from the experts. The experts have estimated the proportion of pig discarded comparing their system to the values used in the cost model for D1. They all expressed that they do not expect any changes in terms of meat quality (with the exception of the Improved electrical stunning experts, who reported a reduction as compared to the conventional electrical stunning). They said that no differences have been found in this aspect in the current literature. However, according to the results reported in this deliverable on meat quality measures during pilot testing of the alternative systems, there are differences in the amount of blood spots and PSE in ham and loin between systems (see relevant section for more detail).

Table - B 5: Summary of technical parameters for each alternative stunning system reported per line. Parameters estimated from their own systems are highlighted *in italics*.

Cost factors, technical parameters	Optimised CAS system		Helium stunning system	Argon retrofit system		Improved electrical stunning process
	Backloader system	The Tunnel solution		Dip-lift	Paternoster	
Throughput pigs/hour per stunner	<i>650</i>	<i>650</i>	<i>50 to 90^a</i>	<i>40% reduction as compared to a conventional CO₂ system^b</i>		<i>170</i>
Number of people per line	Same as CO ₂ -2		<i>5</i>	<i>Lower than CO₂ conventional systems</i>		<i>4 (16 people for 4 lines)</i>
Labour related to pre-stunning and stunning, hours/day	Slaughterhouse dependant					
Working hours per day	Slaughterhouse dependant					
Working days per year	Slaughterhouse dependant					

Water for stunning m ³ /day	Same as CO ₂ -2	Unknown	Same as conventional CO ₂ stunning system	Same as conventional CO ₂ stunning system	Same as conventional CO ₂ stunning system	<i>0.75 (3 m³ for four lines)</i>
Electricity for stunning, kWatt/day	Idem	Idem	Idem	Idem	Idem	<i>144^d (576 for four lines)</i>
Gas for stunning, tonnes/day	Idem	Idem	<i>1.49 x 10⁻⁴ ^c</i>	Idem	Idem	Not applicable

^a By improving the speed of the automatic stunner loader and the tower a throughput of 90 pigs per hour per stunner could potentially be achieved. Further increase in throughput may be possible with a larger gondola (doubled in size) to accommodate a maximum of 10 pigs i.e. 180 pigs per hour per stunner.

^b The reduction is estimated on the assumption that an increase in 40% of exposure time would result in a reduction in 40%. However, the increase in exposure time does not necessarily mean a reduction of throughput at the same rate.

^c Amount of helium used daily is estimated considering the total volume of the tower and a daily recovery rate of helium of 90%. For a tower of 9 m³ the initial fill is 1.49 x 10⁻⁴ tonnes of helium.

^d Amount of electricity estimated based on the amount used in their conventional electrical stunning system.

Table - B 6: Summary of cost parameters for each alternative stunning system. Comparisons are made against study cases reported in D1. Parameters estimated from their own systems are highlighted in *italics*.

Cost parameters	Solutions		Helium stunning system	Argon retrofit system		Improved electrical stunning process
	Backloader system	The Tunnel solution		Dip-lift	Paternoster	
Installation costs € (per stunner)	<i>2.5 m^a</i>	<i>1.8 m^b</i>	<i>1300K^c</i>	<i>new CO₂ stunner + 30-50K^d</i>		561600
Maintenance €/year	Not provided	Not provided	Same as conventional CO ₂ stunning system	Same as conventional CO ₂ stunning system		<i>Same as Electrical-1</i>
Costs per discarded pig, €	Slaughterhouse and country dependant					
Proportion of pig discarded	Same as CO ₂ -2		Same as conventional CO ₂ systems	Same as conventional CO ₂ stunning systems		Less than Electrical-1
Labour €/hour	Slaughterhouse and country dependant					
Gas price € per tonnes	Cost obtained from the relevant study case		<i>80 to 100 times more expensive than CO₂</i>	<i>4 to 6 times more expensive than CO₂</i>		NA
Electricity €/kWatt	Slaughterhouse and country dependant					
Water €/m ³	Slaughterhouse and country dependant					

^aInstallation costs include the cost of the stunner and any additional equipment i.e. backloader system includes a backloader and a retrofit system

^b This includes the cost of the backloader (1300k€) and the retrofit system (1200 k€).

^b This includes the tunnel and the automatic driveway

^c This is the cost of the whole project for one line i.e. it includes costs that are not a function of the number of lines and therefore additional lines might be cheaper.

^d The gas delivery system costs 30K to 50K €

Estimation of technical and costs parameters for each alternative as implemented by each of the study cases

We estimated the technical and costs parameters for each of the study cases implementing the relevant alternative stunning system. The aim was that the case study should reach their current daily production level i.e. total number of pigs slaughtered in a day using the throughput of the new alternative system while maintaining the number of slaughter days per year. Initially, we adjusted the number of lines necessary to get this number. We tried to maintain the number of lines of the current system as much as possible due to likely space limitations.

If the new system did not reach the target daily production level with the additional lines, we adjusted the number of slaughter hours per day. We assumed that this would not be more than two shifts of 7.5 h each or the number of hours used at the current slaughterhouse, whichever was higher. The aim was to avoid problems with regulations for working hours.

If after adding lines and adjusting the number of slaughter hours it was not possible to reach the total number of pigs slaughtered in a day by the case study, the number of lines was increased further until getting close to this number. If after this the number of slaughtered pigs per day was higher/lower than the initial level, this was corrected by adjusting the total hours of slaughter per day. Finally, we adjusted the number of people and amount of resources needed. The number of people used for each case study with the alternative was assessed case by case as it depends on the number of lines, throughput and number of people needed for the alternative system to work. However, for all systems it was assumed that lines would work intercalated so that the use of labour could be optimized.

The alternative systems are being implemented in each of the study cases. This means that the cost per pig for the case study with the alternative system implemented should include the installation investment of their own systems (already estimated in D1), when relevant, and any installation investment regarding the stunning equipment needed for the alternative system. The installation investment of the study cases is not reported here but added to the cost per pig calculation. The parameter 'Installation investment' is the cost of the stunning equipment of the alternative stunning systems but excluding any equipment from the previous system. The same was done in the case of the cost of maintenance.

Challenges

There were several challenges encountered for the economic analysis for the alternative methods (Table - B 7).

Table - B 7: Challenges when analysing economic data.

Challenge	Solution used	Implications
Installation investment cost will vary e.g. depending on the current stunning system in place and infrastructure of the slaughterhouse.	Experts of the alternatives methods were provided with an example slaughterhouse for each of the conventional stunning methods for them to estimate installation investment they may incur to adapt the current system to the new one.	There is a varied configuration of slaughterhouses in terms of number of pigs slaughtered per hour, type of stunning method, and current infrastructure and configuration which will not be represented in the example slaughterhouses provided here.
Maintenance cost will vary as changes necessary to	Idem	Idem

adapt the new method will depend on the current infrastructure and configuration of the slaughterhouse.		
The cost of inputs varies a lot between and within countries e.g. electricity, gas, labour.	The cost per pig was calculated for each of the study cases once the alternative system was implemented. The cost of inputs was taken from the study cases reported in D1.	The sample of slaughterhouses used in D1 is small and includes four slaughterhouses using CO ₂ systems (3 paternoster and 1 dip-lift) and one using electrical stunning. The estimation of the costs will likely not describe the reality for all slaughterhouses and countries.
It is difficult to know how the market will set the price for helium and argon as the use at a commercial scale in slaughterhouses is inexistent.	An estimation for the price of helium and argon was made by AirLiquide.	The estimation of helium and argon price is a projection based on their current availability, other uses of the gas, and complexity of extraction. The price of gas varies according to energy and transportation costs, form in which the gas is delivered, customers' annual demand and actual availability.
There is a limited commercial experience of the alternative stunning methods.	Data provided here correspond to estimates done by the experts.	Data represents the projections of manufacturers rather than being a description of the market.
Meat not suitable for human consumption may be used for other markets. We expect that the efficiency of use will vary from slaughterhouse to slaughterhouse i.e. the relative cost to the slaughterhouse may vary.	Experts made an estimation of the proportion of pig discarded as compared to the study cases reported in D1. Values used here correspond to the relevant conventional stunning system.	This is a simplification of what happens in a slaughterhouse regarding loss in meat quality. This calculation does not take into account the meat that can be used for other markets different than the human food industry. Additionally, the proportion of pig discarded corresponds to an estimate.
The cost of discarded pig may vary depending on the farm, slaughterhouse and country.	The cost associated to meat quality issues was estimated using the cost of a discarded pig expressed as the price paid to the farmer, and the proportion of the pig likely to be discarded due to meat quality issues. The cost of discarded pig was obtained from study cases reported in D1.	This will only represent the situation for the case studies. However, the cost paid can easily be replaced by the values reported in EUROSTAT and AGRIDATA, by year and country.

<p>Days with slaughter per year and hours of slaughter per day have been selected in D1 to estimate the cost of labour. However, this information is not available for the alternative methods. These parameters may depend on the size of the slaughterhouse. A small slaughterhouse will likely slaughter pigs only a few days a week, whereas a bigger one might have the capacity to slaughter pigs most days a week.</p>	<p>The days of slaughter per year and hours of slaughter per day will be estimated through calculating the costs of each of the case studies when implementing the alternative stunning system. Days of slaughter were maintained however slaughter hours per day were adjusted so that the new system would reach the same number of pigs slaughtered per hour. The assumption was that the maximum amount of slaughter hours per day would be the same as the current system or 2 shifts of 7.5 h, whichever was the longest.</p>	<p>Labour cost will be limited to the estimation of the pig throughput per stunner done by the experts without any experience in an actual commercial slaughterhouse. Additionally, it will be limited by the estimation of how many people will be needed for a certain number of lines. Moreover, it may be possible that slaughter hours per day could be higher. This will impact the calculation of how many lines are needed as well as the labour cost. Also, the number of working days and working hours/day considered here may vary by country. The same way the cost per hour of labour estimated here may not be representative of all countries</p>
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Environmental impact

As no quantitative analysis was possible, a qualitative analysis was performed to analyse the environmental impact of the four new alternatives. The parameters chosen to determine the environmental impact appear in the PigStun Deliverable 2. These parameters were obtained based on questions (via email) to the four experts representing each alternative. The answers to the questions are used as data for the environmental impact. The experts were asked for information on the following parameters for resource use on a commercial scale:

- Water resources per day
- Amount of wastewater and treatment of wastewater
- Use of disinfectant per day
- Energy use per day (Electricity, diesel, gas, etc.)

Additional questions asked for only the alternatives with gas for stunning:

- Gas for stunning in the CAS systems:
 - amount of gas per day
 - How much is possible to recover or reuse
 - How much gas for the first fill-up at the start of the slaughter day
 - How many times does it need to be refilled with gas
 - What is happening with the gas at the end of the day

Questions about the availability, cost, and acquisition of alternative gases were sent to an expert from Air Liquide (company selling gas). The following questions were sent to the expert about availability:

- What will the estimated costs be for argon and helium compared with carbon dioxide?
- How easy or hard is it to obtain helium and argon compared with carbon dioxide?
- Can argon, helium, and carbon dioxide be recovered or reused?
- How many suppliers will be able to deliver argon and helium compared to carbon dioxide?
- Security of supply for helium and argon compared with carbon dioxide

The efficiency of the stunning system was investigated, as Mogensen et al. (2016) stated that the environmental impact can be affected by the amount of input and output from the system. These questions were sent to the experts from each alternative on a commercial scale, and were as follows:

- Pigs per hour going through the system
- Lairage time
- Stun-to-stick time

One additional question was asked to the alternatives using gas for stunning:

- Concentration of the gas in the CAS- system

After receiving the responses, one-on-one meetings were held with the experts representing each alternative. These meetings were used to clarify and validate the information through discussion and follow-up questions.

Web of Science was searched for publications on the environmental impact of stunning with high concentrations of CO₂. The words used were Stunning AND Pig Or pigs OR Swine OR pork AND environmental impact OR environment OR carbon footprint OR LCA OR life-cycle assessment OR life cycle assessment OR Greenhouse gas OR sustainability or climate change. Web of Science was also used to search for the environmental impact of stunning with electrical stunning the words used were Stunning AND Pig OR pigs OR Swine OR pork AND environmental impact OR environment OR carbon footprint OR LCA OR life-cycle assessment OR life cycle assessment or Greenhouse gas OR sustainability or climate change.

Social impact

As no quantitative analysis was possible, a qualitative analysis was performed to analyse the social impact of the four new alternatives. The parameters analysed were addressed in the Deliverable 2 document and were determined to be work accidents and worker illness. These parameters were obtained based on questions (via email) to the four experts representing each alternative. The answers to the questions are used as data for the social impact. The experts were asked for information on the following parameters for the social impact on a commercial scale.

- Risk of work accidents
- Toxic levels of gas
- Noise level
- Change of labour time.

After receiving the responses, one-on-one meetings were held with the experts representing each alternative. These meetings were used to clarify and validate the information through discussion and follow-up questions.

To try to gather further relevant data, emails were sent to the authority for the occupational environment in the 5 countries with the highest number of slaughters per year described in Deliverable 1. The countries included were Spain, Germany, France, Poland, and Denmark. Unfortunately, only two provided answers.

Ease of conversion

Data used in the evaluation of ease of conversion were collected through a combination questionnaire sent out to the experts of each alternative system tested in this project in addition to information gathered during the consortium meetings. The questions were focused on describing the necessary modifications to the abattoir when going from an existing CO₂ system to one of the alternative systems.

Challenges encountered during data collection

In general, the answers received on the questionnaire on transitioning from an existing CO₂ stunning to one of the alternatives are not sufficiently detailed to form the basis for a thorough analysis of ease of conversion. The main issue is that the new systems (except for optimised electrical stunning) are not commercially available in high throughput scale yet. This makes it difficult to evaluate the cost of a finished system, as no analysis has been carried out to determine how the specific system is to be designed to be scaled up. This means that several decisions for scaling up has not been made yet. This includes decision about the slaughterhouse construction – also in relation to constructions of high significance to animal welfare.

Questionnaire

The questionnaire designed for evaluating the transition from a CO₂ stunning system to an alternative system in pig abattoirs is structured to gather comprehensive information on the necessary modifications across various operational areas. The primary focus is on understanding the changes required in the existing infrastructure and processes to accommodate the new stunning system. Participants are first asked to describe any modifications needed in the arrival area, specifically whether changes are necessary in the way pigs are received. This includes considerations of equipment, logistics, architecture, plumbing, and electrical systems. The questionnaire then addresses the lairage, inquiring about potential rebuilding or modifications required to support the new system.

The next section focuses on the driveway towards the stunner, asking whether any structural changes are needed to facilitate the transition. The core of the questionnaire examines the stunner itself, questioning whether the existing system can be used with minimal modifications or if a complete rebuild or replacement is necessary. Participants are also asked to evaluate the sticking area for any required modifications. For each of these areas, respondents are encouraged to consider what existing equipment and materials can be reused, the logistics of implementing changes, and the expected duration of reduced or cancelled slaughtering operations during the transition period.

Additionally, the questionnaire seeks to understand the financial implications of building a completely new alternative system. If precise cost estimates are unavailable, respondents are asked to identify which aspects of the new system would be more expensive or cheaper to establish compared to a high-throughput CO₂ stunning plant. Finally, the questionnaire probes the expected operational capacity of the new system, specifically the number of pigs that can be processed per hour with one stunner. If there is a reduction in capacity compared to the current high-throughput CO₂ stunning systems (650–700 pigs per hour), participants are asked to suggest measures to address this. Options include extending the existing stunner, adding additional stunners, or proposing alternative strategies such as reducing intake or extending slaughtering hours.

This structured approach aims to gather detailed insights into the practical, logistical, and financial aspects of transitioning to an alternative system, ensuring a thorough evaluation of its feasibility and impact on existing operations.

Estimating the cost

To estimate the cost of implementing alternative stunning methods for pigs, a comprehensive approach was undertaken. This involved conducting interviews with manufacturers and parties responsible for implementing these systems to gather first hand insights into the costs involved. Additionally, data and results from previous project deliverables, specifically Deliverable 1 through Deliverable 3, were incorporated to ensure the most thorough analysis possible. A critical aspect of this study was scaling the throughput of each alternative stunning system to accommodate high throughput (600–700 pigs per hour is

used to exemplify), as coordinated with the Work Package (WP) leader. This scaling was essential to maintain consistency and comparability across different methods. The cost analysis was divided into two main components: the price of the stunning equipment itself, and encompassing other costs associated with transitioning to a new stunning method.

When scaling to high throughput, the process involved dividing the target of 600 pigs per hour by the highest estimated throughput of each alternative system and rounding up to the nearest whole number. For example, if an alternative system had a throughput of 105 pigs per hour, six stunners would be required to meet the 600 pigs per hour target, rather than rounding down to the, technically correct, 5.7 stunners. This approach ensures that the capacity requirements are fully met without underestimating the number of stunners needed. Furthermore, the analysis included a detailed description of other known costs associated with each alternative method during the cost calculation phase. These costs could include infrastructure modifications, training for personnel, and potential downtime during the transition period, but vary based on input from the relevant parties. By evaluating these factors, the aim was to provide an overview of the financial implications of adopting alternative stunning methods, thereby aiding stakeholders in making informed decisions regarding the most feasible options for pig stunning in slaughterhouses.

Appendix C: Abbreviations

Abbreviations

APC	Aversive Physical Contact
Ar	Argon
AU	Aarhus University
BM	Benchmark
CAS	Controlled Atmosphere Stunning
CI	Confidence Interval
CI95	95% confidence interval
CO ₂	Carbon dioxide
D1	Deliverable 1
D2	Deliverable 2
D3	Deliverable 3
D4	Deliverable 4
DMRI	Danish Meat Research institute
DTI	Danish Technological Institute
EFSA	European Food Safety Authority
EIA	Environmental Impact Assessment
EMM	estimated marginal means
FAO	Food and Agriculture Organization of the United Nations
FLI	Friedrich-Loeffler Institute
GLM	Generalized Linear Model
He	Helium
IRTA	Institut de Recerca i Tecnologia Agroalimentàries
LoP	Loss of Posture
L-value	measure of the lightness/paleness of the meat
LPC	Lasting Physical Contact
MRI	Max Rubner Institute, Federal Research Institute of Nutrition and Food
NGO	Non-governmental organization
pH45	pH measured 45 minutes post-mortem
pH24	pH measured 24 hours post-mortem

PM	post mortem
PPC	Painful Physical Contact
PSE	pale, soft and exudative
SD	Standard deviation
T45	temperature measured 24 hours post-mortem
T24	temperature measured 24 hours post-mortem
QCT	Quick Chill Tunnel
WP	Work Package
WR	Stichting Wageningen Research



For further information, please contact:

Marien Gerritzen

marien.gerritzen@wur.nl

+31 317 480568

