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Critical analysis of the PigStun project outcomes

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Executive Summary

Carbon dioxide (CO₂) stunning is the most commonly used stunning method for pigs, however, there are concerns about the impact on animal welfare due to the aversiveness of exposure to high concentrations of CO₂ and delayed insensibility. While there is public pressure to move away from CO₂ stunning, the other main method of stunning, electrical stunning, has its own welfare concerns, particularly around the negative handling associated with moving pigs and the use of restraint, and comparatively higher re-stunning rate.

The EU commissioned the PigStun project, which tested potential alternative methods of stunning of pigs focused on improving animal welfare. The project reported their findings as five different deliverables, which include a description of current practices in Europe, the selected alternative methods and the methodology used to test these alternatives, the results and recommendations and a dissemination plan.

This report critically assesses the methodology and outcomes of the PigStun project, as presented in reports D2, D3 and D4, and discusses the applicability to the Australian pork industry. Additional information was sourced from PigStun Webinars, the TIGER project reports and related presentations and personal communications with PigStun collaborators.

PigStun methodology

The PigStun project consisted of several standalone projects conducted by different research groups in very different settings. The alternative gasses of argon and helium were compared with CO₂ gas in different systems. Benchmark data of three commercial CO₂ systems as well as an improved electrical stunning system was also included.

The Argon retrofit trial compared argon to CO₂ stunning in the same setting. While comprehensive measures during the stunning procedure were recorded, observations of pre-slaughter conditions and handling were not included. Only two pigs were loaded per gondola, which does not represent conditions at most commercial abattoirs.

The Helium system trial attempted to compare helium stunning to CO₂ stunning. However, not only were the stunning systems different, with pigs ascending into helium or descending into CO₂, it also included very different handling systems prior to slaughter. Only a limited number of pigs were observed during CO₂ stunning, and the results are difficult to interpret.

The optimised CAS (Controlled Atmosphere Stunning) system trial compared the effects of CO₂, argon and helium by removing the effects of pre-slaughter handling and other environmental factors prior to slaughter. This was achieved by allowing pigs to acclimatise for an hour at the entrance of the gondola before gas exposure. This was a modified version of the initial system, which would have moved groups of pigs in boxes and exposed them to gas stunning without the need for handling.

The improved electrical stunning system was described in detail, however, observations are not compared to another stunning system. This system includes improvements in design of the raceways leading to the electrical stunner, the minimal use of a 'low voltage' prodder and staff education in low stress handling. In addition, there was a limit on the number of pigs stunned per hour, to reduce the time pressure on moving pigs along the raceway.

Some data from commercial CO₂ plants were also included as benchmarks, however, essential information on the exact stunning system (paternoster or dip lift) and preslaughter handling was not provided. Overall, the measures that were taken (mainly behavioural responses and meat quality

measures) are very similar to those in most published literature. While statistical analyses were performed on the generated data, the details of these analyses are often lacking.

Outcomes of the PigStun project

The main results of the PigStun trials are presented in deliverable D4. These results have not yet been subjected to peer-review and are not published in scientific journals and should therefore be considered preliminary. However, the results largely confirm existing knowledge from previous research on stunning methods for pigs.

While both argon and helium are less aversive to pigs than CO₂ and pigs react to them with less agitation, time to unconsciousness is longer and some pigs still experience hypoxia resulting in air hunger and gasping before losing consciousness. Current CO₂ systems have the potential to be converted to using argon, but a transition to helium would require a different system and the expense of helium gas would rule this out regardless. To achieve satisfactory stunning efficiency using argon (in residual oxygen of less than 2%), exposure needs to be extended compared to CO₂. It is not clear how exposure duration and concentration affect the maximum stun to stick interval, which may have to be assessed for each individual abattoir.

The improved electrical stunning system resulted in prodder use with a 'low voltage' prodder on about 18% of pigs at the entrance of the stunner and a re-stunning rate of 0.6%. Overall, this system appears to be an improvement on most commercial electrical stunning systems, although the contribution of each individual change is not clear. Some of the changes, such as minimal use of prodders in a well-designed raceway system and staff trained in low-stress handling could be achieved in current systems and should be considered best practice. The welfare benefits of low voltage prodders deserve further investigation as a low-cost improvement to animal welfare.

Meat quality measures were similar for all gas systems, although some measures showed a reduction in some meat quality measures with argon and helium stunning compared to CO₂ in the optimised CAS system. The effect on meat quality of the improved electrical stunning method is difficult to assess, as there was no control group under similar conditions. However, there were indications of lower meat quality compared to CO₂ stunning that are widely reported in the literature, particularly with regard to drip loss, bloodspots and the potential development of PSE, which may be a particular issue for the Australian market.

All alternative stunning systems included in the PigStun project result in slower throughput and therefore result in significant cost increases. The economic analysis of the alternative stunning systems was greatly limited by missing and incomplete information of the different systems. In addition, there are both technical and economic issues associated with the transferability of the investigated systems to Australia.

Argon may be the most practical alternative to CO₂ but requires commercial-scale trials to confirm benefits to welfare, understand meat quality implications and operational and economic feasibility. The PigStun project has added to the knowledge gaps that still exist with regards to the alternatives to CO₂ stunning but many questions remain unanswered. At this stage, it is premature to enforce transition to argon in commercial settings until some of these questions, including those related to animal welfare, market requirements and processing capabilities, are answered.

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I Background to Research

Stunning is an important step in the slaughter process that aims to intentionally cause unconsciousness without pain and suffering. Carbon dioxide (CO₂) stunning is the most used method accounting for greater than 85% of pigs in Australia and at least two-thirds of pigs in Europe, with electrical stunning accounting for the majority of the remainder. Both methods have the potential to impact the welfare of the animal. CO₂ stunning does not induce insensibility instantaneously with the potential for pain and distress because of the pig's aversion to high concentrations of CO₂ and irritation of mucosal membranes, whilst high throughput electrical stunning requires pigs to be coerced into single file and restraint prior to stunning, often with the use of goads or electrical prodders.

In 2021, the European Health and Digital Executive Agency (HaDEA)¹ called for applications for the “Development of non-aversive stunning methods for pigs” with the aim to encourage EU pig slaughterhouses using high CO₂ concentration to stun pigs to convert to more animal welfare friendly alternatives. With alternatives meaning a method that does not expose conscious pigs to gas mixtures containing more than 40% CO₂, with these being suitable for high throughput slaughterhouses (> 800 pigs per hour).

The PigStun consortium brought together researchers, suppliers and processors from Germany, Denmark, Spain and the Netherlands to explore and test alternative methods to improve animal welfare during pig stunning in slaughterhouses.

The PigStun project aimed to motivate pig abattoirs across the EU to shift away from using CO₂ for stunning and adopt more humane alternatives; to be achieved by testing potential alternative methods and developing strategies focused on improving animal welfare. The PigStun consortium project team produced five major deliverables for this initiative. Each deliverable describes a step in the project's process, and the four main deliverables provide a scientific account of the project's findings:

- Deliverable D1: A report that describes the stunning practices for pigs in high-throughput slaughterhouses and their socio-economic drivers.
- Deliverable D2: A description of the planning phase, the selection of alternatives to be implemented, the scientific, technical and socio-economic data to be collected, and the benchmark ranges obtained from conventional commercial practice.
- Deliverable D3: A report on implementing the selected alternatives under conditions similar to the commercial situation and collecting the pre-selected data.
- Deliverable D4: The analyses and comparison of the results of the selected alternatives, and the recommendations addressed to slaughterhouses and other stakeholders.
- Deliverable D5: The dissemination plan of the PigStun project results to enable stakeholders to gain knowledge and support decision making on possible application of alternatives for high CO₂ stunning in pigs.

These reports are now publicly available online at: <https://eurcaw-pigs.eu/dossier/pigstun>

¹ HaDEA SMP-FOOD-2022-PigStunning https://hadea.ec.europa.eu/news/pig-stunning-grant-development-non-aversive-stunning-methods-pigs-2022-04-01_en

2 Objectives of the Research Project

APL's aims in the commissioning this work was to critically assess the PigStun project using a structured framework to evaluate its scientific foundation, practical results, and applicability to the Australian pork industry.

Key objectives include:

- Assessing the effectiveness, feasibility, and ethical soundness of the project's approach.
- Evaluating the scientific, economic, and social merits of proposed alternatives.
- Reviewing key deliverables (D2–D4) for their contribution to evidence-based decision-making.
- Identifying limitations such as data gaps, scalability issues, and trade-offs between welfare, cost, and logistics.

3 Research Methodology

The authors met regularly to discuss each aspect of the PigStun reports and the evaluation. The reports D2, D3 and D4 from the PigStun project were thoroughly reviewed and the methodologies used for each system comparison in relation to both animal welfare and meat quality were summarised to assist with the interpretation of the results. Information was also obtained from the webinars and factsheets sourced from the PigStun website both to clarify details and add further information otherwise not included within the reports. In addition, the authors met with Dr Antonio Velarde and contacted other key individuals from the PigStun team to obtain details on the methodology that was either missing from the report or required further clarification, and the implications and recommendations that came out of the PigStun reports. Contemporary analyses of the PigStun reports were also reviewed and included where appropriate.

The methods and measurements used by the PigStun project were compared to that used by other published research assessing both welfare and meat quality in pig abattoirs, including research conducted in Australian commercial abattoirs. The benchmark results and performance indicators were also compared to data reported previously in the scientific literature from similar facilities.

4 Evaluation of PigStun methodology

The PigStun project utilises data from several standalone projects conducted by different research groups in very different settings. Each project experienced a unique set of challenges in relation to experimental design and as a result, there are discrepancies in the way the work was conducted, and the way the methods have been written in the PigStun reports. The following sections are an attempt to summarise the methods described in D3—at times using details sourced from D2, D4, PigStun Webinars², TIGER³ (*Testing Inert Gases in order to Establish Replacements for high concentration CO₂ stunning for pigs at the time of slaughter*) reports and presentations such as those given at EAAP 2023, and per discussions with the researchers.

4.1 *Description of PigStun alternative systems and methods used for comparison prior to, and during, stunning.*

A high-level summary of the methods for each system comparison is provided in Table I.

² https://eurcaw-pigs.eu/search/pigstun+webinar*?taal=en

³ <https://www.fli.de/fileadmin/FLI/ITT/Projekte/TIGER/TIGER-Abschlussbericht-Zusfassung.pdf>

Table 1. Summary of methodology used for the comparison of the alternative systems

Method description	Alternative system comparison study							
	Argon retrofit		Helium system		Optimised CAS [†] (Box system)			Improved electrical stun
	Argon	CO ₂	Helium	CO ₂	Argon	Helium	CO ₂	
System location	Commercial		Small scale commercial			Experimental		Commercial
Sample size (pigs)	300	300	169	35	54	52	54	180
Number of source farms	8							
<i>Pre-stun Handling</i>								
Lairage time (h)	>6		2	Not provided		1-3		6
Group sizes (pigs per pen)	6-8		5-10	Not provided		9		6-8
Handling method	manual		robotic arm	manual		manual		manual
Behaviour observations	None taken		Direct observation (n=22 pigs)	Not provided		Video		Video
<i>Stun description</i>								
Stunner design	Diplift		Custom “gondola style” system	Diplift	“Proof of concept” optimised CAS			Automated head to chest electric stun (Midas*)
Pigs per stun	2	2	5	Not provided		3		1
Gas concentration (%)	95	90	<1% (residual O ₂)	Not provided	98	98	88	N/A
Stun/exposure time (s)	250	180	200	120	480	480	360	2.5 s (Head), 2.4 s (Chest)
Processing speed (pigs/h)	22	25	51	Not provided		4		175
Behaviour observations	Video		Video	Video?		Video		Video

[†]CAS, Controlled Atmosphere Stunning, *Midas Electrical Stunning System, Marel <https://marel.com/en/products/electric-stunning-system-midas/>

4.1.1 Argon retrofit system

- Commercial
- 300 animals tested per gas treatment over 14 days (2 days per week over 7 weeks)
- Pigs originated from 8 different suppliers, the order of slaughter was adjusted in an attempt to balance the source of pigs across treatments
- 3 gases were used in this study, CO₂, argon and nitrogen-argon mixture, however only the results for CO₂ and argon are reported within PigStun.

4.1.1.1 Pre-stun handling

- Pigs arrived the morning of slaughter
- Pigs were slaughtered in the evening (between 6pm-11pm), therefore >6hrs lairage time
- Pigs housed in groups of 6-8 pigs
- Pigs moved in groups of 2 to the stunner (pigs were marked with spray mark for identification immediately prior to entering gondola)
- Detailed description of pre-slaughter handling in this system is not provided, however it is assumed that manual handling was used (i.e. no automatic gate system)
- The order of the gas used in the stun system was randomised each day (each day all gas mixtures were used: CO₂, argon and nitrogen-argon [results not reported] mixture) to minimise effects of handling which could not be controlled for.

Measurements

- No assessment of animal handling or animal behaviour pre-slaughter was conducted in this experiment, other than entry to the stunner.

4.1.1.2 Stun system

- Dip-lift system with alternative gas retrofitted
- Each gas (CO₂, argon and nitrogen-argon mixture) was tested on each day and the order “shuffled”
- Gas concentrations: argon 95% (N₂ 4%, O₂ 1% - target at 50 cm below top of pit); CO₂ 90% (N₂ 8%, O₂ 2% - target at 50 cm below top of pit)- measured by residual oxygen.
- 2 pigs per gondola
- Processing speed: argon 22 pig/hr, CO₂ 25 pig/hr
- Stun/exposure time: argon 250 s (dwell time), CO₂ 180 s⁴

Measurements

- Animal behaviour/handling on entrance to stunner (reluctance to move) scored on a 5 point scale where 0 represents no reluctance and 4 represents “lasting painful contact” used⁵
- Behaviour in the gondola. Data was collected as part of the TIGER project which used a more extensive ethogram, the data was summarised (selected scores combined) to fit the PigStun categories

⁴ Source TIGER final report, [Projektabschluss TIGER](#)

⁵ The ethogram for this scale is in D4 Appendix B, Table 2 page 137

4.1.2 Helium System

- Small scale commercial
- Data collected over 5 test days (behaviour and meat quality)
Local CO₂ Control n= 35 pigs, Helium n=169 pigs

4.1.2.1 Pre-stun handling

- Pigs arrive morning of slaughter
- Lairage time approx. 2 hrs (Water provided, no food)
- Housed in groups of 5-10 pigs
- Manual handling from arrival to raceway
- Pigs re-grouped prior to entry to raceway to reduce to 2-5 pigs
- Robot controlled push door moves the pigs into the helium stunner (no details provided on how long the raceway is, but can hold 2 groups of pigs at a time)
- Local CO₂ control: manual handling

Measurements

- Animal behaviour and handling observed during unloading and lairage using direct observations on n=22 pigs in the helium system, movement to and entrance to stunner was not recorded
- No measurements on animal behaviour or handling were collected for the local CO₂ comparison

4.1.2.2 Stun system

- Experimental “gondola style” gas system, the gondolas move up into the helium, or down into the CO₂⁶
- 5 days selected for video observations using BORIS⁷
- 2 to 5 pigs per gondola
- Target concentration of residual oxygen in the helium system was <1% (when this target was reached the gondola would move up into the gas, suggesting that the gas was monitored and adjusted after each cycle)
- Processing speed: Helium 51 pigs/hr
- Stun/exposure time: Helium 200 s, CO₂ 120 s
- Local CO₂ control: small scale commercial dip-lift, 70 pigs per hr, 2-3 pigs per gondola

Measurements

- One or two animals were selected for coding using BORIS in each gondola
- Entrance to the gondola was assessed using video footage, only the first pig showing a given behaviour was taken into consideration.
- Animal behaviour in the gondola

⁶ This information came from the webinar [PIG STUNNING DEVELOPMENT OF NON-AVERSIVE STUNNING METHODS FOR PIGS FINAL EVENT - Streaming Service of the European Commission](#)

⁷ Behavioural Observation Research Interactive Software <https://www.boris.unito.it/>

4.1.3 Optimised CAS (Box) system

- Experimental
- argon n= 54 pigs, CO₂ n=54 pigs, helium n=52 pigs
- Each gas was tested for 2 weeks at a time consecutively, one replicate of each⁸.

4.1.3.1 Pre-stun handling

- Pigs arrive in the morning prior to slaughter
- Lairage time approx. 1.5 hr
- Pigs were housed in a group of 9 (only 9 pigs were slaughtered per day)
- Pigs were manually moved in groups of 3 into the stunning box which transports the pigs into the stunner.

Measurements

- Animal behaviour and handling observed during unloading and lairage using direct and indirect (GoPro cameras) observations, movement to and entrance to stunner was not recorded
- 5 pigs (out of each group of 9) chosen at random were fitted with HR monitors

4.1.3.2 Stun system

- Box lift to PoC (“Proof of concept”) machine. This is an optimised CAS system through which groups of 4 pigs are transported in boxes and exposed to either argon, or CO₂ or helium.
- The same machine was used to test CO₂, helium and argon in consecutive weeks
- Animals are loaded into the stunning box, and the box moves through the machine in a specific route depending on the gas used. E.g. upwards for helium or downwards for argon and CO₂
- Processing speed: 4 pigs/hr (includes a wait time of 45 min at the first stop, prior to gas exposure)
- Stun/exposure time: CO₂ 6 min, argon 8 min, helium 8 min
- Gas concentration: CO₂ 88%, argon 98% (≤2% residual O₂), helium 98% (≤2% residual O₂)

Measurements

- Entrance to and behaviour within the stun box was assessed using video footage
- Heart rate monitors on allocated pigs recorded heart rate (not reported)

⁸ This information came from the webinar [PIG STUNNING DEVELOPMENT OF NON-AVERSIVE STUNNING METHODS FOR PIGS FINAL EVENT - Streaming Service of the European Commission](#)

4.1.4 Improved electrical stun

- Commercial
- Placement of electrodes was observed for 60 pigs on 3 consecutive days (n=180 pigs)
- Compared to CO₂ benchmarks

4.1.4.1 Pre-stun handling

- Lairage time approx. 6 hrs
- Water and enrichment provided in each pen
- Pigs housed in groups of 6-8 individuals keeping the same groups as they were during transport or groups of 36 pigs per pen (note there are inconsistencies in the description of group sizes: initially held in compartment groups off the truck 6-8 animals, but in the description of figure 52 the smaller group size is 12 pigs)
- Improvements to pre-stun area design:
 - Moved in groups to raceway
 - Reduced visual access to stockpeople
 - Free-choice raceway entrance
- Improvements to pre-stun handling
 - Use of low voltage (45 V per discussion with A. Velarde) stimulator instead of a traditional electric prod (Electric prodders currently used in some Australian abattoirs can generate up to 8000 volts per pulse)?
 - The low voltage stimulator is only used at the end of the raceway, workers use brushes to stimulate the pigs to walk in other areas
 - Workers are not allowed to swing their upper arm to hit pigs
 - Cameras are used to detect incorrect use of the stimulator which is only allowed to be used on the first pig/leading pig if it is not moving and not on the pigs that follow

Measurements

- Animal behaviour and handling observed during unloading, lairage movement to and entrance to stunner using direct observations

4.1.4.2 Stun system

- Automatic electrical head to chest stun – Marel Midas Electrical Stunning System
- Stun/exposure time: 2.5 s head, 2.4 s chest
- Minimum current to head is 1.25 A, minimum voltage to chest is 75 V
- Processing speed: 700 pigs/hr Note this is the speed of all 4 stun units operating, the speed through one stun unit was 175 pig/hr and only one stun unit was assessed for the stun related variables

Measurements

- Animal handling and behaviour on entrance to the raceway and the stunner was assessed using video footage

⁹ <https://www.scintex.com.au/products/cattle-prodder>

4.2 Soundness of testing protocols and performance indicators.

A comparison of the measures taken within the suite of PigStun studies in relation to studies conducted within commercial Australian pig abattoirs (by this group) and other similar studies conducted in Europe is provided in Table 2. The measurements taken and the protocols used for the observations within the gondolas are comprehensive and cover those commonly assessed in previous studies. However, some of the common variables assessed in previous studies related to pre-slaughter handling and lairage were not measured (e.g. skin injuries, stocking density).

In particular, the study involving the Argon retrofit system lacks any assessment of the conditions and the handling that the animals experience prior to slaughter. While the gas treatments were randomised as much as possible within this study, the differences in dwell times may have relieved some pressure on the movement of animals to the stunner in the argon treatment. Thus, there may have been unrecorded differences in the handling and speed of movement for the pigs between treatments although this may have been minimised to some degree through the use of a slower than commercial processing speed with only 2 pigs loaded into each gondola. The decision to use a processing speed slower than a commercial rate is a limiting factor when trying to demonstrate the welfare benefits of argon over CO₂ in commercial abattoirs, as the pigs may respond quite differently to the gases in the larger group sizes commonly used in commercial settings (Bonnichsen *et al.*, 2024).

In the Helium system, pigs are moved towards the stunner automatically using a robotic arm, whereas in the local CO₂ system used for comparison the pigs are moved from lairage to the stunner using manual handling. The lack of observations on pre-slaughter handling, stocking density and animal behaviour within the local CO₂ system and the differences in design may have contributed to the differences in behaviour seen in the gondolas within this comparison, as it confounds the different gases used (helium vs CO₂) and the different handling system (robotic vs manual). This study also lacks a balanced design in that 169 pigs were assessed for the helium system while only 35 animals were assessed in the CO₂ comparison. Focal animals were observed in the gondolas to enable more detailed observations, however it is not clear how the focal animals were selected. In addition, if 2 focal pigs were in the gondola at the same time, only the first pig to show a behaviour was recorded and it was “assumed for the analysis that both animals coded for that gondola exhibited the behaviour observed in the first pig”, no details are provided on how often 2 pigs were coded in the same gondola, or if the same protocol was used for the behaviour observations conducted at the local CO₂ comparison.

The optimised CAS system is an experimental system which provides an excellent opportunity to compare the effects of the different gases through the ability to completely standardise the pre-slaughter handling and environment across all the gases. While the pre-slaughter handling was standardised across the treatments, each gas was tested within a single 2-week block thus it is possible that some of the differences seen could be confounded by conditions unique to a particular 2-week block. This system was described in D2 as a multiphase system in which the pigs were exposed to low concentrations of gas in an induction phase before moving into a higher concentration, however this functionality was either not used or the details of this have not been provided. In addition, approximately 50% of the pigs observed for each gas treatment were fitted with heart rate monitors, however these results have not been reported.

There is no local CO₂ or standard electric comparison for the improved electrical stun. The only control comparison for this study was the benchmark for a high concentration CO₂ stun facility, which is very difficult to compare as not only is the handling in the facilities very different, but the method of stun also differs substantially. No details are provided on the type of CO₂ stun facility, i.e. dip lift or paternoster, or the pre-slaughter handling (i.e. manual handling in groups or single file? use of automatic push gates?). It would have been useful to compare the behaviour of the animals within this “improved” system to the behaviour of animals in another electrical stun system, or in the same system prior to

the enhancements. Without this comparison, there is no scientific evidence that the enhancements have improved welfare based on the information provided in this report. Based on the description of the methods for this study only one stunner (out of four) was observed. Depending on the facility design, it is feasible that only pigs that chose a particular direction were observed and since lateralization has been shown to be associated with personality traits in pigs (Goursot *et al.*, 2018) there is a potential that the observations may therefore have been biased towards animals of a particular personality (e.g. bold or fearful). Only 60 animals were observed per day, based on the reported methods it is not clear whether the animals were observed consecutively, or spaced out across the day. A more rigorous design would observe more animals (and at regular intervals across the day), more stunners and randomise the order in which the stunners are observed.

Table 2. Comparison of commonly used measures to assess animal welfare in pig abattoirs. X indicates the measure was assessed within the study, C indicates the measure was controlled within the study

	PigStun			Australian studies		European studies		
	Optimised CAS	Argon retrofit	Helium	Improved Electric	Jongman et al. (2021)	Hewitt et al. (2025)	Llonch et al. (2012)	Brandt et al. (2015)
Country					Australia	Australia	Spain	Denmark
Abattoir type	Experimental	Commercial	Small scale commercial	Commercial	Commercial	Commercial	Experimental	Commercial
Stun system	Proof of concept	Dip-lift	Custom gondola style system	Head to chest electric	Paternoster	Paternoster	Dip-lift	Paternoster
<i>Pig attributes</i>								
Genetics	X	X	X ¹				C	
Sex	X	X	X		X	X	C	
Weight	X	X	X	X		X		
Transport time						X	C	X
<i>Lairage</i>								
Time in lairage						X		X
Activity	X		X ²	X	X	X		X
Stocking density					X	X	X	C
Skin injuries					X	X		X
Heart rate	X ³							
<i>Pre-stun handling</i>								
Tactile	X	X	X ²	X	X	X	X	X
Auditory	X		X ²	X	X	X		
Visual					X	X		
Use of prodder				X	X	X		
Response to handling	X		X ²	X	X	X		X
Speed of movement					X	X		
Reluctance to enter stunner	X	X	X	X				

	PigStun			Improved Electric	Australian studies		European studies	
	Optimised CAS	Argon retrofit	Helium		Jongman et al. (2021)	Hewitt et al. (2025)	Llonch et al. (2012)	Brandt et al. (2015)
Crowding in raceway								X
<i>Inside the gondola</i>				N/A				
Pigs per gondola	C	C	C		X	X		
Latency to gas exposure	X	X	X		X	X		
Latency to loss of posture	X	X	X		X	X	X	
Latency to cessation of convulsions	X	X	X			X	X	
Activity	X	X	X		X		X	
Vocalisations							X	
Lying	X	X	X					
Abnormal breathing	X	X	X		X		X	
Heart rate	X ³							
<i>Post-stun</i>								
Brain stem activity							X	
Re-stun (frequency)	X	X	X	X	X			
Plasma cortisol					X	X		
Plasma haptoglobin						X		
L-Lactate						X		X
Albumin								X
Total protein								X
Glucose								X
Creatine kinase								X
pH								X

¹While genetics were noted for the helium trial there was no information on whether there was any attempt to balance this across treatments or control for this in the statistics. ²Unclear if this measure was also taken at the local CO₂ plant, the results presented are presumably for the helium treatment. ³Heart rate was measured however no results for this measure were presented.

4.3 Description of PigStun alternative systems and methods used for comparison of meat quality post-stunning.

Stunning method has the potential to influence meat quality, with electrical stunning consistently resulting in higher levels of PSE, drip loss, petechiae and ecchymosis when compared to CO₂ stunning (Channon *et al.*, 2000; Velarde *et al.*, 2001). Consequently, it was included as an assessment protocol within the PigStun project. There was some variation with measures taken across the different stunning methods, and benchmarks, however, at least loin (*Longissimus thoracis et lumborum*, LTL) pH at 45 minutes and at 24h post-mortem and temperature profiles were measured for all methods. With these meat quality measurements following the standard operating procedures from the EU-funded project mEATquality (Wageningen Research <https://meatquality.eu>), with noted exceptions. Descriptions of the meat quality assessment methods used for each stunning method can be found in Table 3.

The three alternative gas systems were experimental setups, although the Argon retrofit and helium system work was conducted within commercial facilities, that enabled a greater level of control by the research teams. The improved electrical stunning system was implemented into a commercial abattoir with the collection of data appearing to be less controlled with not well-defined methodology – measures were taken but there is no description of how.

Objective colour scores were conducted as per standard practice (Van Oeckel *et al.*, 1999). Drip loss measures did differ between systems, with the widely adopted EZ-DripLoss system being utilized as well as retail tray measures, comparison between stunning methods is therefore more difficult, however high correlations between methods have been shown in the past (Otto *et al.*, 2006). The assessment of bloodspots followed the protocol established by Dich-Jørgensen *et al.* (2017) with the addition of two categories, zero blood spots or < 5 per muscle. An estimation of the proportion of PSE in both loins and hams was made using thresholds based on pH₄₅ values derived from Kim *et al.* (2014) where a threshold of pH₄₅ below 5.8 indicated PSE in loins and Aaslyng and Hviid (2020) where the probability of PSE developing was higher when pH₄₅ falls below 6.1. The Argon retrofit study added assessment of the *M. semimembranosus* (SM) to many measures, however only the LTL was used by PigStun for comparisons.

There are minimal descriptions of the statistical analyses performed to determine differences between treatments within systems, although statistically different conditions are indicated in compact letter form. Continuous variables were assessed using linear models (ANOVA or regression) and binomial data via generalised linear models. Gelhausen *et al.* (2025) does describe the generation of linear mixed models and the use of ANOVA for comparisons utilizing R for her additional measures within the Argon retrofit study.

Benchmark indicators for meat quality (pH and temperature at 45 mins and 24h post stunning) were obtained at two commercial CO₂ stunning plants (n = 45, n =40) and one electrical stunning plant (n=50). Additionally, three studies were also included as benchmarks for the comparison of results.

- Rybarczuk *et al.* (2015) investigated the impact of blast chilling on pork quality – 60 carcasses, CO₂ stunner, one half-side 70 min blast chill at -24 °C followed by conventional chilling (1 °C), other half-side held at 1 °C for 24 hours. Reported pH and temperature declines, colour and drip loss between two chilling methods.
- Aaslyng and Hviid (2020) sampled from four main slaughterhouses in Denmark (65% of national pig kill), all plants utilizing backloader CO₂ stunners and blast chillers (-22 to -18 °C) – 248 carcasses for pH declines, colour and EZ-DripLoss.
- Mantis *et al.* (2019) sampled commercial pigs from 9 farms at a single abattoir applying head-only electrical stunning – 590 pigs, conventional chilling at 2 °C for 24 hours. Reported pH and temperature at 45 min and 24h, colour and EZ-DripLoss.

Table 3. Meat quality assessment methods for each of the four alternative stunning methods included in the PigStun project.

	Argon retrofit	Helium system	Optimised CAS (Box system)	Improved electrical stun
pH & temp 45 min	LTL & SM	SOP <i>mEATquality</i> [†]	LTL last rib, duplicate both sides	Yes
pH & temp 24h	LTL & SM	SOP <i>mEATquality</i>		Yes
Drip loss	SM, retail shelf MAP packaging held at 4 °C, 72h. Meat slices weighed before and after.	Differed to SOP <i>mEATquality</i> (no explanation). Same LTL used for drip loss and colour	LTL, 48h EZ-DripLoss	Yes
Colour	<i>M. Gracilis</i> 40h post-slaughter. Bloom 30 mins, aperture 8 mm, illuminant D65, observer 10°, average of 6 replicates. L* a* B* Minolta CR-400	SOP <i>mEATquality</i> CIE L* a* b*	LTL 24h post-slaughter. Bloom 30 mins, aperture 8 mm, illuminant D65, observer 10°, average of 5 replicates. L* a* B* HunterLab	Yes
Bloodspots	SM & <i>M. Gracilis</i> 4-point scale – 0, none; 1, <5 blood spots; 2, <30 blood spots; 3, >30 blood spots	Protocol shared with PigStun for use in Denmark pilot testing and electrical stunning. <i>M. Gracilis</i>	<i>M. Gracilis</i> & <i>Psoas major</i> 3-categories – multiple point bleeding, 5-30 spots, >30 spots. Dimensions of maximum 5 spots recorded. Converted to % blood spots (number of bleedings/total number of muscles assessed)	Yes
Comments	Additional measures taken as part of TIGER (PhD – shear force, sensory, gene expression) Gelhausen et al., 2025.		The first protocol with greatest level of description in D3. Carcase dissection plan explained.	Minimal description provided. Assumed followed <i>mEATquality</i> SOPs.

LTL, *Longissimus thoracis et lumborum*; SM, *M. Semimembranosus*; [†]*mEATquality* protocols – pH 45 min (24h), the pH is measured at 45 minutes before carcasses enter the cooling (24 hours post-mortem), by electrode insertion in the LTL at the last rib (T13-L1 level). Temperature, temperature is measured at the same time and location as pH.

5 Outcomes of the PigStun project

5.1 Summary of animal welfare outcomes of Controlled Atmosphere Stunning trials included in the PigStun project

This section outlines results of trials on three Controlled Atmosphere Stunning (CAS) systems (CO₂, argon and helium), an improved electrical stunning system as well as benchmark data from three commercial CO₂ abattoirs. The animal welfare outcomes of these trials, as presented in report D4, are summarised below.

The **Argon Retrofit system** was used to test both argon and CO₂ in the same dip-lift system, so results for both gases can be compared. The residual concentration of O₂ was <1% for both gases, but concentration of the respective gases does not appear to have been measured.

In this trial, pigs started showing a response to both gases soon after descending (CO₂ after 6.9 s and argon after 7.9 s), which was 5.0 and 6.4 s before loss of conscious respectively. These responses included strong agitation for pigs exposed to CO₂ for 60% of pigs on average 6.8 s before loss of posture, while only some pigs (2.3%) showed strong agitation to argon at around 3.2 s before loss of posture. In addition, 59% of pigs showed abnormal breathing in response to CO₂, which was not seen in any of the pigs exposed to argon.

The average reaction score (out of 3) for argon was 0.9 as opposed to 2.3 for CO₂. Although argon was clearly less aversive to pigs than CO₂, some pigs still showed an aversive response to argon exposure. The reaction score to CO₂ was higher in this trial compared to the helium and Optimised CAS system trials but similar to the average of the benchmark of commercial abattoirs. The time until lying still and last movement was quicker for CO₂ (45 s and 143 s) compared to Argon (50 s and 173 s).

The average cycle duration for argon (4.5 min) was longer than for CO₂ (3.3 min), which resulted in an 100% effective stunning rate for both gases. No re-stuns were required but no information on the stun/stick interval is provided, and number of observed pigs was low (N=142 for argon and N=106 for CO₂). Therefore, it is not clear how the maximum stun to stick interval compares between the two gases in this system.

The **Helium stunning system** study compared helium with CO₂ in small scale commercial facility using two different stunning systems (with separate race and lairage) in the same location. The Helium system is a custom made “gondola style” system in which the pigs are raised into the helium, whereas the CO₂ system used was a dip-lift system where the pigs are lowered into CO₂. The first response to gas exposure relative to the start time of descent was quicker for CO₂ (21 s) than compared to ascent for helium (40 s), and all pigs showed a (mostly moderate) response to CO₂ (score of 1.9 out of 3) while only 41.4% showed a (mild) response to helium (score of 0.4). However, loss of posture for CO₂ was 24.5 s after the start of descent, which was only 2.7 s after the first reaction to CO₂ exposure. Loss of posture for helium was 49.4 s after exposure and 9.4 s after the first response to helium. While none of the pigs exposed to helium showed an agitated reaction, an agitation reaction in pigs exposed to CO₂ was seen almost immediately after pigs started to react to CO₂. However, strong agitations in response to CO₂ were mostly seen after pigs lost posture and were presumably conscious. In addition, abnormal breathing was only observed in 2.9% of pigs exposed to CO₂, while none of the pigs exposed to helium showed this behaviour.

While time to lying still (from start of descent) was very similar for both gases (around 75 s), time to last movement was shorter for CO₂ (137 s vs 182 s). Cycle duration for CO₂ and helium, as used for the calculation of re-stunning, was nearly twice as long for helium at 120 s vs 200 s. This resulted in a re-stun rate of 1.2% (with low numbers of pigs) for helium in animals that showed signs of

consciousness immediately after stunning. No re-stuns were reported for CO₂. Due to the short stun to stick interval it is not clear what the potential maximum stun to stick intervals would be.

The **Optimised CAS (Box) system** compared CO₂, argon and helium in the same experimental system, where the pre-handling stress was greatly reduced. Pigs started showing a response to CO₂ within 22 s of descent and a total of 18 s before they lose posture. Responses to argon were first seen within 43 s of the start of descent and for 24.3 s before they lost posture. Exposure to helium resulted in first responses at 30.5 s after descending, and for 49.5 s before loss of posture. Therefore, the duration between first response to exposure until loss of posture was greater for all gases compared to those measured in the previous trials.

While responses to CO₂ were clearly stronger than the other 2 gases (scores of 1.5 to CO₂, 0.9 to argon and 0.7 to helium), the aversive responses were shorter for CO₂ than for argon and much shorter than for helium. Note that the agitation score to CO₂ was lower in this system than the other systems studied, most likely due to the low stress handling. On the other hand, abnormal breathing was seen in 72% of pigs exposed to CO₂, while this was less for argon (15%) and helium (33%), and was higher for all gases in this system compared to the other trials.

In summary, across all trials CAS trials stronger aversive responses were seen to CO₂ compared to the alternative gases, as well as a higher proportion of abnormal breathing. Although aversive responses to both argon and helium were less pronounced, they were still observed with less frequency. However, the time between first response to gas exposure and loss of posture was shorter for CO₂, resulting in a shorter total duration of aversive responses. Total dwell time was longer for both alternative gases compared to CO₂ but there is no comparison on maximum stun to stick intervals to ensure that pigs remain insensible until death under commercial conditions.

Preslaughter handling was observed to some extent in all systems/trials. However, every system incorporated different designs and type of handling, which makes it hard to compare between different gases. However, there should be very little awareness of the gas the pigs are about to enter, so no difference between gases per se is expected. The observed differences are most likely due to facility design and methodology.

In the **Argon Retrofit system** pigs moved to the stunner containing CO₂ were slightly harder to move, requiring more aversive interactions (painful physical contact) and earlier intervention before entry to the stunner (prodder?) than pigs entering argon. However, the proportion of pigs that needed these interactions were similar at around 50-55%. Lasting painful contact was again similar between the systems, with 0.3-0.7% of pigs receiving these. It is not clear why a difference was observed, as concentrations of gas should be below aversive levels at the point of entry. It is possible that higher stress levels in pigs exposed to CO₂ can result in pheromones in urine, thus providing a negative stimulus for pigs to enter the gondolas.

The **Helium stunning system** used different facilities and handling methods in the comparison with CO₂. In particular, pigs were moved with a robotic arm into the Helium stunner, while pigs were handled manually before entry into the CO₂ stunner. Consequently, 31% of pigs were reluctant to move into the CO₂ stunner, resulting in painful aversive contact, while pigs showed little hesitation in entering the Helium stunner and aversive contact was used on a smaller number of pigs (9.5%). Due to the design of the **Optimised CAS (Box) system**, no reluctance to enter was observed.

The advantage of gas stunning compared to electrical stunning is the opportunity to move pigs in groups, preferably using hydraulic gates. Electrical stunning requires pigs to enter in single file, which pigs are reluctant to do, and often necessitates aversive handling.

5.2 Observations of Improved Electrical Stunning and CO₂ benchmark abattoirs

The **improved electrical stunning system** was specifically designed to reduce reluctance to enter the raceway and stunner. Reluctance to move into the raceway was seen in 31.7% of pigs. This resulted in the use of brushes as handling aid on 93.9% of pigs to motivate them to enter the raceway. In addition, 62.8% of pigs were reluctant to approach the electrical stunner. Low voltage electrical prodders were used in this area on 18.3% of pigs. There is no technical information on these prodders, nor how the responses of pigs compare to traditional prodders. Incorrect placement of electrodes and consequent re-stunning rates were 0.6%.

The **benchmark commercial CO₂ stunning** systems are not well described in the reports, nor was any justification given for their selection; therefore, it is difficult to comment on their performance. Pigs in abattoir B were all (100%) reluctant to move into the stunner and all needed aversive physical contact to encourage them to move. It is assumed that pigs in this abattoir entered in single file, rather than in groups. In abattoir C 65.6% were reluctant to move, but only 10% needed aversive physical contact to enter. No information was collected on entry to the stunner for benchmark abattoir A.

All pigs responded to exposure to CO₂, but the magnitude of response differed between abattoirs, from 25 to 75% strong agitation. The first response was seen between 10-11 s after descending and between 5.7 to 10.3 s before loss of posture. Strong agitations were seen from between 0.3-2.4 s before loss of posture, in between 11.8 to 35.2% of pigs and abnormal breathing was seen in 3.5 to 36.7% of pigs. The abattoir with the least agitation reported the most pigs that showed abnormal breathing (which was also the abattoir with the most negative handling interactions). Cycle duration varied from 207 s, 195 s and 158 s with re-stunning rates reported as 0.0, 0.7 and 2.0% respectively.

5.3 Summary of meat quality outcomes of trials included in the PigStun project

Statistical comparisons are only able to be made within each of the alternative gas stunning system assessments that had local controls with CO₂ stunning. The results are summarized in Table 4.

Within the **Argon retrofit** assessment only initial pH (pH₄₅) differed, although the subsequent lack of differences between measures would suggest this difference was inconsequential, with no impacts on pH at 24 hours, colour, drip loss, the incidence of bloodspots or the proportion of pigs likely to exhibit PSE.

The helium treatment within the **Helium system** had a lower initial pH, but no difference in ultimate pH, compared to CO₂, with muscle temperature differences also noted, an initially lower temperature but ultimately higher temperature at 24 hours. Despite the lack of difference in ultimate pH, meat from the helium treatment was significantly paler (L*), less red (a*) and more yellow (b*) than that from the CO₂ stun treatment and had a higher drip loss. Although differences in the potential incidence of PSE in hams were not statistically significant, they support the color and drip loss results.

Argon, helium and CO₂ were all compared within the same **optimized CAS (Box) system**. Initial pH differed between treatments with argon showing a rapid fall in pH (pH₄₅ = 5.9), followed by helium (6.1) and then the control CO₂ treatment (6.4) remaining at “normal” levels. These pH₄₅ values are reflected in the high potential for PSE to develop in both the loin and ham of argon and helium treatment pigs. Ultimate pH was unaffected by treatment, nor was lightness (L*) of the LTL. The helium treatment was more red (a*) and the argon treatment less yellow (b*) but these measures were not materialistically different. Stunning pigs with argon resulted in a higher drip loss than when stunning with helium which in turn had a higher loss than the CO₂ treatment. The incidence of bloodspots was significantly higher in the argon (0.6%) treatment compared to CO₂ (0.1%), with helium (0.4%) being intermediate.

Without a local control, the measured outcomes within the **improved electrical stunning system** can only be assessed from a higher-level perspective in comparison to the benchmark and other systems. The lower ultimate pH and higher levels of drip loss of the improved electric stunning system is in line with the benchmark and broader literature (Channon *et al.*, 2000; Mantis *et al.*, 2019). The greater incidence of bloodspots in the improved electrical stunning (0.9%) system was also in line with expectations (Channon *et al.*, 2002), with greater than 50% of pigs having presence of bloodspots.

Table 4. Results of meat quality assessment for each of the four alternative stunning methods included in the PigStun project and benchmark measurements.

	Argon retrofit		Helium system		Optimised CAS			Improved	Benchmark measurements*				
	Argon	CO ₂	Helium	CO ₂	Argon	Helium	CO ₂	ES	I	2	R	AH	M
At 45 min	n = 244	n = 246	n = 50	n = 35	n = 54	n = 54	n = 54	n = 60	n = 50	n = 45	n = 60	n = 246	n = 590
pH ₄₅	6.5 ^a	6.6 ^b	6.3 ^a	6.5 ^b	5.9 ^a	6.1 ^b	6.4 ^c	6.3	6.5	6.4	6.3	6.6	6.4
Temp ₄₅ (°C)	36.6	36.8	39.4 ^a	40.0 ^b	37.6 ^b	37.6 ^a	35.0 ^b	33.1	38.1	36.2	39.2	39.5	37.9
At 24 hours	n = 77	n = 79	n = 50	n = 35	n = 54	n = 54	n = 54	n = 60	n = 50	n = 45	n = 60	n = 246	n = 590
pH ₂₄	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.5	5.8	5.6	5.7	5.5
Temp ₂₄ (°C)	6.0	6.3	5.5 ^a	4.2 ^b	2.8	2.8	2.9	2.6	2.5	1.5	2.3	4.0	6.3
Colour	n = 60	n = 63	n = 50	n = 35	n = 54	n = 54	n = 54	n = 60		n = 40	n = 60	n = 246	n = 590
L*	53.9	53.8	58.6 ^a	47.3 ^b	51.5	52.2	52.3	53.8			55.1	51.9	52.1
a*	8.1	8.6	1.3 ^a	12.6 ^b	5.1 ^a	5.6 ^b	5.1 ^a	6.1			6.5	6.3	5.7
b*	11.6	12.0	12.3 ^a	5.7 ^b	10.1 ^a	10.4 ^b	10.5 ^b	10.9			13.6	3.9	13.3
Drip loss (%)	4.7	4.5	3.7 ^a	2.6 ^b	7.7 ^c	5.3 ^b	2.7 ^a	5.5		2.7	3.0	2.2	4.7
Bloodspots	n = 124	n = 126	n = 50	n = 35	n = 54	n = 54	n = 54	n = 60		n = 39			
Incidence (%)	0.4	0.5	0.5 ^a	0.0 ^b	0.6 ^b	0.4 ^{ab}	0.1 ^a	0.9		0.2			
0: 0 (%)	77.4	74.6	68.0	100.0	59.3	68.5	87.0	43.3		87.2			
1: <5 (%)	8.1	11.1	16.0	0.0	18.5	25.9	13.0	30.0		5.1			
2: <30 (%)	8.9	8.7	14.0	0.0	22.2	5.6	0.0	20.0		5.1			
3: >30 (%)	5.6	5.6	2.0	0.0	0.0	0.0	0.0	6.7		2.6			
PSE Loin (%)	0.0	0.0	0.0	0.0	29.6 ^b	13.0 ^{ab}	0.0 ^a	1.7	0.0	0.0			
PSE Ham (%)	2.9	0.8	22.0	8.6	79.6 ^c	37.0 ^b	0.0 ^a	18.3	6.0	0.0			

^{abc}Means within stunning methods with different superscripts differ significantly. *Benchmark measurements – I, commercial CO₂; 2, commercial CO₂; R, Rybarczuk *et al.*, 2015 CO₂ stun, blast chill; AH, Aaslyng & Hviid, 2020 commercial CO₂ stun, blast chill; M, Mantis *et al.*, 2019, head-only electrical stun, conventional chill. Commercial electrical stunning benchmark measures were also reported in Deliverable 2 (n=50, pH₄₅ 6.6, T₄₅ 37.3 °C, pH₂₄ 5.6, T₂₄ 4.5 °C).

5.4 Summary of economic outcomes of trials included in the PigStun project

The PigStun project attempted to understand the economic impact of the four alternative stunning systems investigated. A baseline of production characteristics and costs was established through a questionnaire of commercial slaughter plants from four different countries – Denmark (CO₂-1), Germany (CO₂-2), the Netherlands (CO₂-3), Spain (CO₂-4, Table 5). The stated range of production characteristics is quite common in modern slaughter plants across much of the globe owing to the limited number of specialised equipment suppliers. Similar chain speeds (400-700 pigs/h), system types and capacity (Paternoster, 5-8 pigs per gondola), CO₂ concentrations (90-92%) and cycle times (225 s) have been reported for Australian plants (Jongman *et al.*, 2021; Hewitt *et al.*, 2025).

Parameters were centred on the lairage through to sticking and covered included installation and maintenance costs, labour related to pre-stunning and stunning, resource use such as water, electricity and gas and their costs. The systems differ significantly in operation and thus costs varied as well – labour as a proportion of total costs varied from 36 to 71% and gas costs varied between 14 and 23% of total costs. The electrical stunning operating costs baseline (which was also the plant that the improved electrical stunning work was applied) was 32% cheaper than the average CO₂ plant, although it was only marginally lower than CO₂-3 that was operating in the same jurisdiction (€0.352 vs €0.358 per pig).

The operating costs of the alternative systems were also determined through a series of questionnaires of the leaders of each system. Deliverable D4 specifically notes that most of the parameters measured correspond to estimates only made by the system leads rather than actual empirical measurements. Outside of the improved electrical stunning system there are no large-scale commercial installations of the tested alternatives and therefore these numbers represent an academic rather than economic evaluation.

All the tested systems are more expensive than the current cost of production when their application is modelled against the case studies (Table 5). The **optimised CAS (Box) system** was the cheapest alternative (1.30 - 1.38 x) as the modelled alternative is only applying an improved climate and an automatic driveway to existing backloader CO₂ paternoster systems, it should be noted that this is not an economic evaluation of the system tested in PigStun. The proposed tunnel system, based on the concept currently available for broilers¹⁰, was not at a development stage that enabled economic analysis. The **improved electrical system** was also suggested as a relatively low additional cost option (1.69 x) due to its lower installation cost and reduction of ongoing costs (ie no gas costs), however, it should be noted that the pre-stunning area that is essential to the operation of the improved electrical stunning system – S-curve design, high side walls and two-choice raceway entry system were not included in the modelled costs as the design and materials cost was not available at the time of reporting.

The **Argon retrofit system** was costed via two methods, the first being a retrofit of the existing CO₂ stunning equipment and additional stunners if required, and the second being a replacement stunning system with improved capacity. The longer exposure time required – 250 s for a dip-lift system to achieve 99.5 % stunning effectiveness – increases dwell time by 40% compared to the CO₂ equivalent reducing both throughput and labour efficiency, whilst the price of argon is estimated to be 5 times more expensive than CO₂. The retrofitting of existing systems and additional stunner lines would see costs increase by 2.55 x, however, if an additional capacity argon system was available to offset the 40% reduction in throughput costs would only increase by 1.57 x. This also assumes that no meat quality issues occur – it should be noted that whilst the Argon retrofit study showed no additional meat quality issues, there were issues when argon was tested in the optimised CAS study.

¹⁰ Marel CAS SmoothFlow <https://marel.com/en/products/cas-smoothflow/>

The **Helium system** is the most expensive system with an operational cost averaging 3.05 x the cost of current commercial CO₂ systems. The costs are a factor of the price of helium which is estimated to be 80-100 x the cost of CO₂ and the low throughput capacity. The tested pilot system had a capacity of 50 pigs per hour although the experts were confident of being able to achieve an optimised capacity of 90 pigs per hour. Again, this system is not compatible with existing infrastructure so an installation from scratch is required. This 3.05 x cost is also predicated on the ability to recover 90% of the helium used in each cycle, if both the daily top-up and the initial fill are included in the cost per pig this is anticipated to result in a system that is 25 to 67 times more expensive than CO₂.

The Agriculture and Horticulture Development Board of the UK has also commissioned an independent economic analysis of the costs of converting CO₂ stunning systems in the UK to either improved electrical or the Argon retrofit system. They have similarly developed a notional UK abattoir and using many of the same assumptions as the PigStun project but with costs and constraints of the UK (such as the WATOK regulations requiring CAS systems to operate on a stun-to-kill basis and therefore increase further dwell times) included in their modelling. Their calculated cost multiplier for improved electrical stunning was similar to the PigStun CO₂-3 model at 2.64, but the longer dwell time required and its impact on throughput sees the Argon retrofit system costing 3.24 to 3.55 x the current notional cost.

Table 5. Processor production parameters for the four PigStun case slaughter plants utilising CO₂ and a notional UK plant (AHDB commissioned economic analysis), current cost of production, and cost multiplier for the operation of alternative stunning systems.

	PigStun case study				AHDB*
	CO₂-1	CO₂ -2	CO₂ -3	CO₂ -4	notional
Daily capacity	20,000	10,800	9,500	4,900	4,500
Chain speed (pigs/hr)	1,200 [†]	700	600	400	450
System	Paternoster	Dip-lift	Paternoster	Paternoster	Paternoster
Pigs per gondola	7-8	8	6	4-5	-
Cycle time (s)	250	145	180	210	-
CO ₂ concentration (%)	90	98	88	92	-
Current cost per pig					
€ EUR, AHDB in £ GBP	0.735	0.518	0.358	0.639	0.42
\$ AUD (Q1 & 2 FY26 average)	1.26	0.89	0.62	1.10	0.86
Operating cost multiplier					
Argon retrofit	2.21	2.61	2.44	2.92	3.24
Argon retrofit (added capacity)	1.58		1.54	1.60	3.55
Helium system	2.72	2.78	4.79	1.91	-
Optimised CAS (Box system)	1.33	1.30	1.37	1.38	-
Improved electrical	1.48	1.56	2.64	1.09	2.64

*Economic analysis prepared by Europe Economics for the Agriculture and Horticulture Development Board (UK AHDB) – March 2026; [†]this facility utilises two lines with 600 pigs/hr chain speed.

All the alternative systems currently have capacity constraints that would require the installation of additional stunners to maintain throughput, the number of additional stunners per system are outlined in Table 6.

Table 6. Additional stunner line requirements to maintain current throughput at the four PigStun case slaughter plants utilising CO₂ and a notional UK plant (AHDB commissioned economic analysis) for the operation of alternative stunning systems.

	PigStun case study				AHDB*
	CO₂-1	CO₂ -2	CO₂ -3	CO₂ -4	notional
Number of stunner lines					
Current	2	1	1	1	1
Argon retrofit	6	3	2	2	1
Argon retrofit (added capacity)	2	-	1	1	2
Helium system	10	8	8	4	-
Optimised CAS (Box system)	2	2	1	1	-
Improved electrical	8	4	4	4	4

*Economic analysis prepared by Europe Economics for the Agriculture and Horticulture Development Board (UK AHDB) – March 2026.

6 Discussion

6.1 Animal welfare

The PigStun trials compared CO₂ gas stunning to stunning with the alternative gases argon and helium. They also included observations in an improved electrical stunning system and three commercial stunning systems. The results largely confirm existing knowledge from previous research, as described in the literature review on stunning methods for pigs commissioned by APL (Jongman and Hemsworth, 2025; APL Project 2024/0040)

Animals may experience distress from exposure to gas at the first behavioural sign of aversion until loss of posture - a proxy for loss of consciousness. The time to loss of consciousness does not only depend on how it is measured but also on the concentration of the gas and the speed of descent into the pit filled with CO₂ or argon, where the highest concentration is at the bottom (Dalmau *et al.*, 2010), or ascent with the highest concentration of helium at the top. Additionally, the number of pigs in the gondola (Jongman *et al.*, 2021; Bonnichsen *et al.*, 2024), the size of the system and even ambient temperature and other environmental conditions can affect the response to CO₂ (little data is available for argon and helium, but similar influences are assumed). Therefore, comparisons between different systems and different settings are not straightforward.

The time from first response to loss of posture is the best indicator to estimate the total time that animals suffer from poor welfare during stunning, although time to complete insensibility during gas stunning may be about 10 s later, based on EEG readings (Verhoeven *et al.*, 2016). According to EFSA (2020) pigs experience a quicker time to loss of consciousness in argon (13-18 s) than in CO₂ (17-25 s), based on a study by Raj *et al.* (1997). However, later research reports that the time from first exposure to loss of posture is (slightly) longer for argon than for CO₂ (Raj, 1999; Dalmau *et al.*, 2010). This was also found in the PigStun trials that compared argon and CO₂, although the actual time to first responses and loss of posture differed between trials. In the Argon retrofit system, the time from first response to the CO₂ and argon to loss of posture was very short (5.0 and 6.4 s). The respective times in the optimised CAS (Box) system were 18 and 24.3 s, while the time from first response to loss of posture was between 5 to 11 s for CO₂ in the commercial benchmark systems. In both trials that included helium, time to unconsciousness was longer for helium than argon and about double the time compared to CO₂. Observations in Australian abattoirs using CO₂ vary between 7-9 s (Hewitt *et al.*, 2025) and 16-27 s (Jongman *et al.*, 2021) to loss of posture, while Verhoeven *et al.* (2016) found times from first response (sniffing) to loss of posture differed with CO₂ concentration from 26 s at 80% to 19 s at 95%. This data shows large variation in times to unconsciousness from a wide range of research and commercial conditions, however, similar data for argon is not available as this is currently not being used in any commercial setting.

While time until unconsciousness was longer, exposure to argon was much less aversive than CO₂ in the PigStun trials, as pigs react with less agitation and show less breathlessness. Additionally, fewer pigs show an aversive reaction to argon, although some reactions were still observed. This is confirmed by other studies, that also found less aversion to argon than CO₂ but still observed some aversive responses (Dalmau *et al.*, 2010). Direct comparison between helium and argon in the optimised CAS (Box) system suggested that pigs responded fairly similar to both gases, with a slightly milder response to helium, but an increase in the number of pigs that showed breathlessness to helium. This is contrary to Machtolf *et al.* (2013), who observed no aversion responses to helium, the only other research trial on the use of helium.

However, aversive behaviours (including abnormal breathing, escape behaviour and vocalisation) in response to CO₂ have been observed in as many as 100% or as few as 15% of pigs (Steiner *et al.*, 2019), indicating that not only time to loss of posture, but also aversive responses to CO₂ differ between studies. This indicates that responses to CO₂ can be improved with better understanding of the factors

that cause this variation (Steiner *et al.*, 2019). It is not clear what variation to argon may be expected once this is implemented in different commercial settings. Presumably, most research trials use best practice handling and stunning under highly controlled conditions, which may not be replicated under commercial conditions.

There were differences between the Argon retrofit trial and the optimised CAS (Box) stunning systems in terms of responses to the gases and time to loss of posture when pigs experienced similar conditions prior to slaughter. The pre-slaughter handling in the Helium trial was significantly different between helium and CO₂, which may have affected the subsequent responses to gas exposure so that it is difficult to make a comparison. Stress caused by pre-slaughter handling has been shown to affect the response to CO₂ (Jongman *et al.*, 2021) and manual handling is generally considered more stressful than movement by automatic means (Hewitt *et al.*, 2025).

Inert gases cause unconsciousness due to hypoxia, and this can be reversed very quickly once pigs are exposed to oxygen in normal air. Therefore, stun-to-stick intervals need to be kept short to guarantee that animals do not return to consciousness prior to death due to blood loss. If this cannot be guaranteed (and acceptable re-stun rates cannot be achieved), pigs should be exposed to gas until death of all pigs is ensured. Verhoeven *et al.* (2016) found that pigs exposed to 80% and 95% CO₂ showed an iso-electric EEG after 75 s and 64 s respectively, indicating that pigs are completely insensible. However, the total duration of exposure to CO₂ in this trial was more than 5.5 minutes. Pigs were observed for one minute post CO₂ exposure, after which no pigs exposed to 95% of CO₂ showed a corneal reflex or breathing activity, but 2 out of 24 pigs exposed to 80% CO₂ were gasping. Because of their iso-electric EEG, it was assumed that this was rudimentary brain stem activity and not an actual sign of recovery of consciousness. Exposure in the benchmark CO₂ abattoirs in the PigStun project varied from about 2.5 to 3.5 minutes, and only the longest exposure resulted in a 0% re-stun rate. However, it appears that assessments were made immediately post exposure. The criteria for re-stunning are not clear and may not necessarily indicate that pigs were returning to consciousness. Similar data from argon is lacking, although one study by Raj (1999) found that pigs started to show signs of return to consciousness within 50 s after exposure to 90% argon for 3 minutes. Even after 7 minutes of exposure 7% of pigs showed signs of returning to consciousness within 50 s and EFSA (2013) recommends a maximum stun-to-stick interval of 25 s when pigs are exposed to 90% argon for 3min. However, as for CO₂, maximum stun-to-stick intervals and acceptable rate of re-stunning would need to be established for each setting when stunning using argon. Similar results were found for helium, where exposure for 3 minutes resulted reliably in unconsciousness, however, the stun-to-stick interval was limited to 15-30 s (Machtolf *et al.*, 2013). The stun-to-stick interval in commercial abattoirs using CO₂ can be up to 60 s with larger group sizes. Reducing this interval if argon was used would require additional labour, or exposure times need to exceed 7 min.

The observations in the improved electrical stunning system show that improvement on the current electrical stunning systems is possible. However, these observations were made at a single abattoir and only included limited observations, without a standard control. While low voltage prodders are likely to be less aversive than the more commonly used high voltage prodders, no separate research has been conducted on their aversiveness and effectiveness. Electric prodders were still used on 18% of pigs to move them onto the belt into the stunner.

Side-by-side raceways have been recommended by Temple Grandin (2021) as a better alternative than a single race, although the advantages and implications of allowing pigs to choose a left or right entry is not clear. For example, if a clear preference exists for one side, the advantage may be minimal. Automatic electrical stunning has been shown to be highly effective in previous studies, although all studies report re-stunning rates above 0%. These ranged from 0.2% with 100% correct placement of electrodes and a stun/stick interval of 4-8 s (Nodari *et al.*, 2014) to 0.5% using best practice methods (BSI Schwarzenbek, 2013) and even up to 3.3%, with 1.9% of pigs observed to be awake (Von

Wenzlawowicz *et al.*, 2012). Re-stunning rates of semi-automatic and manual electrical stunning are generally higher than for automatic systems.

For a stunning method to be humane, the whole process from low stress pre-slaughter handling and restraint, onset of unconsciousness without fear, pain or distress, and duration of insensibility until death should be considered (EFSA, 2013). The PigStun project investigated a reduction in pre-slaughter stress associated with handling of pigs in a raceway in order to use electrical stunning. However, it is hard to overcome the natural aversion of the pig moving in single file and some negative interactions with people are unavoidable, although they can be reduced by good design of facilities and training of stockpeople. As little detail was provided on the design, handling methods (for example details on a 'low voltage electric prodder') and staff training, it is not clear how the 'improved electrical stunning system' would perform under more standard commercial conditions. Electrical stunning causes instantaneous loss of consciousness and when judged in isolation is an ideal method of stunning. However, the requirement of individual restraint and reduced stunning efficiency and short stun-to-stick interval are an inevitable part of this stunning method and therefore may not be the most humane stunning method available.

Best practice handling systems, moving pigs in small groups using hydraulic gates, are already practiced in most commercial CO₂ abattoirs in Australia. This may still include using forceful handling at times, however electric prodders are rarely used (Jongman *et al.*, 2021). While argon is less aversive to pigs than CO₂, loss of consciousness is not immediate and pigs experience hypoxia resulting in air hunger and gasping before losing consciousness. Therefore, argon may be an improvement on CO₂ but is not an ideal alternative to CO₂.

Several possible alternatives were not studied as part of the PigStun project. While originally flagged as part of the project, a tunnel system design was abandoned due to lack of commercial interest. A tunnel stunning system would open the possibility of other, more humane gases, such as carbon monoxide (CO) or nitrogen (N₂). CO has been used to euthanize a wide variety of species and is not associated with distress or pain (Hickman, 2023). However, rats did show some avoidance to CO concentrations between 5-7%, presumably due to hypoxia (Makowska and Weary, 2009). Because CO is highly toxic and odourless, there is a reluctance to use it, but a closed tunnel system may improve safety to humans. A tunnel system could also be incorporated in a two-phase stunning system with an induction phase using argon and death caused with CO₂, as suggested by Raj (1999) and Sindhøj *et al.* (2021). A gas mixture of 80% N₂ and 20% CO₂ was also found to be less aversive than a high concentration of CO₂ but required longer exposure times and oxygen level below 2% (Atkinson *et al.*, 2020; Llonch *et al.*, 2012). Responses to this gas mixture may be similar to argon, but it may be a more cost-effective alternative.

6.2 Meat Quality

Similarly to the findings on impacts on animal welfare, the meat quality results also reflect current knowledge of these alternative stunning systems. A significant reason for the widespread adoption of CO₂ stunning systems was the improvement in meat quality and reduction in defects when compared to electrical stunning systems. Electrical stunning systems have lower ultimate pH and higher levels of drip loss (Channon *et al.*, 2000; Mantis *et al.*, 2019) and a greater incidence of bloodspots (Channon *et al.*, 2002) because of vascular damage during the sudden tonic contraction of muscles that occur as part of the stunning process (Gregory, 1985).

There are, currently, two approaches to controlled atmosphere stunning, hypercapnic/hypoxia (CO₂) or hypoxia where alternative gases are used to exclude oxygen to below two per cent of the environment. Argon and helium were the gases of interest in the studies of PigStun but nitrogen, as

N₂ (TIGER) or N₂O (nitrous oxide, Terlouw *et al.*, 2021) have also been investigated, however, the method rather than the gas utilised is important and will be the focus of this discussion. In general, the hypoxic treatments in this study resulted in poorer meat quality than their contemporary CO₂ controls or benchmark studies. Generally, drip loss, the incidence of bloodspots and the potential for PSE were higher in hypoxic treatments, but differences in colour were stark in some studies but non-existent in others.

The behaviour of animals during the stunning process may go some way to explain these differences. In the helium system, the time to loss of posture (49.4 s vs 24.5 s) and last movement (182.3 s vs 137.1 s) were both extended, with similar results in the optimised CAS (Box) system – time to loss of posture (argon 64.4 s, helium 80.4 s, CO₂ 40.2 s) and last movement (argon 247.7 s, helium 229.7 s, CO₂ 229.7 s). Muscle activity requires metabolism, which in an anaerobic environment would result in the accumulation of lactic acid and an increase in temperature (as found in the optimised CAS (Box) system).

As previously stated, the higher incidence of bloodspots in electrical stunning is associated with vascular damage during the sudden tonic contraction of muscles (Gregory, 1985). However, this does not occur in hypoxic stunning, with the increased incidence postulated to be related to the extended period of muscle activity. Acute hypoxia does however induce sympathetic activation, with human studies showing hypoxia significantly increases baseline systolic blood pressure, pulse pressure and heart rate (Fox *et al.*, 2006) and induces a peripheral vasodilation that balances central tachycardia and vasoconstriction (Richalet *et al.*, 2017). These mechanisms would appear to be a potential cause of the increased bloodspots observed in these studies.

The lack of differences in ultimate pH but significant differences seen in lightness (L*), redness (a*) and yellowness (b*), drip loss and potential incidence of PSE are of interest given pH at 24 hours is recognized as the best predictor of pork quality (Boler *et al.*, 2010). This reduces the potential for processors to classify carcasses for meat quality prior to boning. A potential explanation of these findings may be found in gene expression work recently published by the TIGER project (Argon retrofit), that found a group of downregulated genes in the inert gas groups (Gelhausen *et al.*, 2026) that had previously been found to be downregulated in pork exhibiting PSE characteristics (Zequan *et al.*, 2022).

An overall assessment of meat quality measures from tested and benchmark systems would suggest that the alternative systems still require further refinement to deliver an industry acceptable level of quality particularly with respect to drip loss and the incidence of bloodspots. Specific market characteristics, such as a significant proportion of product being further processed into manufactured meat, may enable processors to accommodate such failures in quality. Indeed, myopathies in broiler chickens such as wooden and spaghetti breast are handled in such a manner (Santos *et al.*, 2021). However, markets such as Australia that are primarily focussed on the supply of whole muscle fresh pork and signature products such as bone-in cured and smoked hams would have less ability to manage such inferior quality. The apparent lack of relationship between ultimate pH and water-holding capacity is also of concern, reducing the ability to screen inferior product prior to boning.

6.3 Economics

The economic analysis of the alternative stunning systems was greatly limited by the incomplete information available, whilst being further complicated by key missing information being different between systems. For instance, the cost of the pre-stunning area was not available for the improved electrical stunning system. Given the animal welfare benefit of the improved electrical stunning system resides in the reduction of negative human interactions and improved choice during this pre-stunning

area, not including this in the cost estimates means cost comparisons are ultimately meaningless for commercial adoption.

Outside of the uneconomic cost of helium gas – estimated at 80-100 times the price of CO₂ due to its limited availability and prioritising of its use for medical and scientific purposes, the largest economic impact is in reduced throughput of the alternative systems and the steps required to address this issue – mainly through the installation of multiple stunners. Modern commercial abattoirs using CO₂ stunning have chain speeds of 600-700 pigs per hour on a single line. The improved electrical stunning system is suggested to operate at 160 pigs per hour per stunner to reduce negative interactions. It is believed that 90 pigs per hour is achievable in the current Helium stunning system with some additional optimizations, it was tested at 50 pigs per hour. Whilst the increased dwell time (250 s) required to reach a 99.5% stunning effectiveness (5 in 1,000 pigs) in the Argon retrofit system reduces throughput by 40%. In the UK where the WATOK¹¹ regulations require controlled atmosphere stunning to be stun-to-kill the reduction in throughput is likely to be higher. The economic cost is therefore either borne by reducing the number of pigs slaughtered per hour which will impact the economics further along the processing chain – evisceration, chilling and potentially secondary processing, or by installing additional stunners and associated infrastructure – loading raceways, shackling and sticking stations.

Economic comparisons are not really feasible given that hypoxia based stunning systems are yet to be tested, let alone adopted, at commercial scale. However, the best alternative system for a particular site will be influenced by the existing system in place. Switching to an alternative stunning system has been shown to increase the per-pig costs irrespective of the alternative system adopted, whilst there are still considerable uncertainties in the modelling that are unable to be addressed with the current data available.

There are both technical and economic issues associated with the transferability of the investigated systems to Australia, although even PigStun admits such discussions are premature with the need for careful scientific monitoring to “confirm that the animal welfare benefits of the proposed alternatives are maintained when they are scaled up to commercial high throughput rates” (Recommendation 6, Deliverable D4). Considerable gaps and unknowns have been noted by, and within, the PigStun project and therefore by extension to any perceived commercial implementation.

Economic, technical and environmental issues are likely to be site specific. How lower throughput rates are dealt with will depend on the specific capacity restraint – if shift capacity is limited, either through existing shift structures or local ordinance restriction of operating hours, it would require the installation of additional stunners to restore chain speeds, conversely the ability to add an additional shift is likely to be constrained by access to labour. Further economic is therefore not possible at this time.

6.4 Ethics

As defined by EFSA, the most important criteria for assessing the humaneness of a stunning method, the following should be considered: “...immediate onset of unconsciousness and insensibility or absence of avoidable pain, distress and suffering until the loss of consciousness and sensibility, and duration of the unconsciousness and insensibility (until death).” (EFSA, 2013). On the basis of this definition, an expert panel voiced the opinion that exposure to high concentrations of CO₂ is highly aversive and causes pain, fear and respiratory distress and therefore is a serious welfare concern. These adverse responses are reduced when exposed to inert gases (EFSA, 2020), such as argon and

¹¹ Welfare of Animals at the Time of Killing (England) Regulations 2015 – Schedule 1, 29. <https://www.legislation.gov.uk/ukxi/2015/1782/schedule/1>

helium. Even so, inert gases do not cause the immediate onset of unconsciousness, and distress can still be experienced.

A YouGov poll in the UK found that 86% of the survey people were not aware that CO₂ was a common stunning method (Prescott-Smith, 2020). Although the general public may not even be aware of the use of CO₂ stunning for pigs, exposés in the media often elicits a strong negative response. Footage was aired in Australia on ABC 7.30 on 27th March 2023 (Day, 2023) and drew widespread attention to CO₂ stunning of pigs. The RSPCA UK as well as RSPCA Australia advocate for the phase out of CO₂ stunning and it be replaced with less aversive inert gases. However, both currently accept CO₂ stunning for pigs as part of their animal welfare assurance programs.

Animal production systems have an obligation to minimise animal suffering if viable alternatives are available. Based on aversive responses alone, stunning with inert gases may be an ethical replacement for stunning with CO₂, with argon being the most practical and available alternative gas. However, argon has not yet been tested in commercial settings with larger number of pigs per gondola and line speeds seen in most commercial settings. When argon is used to stun pigs, it is vital that O₂ levels are kept very low, to ensure that the total time of exposure and the associated negative experience at least for some pigs, is kept to a minimum. Before regulation bans the use of CO₂, it would be useful to collect data from abattoirs that have voluntarily converted to argon, to ensure that it is indeed a welfare friendly and practical alternative for CO₂. If a premature transition to argon is enforced and responses to argon in some commercial settings results in clear adverse responses to exposure and pigs regaining consciousness after stunning, this not only poses a risk to animal welfare, but also to the public acceptance of stunning with argon.

Both RSPCA UK and Australia recognise the advantages of gas stunning over electrical stunning, with pigs being moved in groups, minimal handling and the lack of restraint in gas stunning systems. Poor handling practices, overuse of electrical prodders and variable designs and the need for individual restraint often cause considerable pre-slaughter stress in electrical stunning system. However, even in current systems, well designed facilities and good stockperson training can reduce pre-slaughter stress. Abattoirs should be compelled to comply with best practice handling, including prodder use limited to a maximum of 25% of pigs. If a low-voltage prodder is found to be as effective as a commonly used prodder (which delivers shocks at around 5000 to 8000V), then these should be used as a lower stress alternative. There are proposals in Europe, and specifically in the Netherlands, to ban the use of high voltage electrical prodders. Currently European regulations clearly state that the use of these devices must be avoided and may only be used in a very specific way, although they do not explicitly prohibit this use (EFSA, 2020).

The improved electrical stunning system reported on in the PigStun project relies partly on a lower throughput to reduce pressure to move pigs as fast as possible. However, economic pressures may be hard to regulate against, if the facilities themselves allow for a faster line speed. Mandatory stockperson training may also reduce the use of aversive handling techniques and improve animal welfare at abattoirs.

Most of the criticism of stunning systems focus on pre-slaughter handling and the stunning method itself, with less attention for stunning effectiveness and stun-to-stick intervals. However, insensibility until death can only be guaranteed if exposure to gas is of sufficient duration to cause death in all animals or if all animals can be bled and die from blood loss before regaining consciousness. Similarly, electrical stunning causing death ensures that pigs do not recover, whereas head-only electrical stunning leaves room for error in both electrode placement and stun-to-stick interval. Obviously, animals starting to regain consciousness before death is a welfare issue. They need prompt re-stunning, which may or may not always happen in a commercial setting, as it requires close observation of all

pigs before and immediately after sticking. High re-stunning rates is not just a welfare issue for pigs but may also affect workers' welfare and morale.

7 Implications & Recommendations

The PigStun project largely confirmed the results in the existing literature. However, the methodology used in some of the trials were confounded and the results were difficult to interpret in terms of their commercial applications. From an animal welfare point of view, argon would be a practical alternative to CO₂ that would improve animal welfare as long as exposure times are sufficient to ensure that animals remain unconscious until they die of blood loss (if not during stunning). This requires exposure to argon, with a residual oxygen concentration below 2%, for up to 7 minutes, depending on the required stun-to-stick interval. Forcing an industry to move from CO₂ to argon stunning would be premature and needs to be tested in a high throughput commercial abattoir using a paternoster system. It is vital that low oxygen levels can be maintained (<2%) and that acceptable stun-to-stick intervals and re-stun rates can be achieved.

While the improved electrical stunning system, as implemented in one particular abattoir, appears to provide for better animal welfare than commonly seen in commercial electrical stunning systems, this seems to be a culmination of several factors. The design of the raceways, education of stockpeople, use of low voltage electric prodders, lower throughput and an automatic stunning system all contribute to better welfare. Most of these improvements are best practice, although it is unclear if a low voltage electric prodder is less aversive, but similarly effective, than a standard high voltage prodder. While a lower throughput would reduce the pressure of moving animals as quick as possible, it is not clear how this could be enforced.

Alternative stunning systems, both hypoxic and electrical systems, continue to deliver inconsistent meat quality outcomes when compared to CO₂ stunning, particularly with regard to drip loss, bloodspots and the potential development of PSE. While extended induction and physical activity may explain some of these results the underlying physiological mechanisms – potentially sympathetic activation in response to hypoxia, needs greater understanding. Whilst welfare improvements are important, for adoption by industry the issues of meat quality consistency, processor usability and market suitability must be addressed. Any transition away from CO₂ needs to be incremental, supported by robust quality data, and align with market requirements and processing capabilities.

The economic analyses clearly indicated that there should be no further pursuit of helium-based systems and that further work on throughput losses is required to offset significant cost increases in argon-based systems. The marginal cost increase of the optimised backloader CO₂ system with improvements in pre-slaughter handling allows for incremental improvements that can lift existing stunning systems to best-practice. It must also be noted that the cost factors are incomplete in the PigStun recommendations and that a priority should be a thorough economic validation at commercial scale before further development.

There is interest in the potential of using a two-phase stunning system of argon to induce initial loss of consciousness followed by CO₂ to complete the process. This may provide the most humane stunning method and potentially overcome some of the meat quality issues associated with argon stunning. The tunnel system may potentially deliver such a multi-phase system and given the economic cost of alternatives further investigation of such a system would appear warranted.

In summary:

- Argon continues to appear to be the most practical alternative but requires commercial-scale trials to confirm welfare benefits, understand meat quality implications and operational and economic feasibility.
- Helium is not, or is ever likely to be, viable due to cost and supply constraints.
- Improvements in pre-slaughter handling in electrical stunning systems is required but needs commercial scale validation across multiple sites to confirm welfare improvements.

- Adoption of alternatives requires careful management to avoid premature adoption risks and ensure compliance with welfare standards, market requirements and processing capabilities.
- The PigStun project has added to, but not answered, many of the knowledge gaps that still exist with regards to the alternatives to CO₂ stunning.

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