A techno-economic-societal assessment of recovery of waste volatile anaesthetics

Ang, Teck Nam; Udugama, Isuru A.; Mansouri, Seyed Soheil; Taylor, Matthew; Burrell, Rob; Young, Brent R.; Baroutian, Saeid

Published in:
Separation and Purification Technology

Link to article, DOI:
[10.1016/j.seppur.2019.06.011](https://doi.org/10.1016/j.seppur.2019.06.011)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Ang, T. N., Udugama, I. A., Mansouri, S. S., Taylor, M., Burrell, R., Young, B. R., & Baroutian, S. (2019). A techno-economic-societal assessment of recovery of waste volatile anaesthetics. *Separation and Purification Technology*, 226, 304-314. <https://doi.org/10.1016/j.seppur.2019.06.011>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

recovery technology is being considered, the findings provide insights on the aspects requiring more evaluation. Based on the insights gained, an informed opinion and perspective on the VA recovery technologies and shortcomings when developing practical VA recovery technologies are provided.

Keywords: inhalation anaesthetics, adsorptive separation, global warming potential (GWP), socio-economic potential, technology readiness level (TRL).

1. Introduction

Since the first volatile anaesthetic vapour administration of chloroform in 1847, medicine has searched for better volatile agents, along the way embracing cyclopropane (1933), trichloroethylene (1934), and fluroxene (1954). The era of modern inhalation volatile anaesthetics (VAs) began in 1956 with the introduction of halothane (Byhahn et al., 2001), followed by methoxyflurane, enflurane, isoflurane, sevoflurane and desflurane. The latter three make up the common agents used in the hospitals in developed countries today.

Methoxyflurane (marketed via the handheld Pentrox[®] inhaler) is undergoing a resurgence in use for short-term analgesia during emergencies and short surgical procedures (Dayan, 2016).

While widely in use in Australia and New Zealand since 1975, it is registered for use in adult patients having trauma-associated pain in Europe from 2015 (Porter et al., 2018). These

agents are non-flammable, halogenated, hydrocarbon anaesthetic compounds possessing similar structure to hydrofluorocarbons (HFCs) or hydrochlorofluorocarbons (HCFCs).

Similar to chlorofluorocarbons (CFCs), these fluorinated VAs impose adverse effects on global temperatures and stratospheric ozone (Langbein et al., 1999; Tanada et al., 1996).

Figure 1 shows the three-dimensional structure of the VAs and the associated problems when

these molecules are emitted to the atmosphere unabated. Although the contribution of VAs to global warming is comparatively small to CO₂, the global emission of VAs from hospitals that sums up to an enormous quantity, inflicts a considerable burden on the atmosphere (Sulbaek Andersen et al., 2010). The atmospheric persistence and infrared absorption properties of the VAs contribute to their global warming potential (GWP). Given that desflurane is administered in a dose twice that of sevoflurane (Delgado-Herrera et al., 2001), and its GWP is almost ten times higher, the GWP of a desflurane anaesthetic is roughly twenty times higher than that of a sevoflurane anaesthetic (**Table 1**). The chlorine-containing VAs emitted to the atmosphere cause destruction to stratospheric ozone (Brown et al., 1989). Despite the presence of international treaties and legislation that restricts the emission of fluorinated gases, VA are excluded from the fluorinated gases compilation due to their ‘indispensable necessity’ in healthcare (Ryan & Nielsen, 2010).

Figure 1: Volatile anaesthetics emissions and the accompanying environmental problems.

Table 1: Global warming potential (GWP) measured over a time horizon of 100 years (relative to one tonne of carbon dioxide equivalent emissions), and potency of the volatile anaesthetics

Volatile anaesthetic	GWP₁₀₀[*]	Potency[†]
Sevoflurane	210	1.8
Isoflurane	510	1.2
Desflurane	1620	6.6

^{*} Adapted from Sulbaek Andersen et al. (2010).

[†] Minimum alveolar concentration (MAC) expressed as a % of 1 atmosphere (Barash, 2013; Kossick, 2014).

The first publication on waste VA capture emerged in the early 1970's. Back then, the studies focused on minimising contamination in the operating room atmosphere, with the intention to eliminate prolonged exposure of medical personnel to waste VAs (Grodin et al., 1985; Kim & Sircar, 1977; Murrin, 1974). As the environmental impact of VAs became more publicised (Charlesworth & Swinton, 2017; Vollmer et al., 2015; Yasny & White, 2012), research attention shifted towards the exploration of approaches in abating their emission. While scavenging systems reduce indoor VA contamination, the emission of VAs to the atmosphere persists. Therefore, practical and sustainable approaches that enable capture of VAs from the operating waste stream before emission are desirable.

Various approaches were reported capable of removing VAs from waste gas stream. For instance, adsorption (Bucher et al., 2017; Mehrata et al., 2016; Ortmann et al., 2016), absorption (Fradette, 2015), and cryogenic condensation (Berry & Morris, 2006a, 2006b, 2009). Of these approaches, adsorption is by far the most extensively investigated process, and it has been implemented in numerous industries, such as the chemical, petroleum, and pharmaceutical industries, to selectively remove organic compounds from the gas or vapour

phase waste stream (Lecomte et al., 2010). The type of adsorbents used to reversibly adsorb VAs include activated carbons, molecular sieve zeolites and metal-organic frameworks (MOFs). Adsorption technology allows recovery of captured VAs at relatively mild conditions. Jänchen et al. (1998) reported nearly complete desorption of desflurane adsorbed on zeolites. The desflurane vapour then condensed to liquid. A more primitive approach is absorption using a water trap. The solubilised VAs and the water is disposed of upon saturation (Fradette, 2015). Water absorption methods may be laborious, and risk VA evaporation to the atmosphere. On the other hand, cryogenic condensation is a relatively technology-intensive approach compared with adsorption, and requires a compressor and a condenser for recovering VAs.

Capturing VAs is beneficial from several standpoints. From the environmental perspective, capturing waste VAs reduces their ecological footprint. From the health and safety viewpoint, it protects medical personnel and patients from unnecessary perioperative and post-operative VAs exposure. Recycling the costly VA agents reduces the running cost of hospitals and provides the ability for hospitals to trade the carbon credit equivalent of captured and recycled VAs under the Carbon Emissions Trading Scheme (ETS) with other industries in New Zealand. The presence of an ETS could also foster the growth in innovation and investment in low-carbon emission technologies (Fan et al., 2017).

A rather comprehensive review addressing the problems caused by uncontrolled emission of VAs and the potential adsorptive technologies has been published by the authors (Ang et al., 2019). To the authors' knowledge, the publications on the adsorptive removal of VAs mainly focus on the technical aspects, such as the adsorption and desorption isotherms (Bucher et al., 2017; Ortmann et al., 2016), kinetics (Chen et al., 2015; Jänchen et al., 1998), and

breakthrough characteristics (Hua et al., 2016). Thus far, there is no reported discussion on the techno-economic aspects of implementing VA recovery technologies in the previous studies, even though the quantification of these aspects are crucial for evaluating the sustainability and applicability of the technologies. In this paper, we adapted a hierarchical systematic framework developed by Mansouri et al. (2017) and Udugama et al. (2017) to systematically identify relevant techno-economic-societal issues in VA valorisation, and developed implementable VA valorisation solutions. This paper specifically included the social benefits associated with the implementation of a VA recovery technology, which is often neglected in most publications of similar fields (Yan et al., 2014). The combinatorial benefits of social and economic aspects were assessed using socio-economic potential analysis, net revenue analysis and detailed economic analysis. The Technology Readiness Level (TRL) concept, which helps to evaluate the maturity of the available removal technologies, was adapted by adjusting its interpretation of each level for VA recovery. To consolidate the proposed assessment methodology, a step considering the governing regulations on the reuse of waste VAs as anaesthetic agent and consumer readiness to the reclaimed product were also included.

The paper was organized to give detailed description of the systematic assessment methodology. Then, the assessment methodology was applied to a real case study based on published information and statistical data of VA usage collected from the hospitals to find a feasible solution. Lastly, the findings were discussed considering various perspectives and scenarios to give the best fitting idea for the recovery of waste VAs.

2. Methodology

The implementation of VA recovery technologies in hospitals requires careful assessment of technology availability, economic incentives, environmental factors, and societal and business (e.g. hospitals and health boards) willingness to adapt to the technologies. To make an informed decision on installing a VA recovery unit at a location such as a hospital, it is necessary to consider the above-stated aspects in a systematic and gated manner where each decision gate is used to reject unsuitable solutions. This approach eliminates impractical solutions and carefully evaluates promising ones as they progress through the decision gates. This section proposes a systematic gated methodology to identify, assess and develop promising VA recovery technologies by making multifaceted considerations (**Figure 2**).

Figure 2: Overview of the proposed systematic assessment methodology.

2.1. Step 1: Socio-Economic Potential Analysis

Firstly, problem formulation identifies the problems and the desired outcomes that need to be achieved. The background of the problems have been described in the Introduction. The desired outcome of the assessment was to maximize the socio-economic benefits from the recovery of waste VAs.

The maximum socio-economic benefits that can be derived from recovering VA by applying a VA recovery technology is calculated by summation of maximum economic benefits that can be derived from the sale of recovered VA and the marginal cost of abatement that can be derived from the reduction of VA emissions. Specifically, a conventional market analysis identifies the maximum economic potential of the recovered VA, i.e. the expected revenue generated from selling the recovered VA purified to medical grade, the most economically lucrative form of VA reuse. The marginal economic benefit is derived from the marginal cost of reducing VA emission. The socio-economic potential is the summation of the expected revenue of selling the recovered and purified VA and the societal benefits of VA recovery, and it is represented by Equation (1).

$$\text{Socio-Economic Potential} = (\text{Best Price}_{VA} \times \text{Volume}_{VA}) + (MCA_{VA} \times \text{Volume}_{VA}) \quad (1)$$

where Best Price_{VA} signifies the retail price of the recovered and purified VA when it is sold as a medical grade VA. It is noted that Best Price_{VA} signifies the most economically attractive outcome and is only used in the initial screening process, and this value may be adjusted to fit its market value accordingly. The Volume_{VA} is the volume of VA potentially captured per year. The marginal cost of abatement of VA emission (MCA_{VA}) signifies the societal cost of the environmental impact of VA, and it cannot be calculated directly from the

emission volume of the VAs. The MCA of greenhouse gases is usually estimated with reference to the emission of one tonne of CO_2 . Therefore, the MCA_{VA} is given by the following equation.

$$MCA_{VA} = MCA_{CO_2} \times \frac{GWP_{100,VA}}{GWP_{100,CO_2}} \quad (2)$$

where MCA_{CO_2} is the marginal cost of abatement of CO_2 emissions, $GWP_{100,VA}$ and GWP_{100,CO_2} are the global warming potential of the VA and CO_2 respectively measured over a time horizon of 100 years, and $(GWP_{100,VA}/GWP_{100,CO_2})$ is the dimensionless CO_2e emission multiplier of the VAs. The list of CO_2e emission multiplier of the VAs is presented in Table A (Appendix I).

The GO criterion of this STOP/GO gate is the identification of a VA source having sufficient economic potential to install the recovery technology. The economic potential threshold (the monetary value) for making a GO decision is at the user's discretion.

2.2. Step 2: Technology Identification

Having recognised a source with significant VA emission, an implementable VA recovery technology is then identified. The identification of the technology can be done in three sub-steps: (I) waste gas stream identification, (II) technology search, and (III) technology readiness assessment.

2.2.1. Step 2 (I): Waste Gas Stream Characterisation

Firstly, the composition of waste gas stream needs to be established. This can be done either through gas analysis such as gas chromatography or literature search. The gas stream composition of the source of interest was identified from Step 1.

2.2.2. Step 2 (II): Technology Search

A technology search of literature and patents is performed to identify all potential VA recovery technologies that can be used to separate VA from the waste gas stream of interest. This sub-step can be facilitated by the establishment of a database, which assesses whether a VA recovery technology is capable of separating VA from a given source of waste gas stream.

2.2.3. Step 2 (III): Technology Readiness Level Assessment

The potential VA recovery technologies identified are then assessed and rated accordingly using a Technology Readiness Level (TRL) assessment, a standardized scale that can be used to rate technologies and their maturity in many different fields (Rybicka et al., 2016). TRL assessment rates a potential technology by assigning a numeric rating ranging from '1' to '9'. Technologies with TRL1 are identified as technologies still at basic concepts, while technologies with TRL9 are ones that have been implemented and are 'flight proven'. The TRL assessment can be employed to rate the technology maturity of potential competing VA recovery technologies. Conrow (2011) provides a description of the TRL scale commonly used by the U.S. Department of Defense and NASA to evaluate the maturity of a particular technology. The NASA definition of TRLs and the interpretation for VA recovery are summarized in **Table 2**.

The GO criterion of this sub-step (and Step 2) is the identification of a VA recovery technology possessing sufficient degree of technology maturity. We recommend focusing on solutions with TRL5 or higher; as solutions at TRL5 or above have a validated technology base that can be adopted to the application and tested. Solutions with lower TRL are often associated with high development cost, which will make the solution economically impractical (Conrow, 2011).

Table 2: NASA definition of TRLs and the interpretation for VA recovery

TRL	NASA Definition*	Interpretation for VA Recovery
9	Actual system 'flight proven' through successful mission operations	Actual recovery technology implemented in hospitals
8	Actual system completed and 'flight qualified' through last demonstration	Actual recovery solution tested in the real hospital environment
7	System prototype demonstration in space environment	Actual recovery solution tested in controlled hospital environment
6	System/subsystem model or prototype demonstration in relevant environment	Prototype of recovery solution tested in hospital environment at pilot scale
5	Component and/or breadboard validation in relevant environment	Recovery solution tested in a simulated hospital or other location at pilot scale
4	Component and/or breadboard validation in lab	Recovery solution tested in a hospital or other location at lab scale
3	Analytical and experimental critical function/characteristic proof-of-concept	Analytical and experimental critical function/characteristic proof-of-concept
2	Technology concept/application formulated	Technology concept/application formulated
1	Basic principle observed and reported	Basic principle observed and reported

* Adopted from Williamson and Beasley (2011).

2.3. Step 3: Net Revenue Analysis

Once a VA recovery technology with a desired TRL is identified, it is then necessary to update the socio-economic potential analysis (Step 1) while incorporating the operational costs. This leads to the proposal of Equation (3).

$$Net\ Revenue = (Best\ Price_{VA} + MCA_{VA} - OPEX_{VA\ Recovery}) \times Volume_{VA}' \quad (3)$$

where $Best\ Price_{VA}$ and MCA_{VA} are the same as in Step 1, while $OPEX_{VA\ Recovery}$ reflects the operational cost associated with the recovery of VA from a given waste gas stream. The volume of VA that can be potentially captured per year should be updated to reflect the actual volume of VA ($Volume_{VA}'$) that can be recovered by considering the efficiency of the recovery process. $Volume_{VA}'$ should be the same as $Volume_{VA}$ in Step 1 before VA breakthrough in the adsorption bed occurs, which is undesirable. It is assumed all VA administered to patients is exhaled and captured by the scavenging process. It is also worth noting, with any recovery technologies, the recycle rate cannot reach 100% even if all VA in the waste gas stream is captured. The recovery technologies are limited by: (1) the bio-metabolism of VAs in patients, (2) the slow release of VAs by patients after the anaesthetic surgical procedure are over, and (3) losses in the downstream recovery and purification processes. Considering the limitations, an initial process recovery efficiency of 75% was applied to improve the relevance of the framework.

The GO criterion of this STOP/GO gate is the identification of a technology that possesses a sufficiently high net revenue. The minimum threshold for the net revenue is US\$ 0, which indicates the installed technology is revenue neutral and it can operate without any additional

economic burden. In practice, it is likely to a high positive number, to ensure a Return of Investment (ROI).

2.4. Step 4: Regulations and Consumer Readiness

Up to this point, the proposed methodology assumes that the recovered VAs would be sold as acceptable medical grade liquid VAs. However, this assumption is subjected to consumer readiness to accept the recovered VAs, and satisfying the prevailing regulations and standards in the recovery process. Both perception and regulation are jurisdictionally dependent. For illustration, the promise of reduced VA cost might prompt regulators to approve the use of recovered VAs among poorer nations and those with socialized healthcare. Distinct price differences might convince patients to accept the use of recovered VAs in jurisdictions where the value pays. There may be legal environments where the recovered VAs cannot be reused clinically as anaesthetic agents, raising options of selling recovered VA to other industries as a raw material or final product, or safe disposal. It is essential to understand the needs and wants of all participants – regulators, medical professionals, patients and the public – through a detailed stakeholder analysis.

2.5. Step 5: Detailed Economic Analysis

Only when a feasible downstream processing design is available, a detailed economic analysis can be carried out to estimate the present value of all future expected cash flows. The calculation requires accurate valuation of the actual revenue generated from reselling the recovered and processed VA, the marginal benefits of abatement and the operating expenses relating to the recovery and purification processes. Equation (4) can be used for the estimation of realisable revenue.

$$279 \quad \text{Realisable Revenue} = (\text{Sales Price}_{VA} + \text{MCA}_{VA} - \text{OPEX}_{VA \text{ Recovery+Purification}}) \times \text{Volume}_{VA}' \quad (4)$$

280

281 The realisable revenue is calculated by the summation of the economic benefits of *Sales*
 282 *Price*_{VA} and *MCA*_{VA} less the operational expenses *OPEX*_{VA Recovery+Purification}. The term *Sales*
 283 *Price*_{VA} is the final realisable sales price of the recovered and processed VA. The sales price
 284 depends on the decisions of the stakeholders as described in Step 4, whether the recovered
 285 VA will be sold as reclaimed anaesthetic agent or as feedstock for other industries. The
 286 *MCA*_{VA} value is assumed to be the same as in Step 1, whereas *OPEX*_{VA Recovery+Purification}
 287 includes the operational costs for recovering VA (as in Step 3) and the cost of purification.
 288 The *Volume*_{VA}' remains the same as in Step 3 with the assumption that the purification
 289 process incurs minimal loss during production.

290

291 Once the realisable revenue is calculated, the present value of future cash flows (PV) of
 292 implementing a VA recovery and purification solution can be calculate using Equation (5).

293

$$294 \quad PV = \text{Realisable Revenue} \times \frac{1-(1+r)^{-n}}{r} \quad (5)$$

295

296 PV is calculated from the discounted annual realisable revenue, where *n* refers to the number
 297 of years and *r* is the cash discount rate. The cash discount rate in this instance also represents
 298 the potential risks involved in implementing a VA technology.

299

300 It should be noted that installation costs have not been considered in PV calculation because
 301 the estimation of internal cost can be complicated by the involvement of contractors. The
 302 information generated can be used as the maximum allowable budget for implementing a VA
 303 recovery unit, as it considers all associated economic benefits and costs.

3. Background of Case Study

The case study adapts information collected from hospitals in three District Health Boards (DHBs) in New Zealand, namely Auckland DHB (39 operating rooms), Counties Manukau DHB (24 operating rooms) and Waitemata DHB (12 operating rooms). The DHBs serve approximately 0.52 million, 0.53 million, and 0.63 million people respectively in the Auckland region. The average annual usage of VAs by the hospitals between 2015 and 2018 is illustrated in **Figure 3**. Sevoflurane and desflurane constitute > 90% of the anaesthetic agents used in the hospitals. The enormous quantities used (sum up to more than 800 tonnes of CO₂ equivalent emissions from the three DHBs) and released to the environment highlights the importance of capturing the waste VAs prior to their emissions.

Figure 3: Average annual usage of volatile anaesthetics from year 2015 to 2018. Sevoflurane and isoflurane have a packaging volume of 250 mL/bottle, whereas desflurane is 240 mL/bottle. The numbers above the bars indicate the equivalent mass of volatile anaesthetics (tonne of carbon dioxide equivalent emission) over 100-year time horizon (GWP₁₀₀). The insert shows the fraction of each volatile anaesthetic used by the hospitals.

322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345

3.1. Step 1: Socio-Economic Potential Analysis

The choice of VA usually lies in the hands of the anaesthetists depending on clinical grounds. Individual clinical decision-making often is infrequently cognisant of cost considerations. The current perspective on recycling VAs is about abating the emissions to the atmosphere, but both adsorptive separation and cryogenic condensation were conceived prior to our current concerns about climate disruption. Capture of VAs at the emission points prior to releasing the waste gas stream protects the atmosphere, and allows for economic and social benefits (and costs), and waste reduction.

Similar to any other resource recovery unit, the initial decision to explore the option of implementing a recovery technology in the hospitals is based on the appeal of the potential economic benefits (economic potential) arising from the valuable resources in waste stream or due to environmental statutory requirements (Mansouri et al., 2017). When both the original and recovered VAs possess similar potency, the main factor affecting the procurement of an anaesthetic agent would be the price. The increasing cost of medicines can be a barrier to less privileged patients when it comes to seeking medical treatments (Pomerantz, 2004). By increasing supply, recovered VAs can be explored to reduce price, and offer a more affordable alternative to purchasers. To explore the potential in commercialising the recovered VAs, the authors assumed that the recovered VAs could be marketed at price equivalent to the original VAs. For the ease of presenting the framework, an indicative price of approximately US\$ 0.68/mL (NZ\$ 1/mL) is used for the original VAs, namely sevoflurane, desflurane and isoflurane.

The New Zealand's carbon market is competitive and the carbon price is expected to go beyond the capped price of approximately US\$ 17 (NZ\$ 25)/MT CO₂ in the near future (Morrison, 2017). To examine the prospect of applying a recovery technology, the capped price was taken as the MCA_{CO_2} in estimating the socio-economic potential. The socio-economic potential of installing a recovery technology was computed for the hospitals (**Table 3**). A project's economic potential demonstrates its potential to install the recovery technology. The socio-economic potential of the hospitals in all DHBs was found to be more than US\$ 150,000 per annum. This implies installing a recovery technology in the hospitals might have benefits in terms of operational cost savings, economic benefits, social benefits and/or environmental benefits.

Table 3: Estimation of socio-economic potential for the hospitals in different District Health Boards in Auckland, New Zealand

	ADHB*	WDHB*	CMDHB*
Average annual VA usage (L):			
Sevoflurane	578	144	355
Desflurane	232	147	99
Isoflurane	55	< 1	1
Equivalent VA mass (MT):			
Sevoflurane	0.88	0.22	0.54
Desflurane	0.34	0.22	0.15
Isoflurane	0.08	< 0.01	< 0.01
Expected revenue (US\$)[†]:			
Sevoflurane	294,780	73,313	181,178
Desflurane	118,361	75,154	50,551
Isoflurane	27,795	255	638
Societal benefits of VA recovery (US\$)[‡]:			
Sevoflurane	2,356	586	1,448
Desflurane	7,033	4,466	3,004
Isoflurane	503	5	12
Socio-Economic Potential (US\$)[§]	450,855	153,778	236,830

* ADHB: Auckland District Health Board; WDHB: Waitemata District Health Board; CMDHB: Counties Manukau District Health Board.

[†] The product of retail price of recovered VA ($Best\ Price_{VA}$) and volume of VA that can be potentially recovered ($Volume_{VA}$). It is assumed that the recovered VAs are marketed at price equivalent to the original VAs (US\$ 0.68/mL). A process recovery efficiency of 75% was used to correct the volume of VA that can be potentially recovered.

[‡] The product of marginal cost of abatement of VA recovery (MCA_{VA}) and volume of VA that can be potentially recovered ($Volume_{VA}$). The MCA_{VA} of sevoflurane, desflurane and isoflurane are estimated to be US\$ 3,570, US\$ 27,540, and US\$ 8,670 per MT, respectively. A process recovery efficiency of 75% was used to correct the volume of VA that can be potentially recovered.

[§] The sum of expected revenue and society benefits of VA recovery.

3.2. Step 2: Technology Identification

3.2.1. Step 2 (I): Waste Gas Stream Characterisation

From literature search, the typical composition of waste anaesthetic gas includes VAs, oxygen enriched air containing exhaled CO₂ and moisture (Fradette, 2015). In cases where nitrous oxide is used, it will also be exhausted unchanged in the waste gas stream. Unlike waste gases of other industries that could be complicated, the composition of waste anaesthetic gas is quite predictable. It usually contains exhausted inhalation anaesthetics diluted in a large volume of air.

3.2.2. Step 2 (II): Technology Search

Based on an extensive literature search and to the best of the authors' knowledge, thus far, only one commercial adsorptive separation solution – *Deltasorb*[®] commercialised by Blue-Zone Technologies Ltd. (Ontario, Canada), has undergone widespread clinical trial. One other company – Anesthetic Gas Reclamation Inc. (Texas, US), has developed a cryogenic condensation *Anesthetic Gas Reclamation (AGR) system* for recovering waste VAs. Although the technology is claimed to be fully tested, it has not undergone trial in hospitals. Techno-economic analysis allows us to examine the practical application of the recovery technologies, their status, and their potential economic benefits. The main characteristics of the technologies are summarised in **Table 4**.

Table 4: Main characteristics of the potential volatile anaesthetic capture technologies

	<i>Deltasorb[®]</i>	<i>AGR System</i>
Brief description	A canister holding Deltazite [®] (a hydrophobic zeolite) that retrofits on the scavenging line of conventional anaesthetic systems in operating rooms. The system is scalable to cater for several operating rooms from a central location in hospitals.	A centralised cryogenic condensation system for removing waste anaesthetic gas from several operating rooms. The system delivers highly efficient (~ 99%) volatile anaesthetic capture when it is paired with the Dynamic Gas Scavenging System (DGSS [®]).
Associated capital cost	Initial cost for canister and installation.	Initial investment in the equipment (i.e. DGSS [®] and the <i>AGR System</i>).
Associated operational cost	Cost for canister exchange.	Condensation energy-related expenses and routine servicing of DGSS [®] and the <i>AGR System</i> .
Advantages	<ul style="list-style-type: none"> • Low start-up cost • Simple set-up and can be implemented to existing anaesthetic systems 	<ul style="list-style-type: none"> • Can maintain removal efficiency for a long period
Disadvantages	<ul style="list-style-type: none"> • Need replacement of saturated canister often • Complicated downstream regeneration and purification processes 	<ul style="list-style-type: none"> • High associated capital cost • High energy cost • Inefficient for recovering very dilute volatile anaesthetics (must be paired with DGSS[®]) • System's onsite recovery unit requires special spatial arrangement

In the case study, hospitals in the DHBs were assumed to adopt one of the recovery

technologies, namely adsorptive separation and cryogenic condensation. **Figure 4** illustrates

the process flow of VA recovery from emitting source, recovery unit to different scenarios of handling the recovered VAs. Reuse of the recovered VAs as anaesthetic agents is preferred. Reusing the recovered VAs as fluorinated feedstock or deconstructing them applies when the preferred approach is not feasible. To begin with, the preferred approach is assumed applicable in the case study.

Figure 4: Flow chart showing the boundaries of each stage and possible scenarios.

3.2.3. Step 2 (III): Technology Readiness

Both *Deltasorb*[®] and *AGR System* possess varying degrees of technology implementation.

Figure 5 illustrates the TRL of the mentioned technologies. *Deltasorb*[®], the adsorptive recovery technology commercialised by Blue-Zone Technologies Ltd., has a TRL of 8. The company claims that the adsorbent in the adsorption system can be regenerated, and the VAs recovered can be further processed for recycling. The company has been researching to commercialise the VA recovery technology, and it possesses an anaesthetic manufacturing facility that has been approved by Health Canada and the Food and Drug Administration (FDA) (Blue-Zone Technologies Ltd., 2009). On the other hand, the *AGR System* of Anesthetic Gas Reclamation Inc. remains at TRL5. Despite claims to be fully tested, there are no reports on the *AGR System* in hospital settings beyond that where it has been developed.

Figure 5: TRL of the volatile anaesthetic recovery technologies.

The application of VA recovery technologies in hospitals is presently uncommon. One determinant of whether VA recovery technologies are applicable in hospitals is the ease of adaptation of the technologies to existing anaesthetic systems. Of the technologies found, the *Deltasorb®* technology exhibits a considerable degree of technology maturity. Therefore, adsorptive separation solution was identified as a suitable technology in this step of the methodology.

3.3. Step 3: Net Revenue Analysis

The primary operating cost of recovery solution would be the cost and service charges to replace saturated canisters. The operating cost in the case study was estimated by taking the *Deltasorb®* application as a model, where it is assumed that the canister is replaced once a week, and the hospitals are charged a monthly service charge of approximately US\$ 230 (C\$ 300) per canister unit installed in hospitals (Armstrong, 2009). The monthly service charge of the *Deltasorb®* application was applied to approximate a nominal service charge for

recovering one litre of VAs by considering the number of operating rooms and VA usage in the hospitals in this case study (refer to Appendix II). The estimated nominal service charge was estimated to be US\$ 130/litre of captured VA, and it was used to calculate the net revenue for the DHBs. In the initial phase of the evaluations, the authors assumed that the reclaimed VAs could be recycled as anaesthetic agents. The ideal net revenue (updated socio-economic potential) for Auckland DHB, Waitemata DHB and Counties Manukau DHB were estimated to be US\$ 366,559, US\$ 125,346 and US\$ 192,407 per year, respectively. The positive net revenues demonstrate that the technology could potentially operate without additional economic burden to the hospitals. However, it is presently too early to conclude without further considering consumer readiness and the regulations controlling the use of recovered VAs.

3.4. Step 4: Regulations and Consumer Readiness

The adsorptive separation solution has been tested and found to be technically feasible. The next consideration would be the societal barriers, i.e. health and safety concerns relating to marketing and use of the reclaimed VAs. To date, the VAs recovered from the *Deltasorb*[®] system has not been granted an approval to market the anaesthetics for clinical use by the United States FDA (Blue-Zone Technologies Ltd., 2009). Recovered VAs consist of a mixture of anaesthetic agents used in hospitals, and may contain unwanted biological agents, and potentially hazardous contaminants generated from anaesthesia processes. For marketable drug products, the impurity level in the recovered VAs must be reduced to levels acceptable to the FDA and ultimately as specified by the United States Pharmacopeia (USP) (Baker, 2007).

In the highly regulated environment of healthcare, recovered VAs will only become commercially viable once the quality and safety compliance of the recovered and original VAs are comparable. Nonetheless, there remain other factors affecting the recycling of recovered VA. Like other industries, hospitals are adverse to capital spending without a clear financial return, unless required by regulating compliance. Although adsorption technologies incur lower capital costs when compared with most infrastructure purchases, the installation of a recovery technology in each operating room requires fixed operation costs. To gain investors' support, the cost savings of having the technology and health aspects of using recovered VAs must be justified (Armstrong, 2009). Furthermore, there may be resistance to the use of recovered VAs as feedstock from incumbent industry. VAs are manufactured from readily available starting materials. Purifying and reselling the recovered VAs and using them as feedstock might not be attractive without an incentive or regulatory pressure for using reclaimed chlorinated- and fluorinated-compounds in the production process.

Considering the current societal situation, the recovered VA could not be sold as a medical grade VA, i.e. $Best\ Price_{VA}$ is zero. Therefore, the gain would constitute only of the societal cost of the environmental impact of VAs, i.e. the marginal cost of abatement of VA emission, which is US\$ 9,920/year for Auckland DHB, US\$ 5,057/year for Waitemata DHB, and US\$ 4,464/year for Counties Manukau DHB. The operating costs of VA recovery are higher than the marginal costs of abatement in the DHBs giving rise to negative net revenue. Therefore, the installation and operation of the recovery technology in hospitals would require an annual investment of approximately US\$ 74,377, US\$ 23,375, and US\$ 39,959 from respective DHB.

3.5. Step 5: Detailed Economic Analysis

Blue-Zone Technologies Ltd. has already carried out the downstream process synthesis as well as process design for both *Deltasorb*[®] desorption system and *Deltane*[™] production plant. With respect to *Deltasorb*[®], the saturated canisters are delivered to a facility for processing: regeneration and purification of the recovered VAs. During the regeneration process, pure nitrogen gas flows through canisters that are placed in a desorption vessel with an operating temperature of 100°C for five hours (personal communication, April 18, 2018). The regenerated adsorbent can be reused in hospitals for adsorptive separation. The desorbed cocktail of VAs is passed to the *Deltane*[™] production plant, where it is liquefied in a cryogenic condenser, filtered to remove particles and water, and distilled to separate the components into pure forms. Theoretically, fractional distillation is able to separate the cocktail into its components based on their boiling points (Campbell & Pierce, 2015). Then, the ‘purified’ VAs can be bottled for distribution. The development of a recovery technology including the downstream processes requires consideration on both the technical and economic aspects. The developed downstream processes should be sufficiently economic, practical and robust to be implemented in bigger scales (Mansouri et al., 2017).

When recovered VAs can be ideally used as medical grade VAs, it is more realistic to consider the operating expenses of downstream processes in calculating realisable revenue. Downstream processes involved are the regeneration of adsorbent and purification of the recovered VAs. **Table 5** summarises the per batch cost estimation of regeneration and purification. The estimated cost for recovering one kg of purified VAs from the adsorbent was estimated to be US\$113. The realisable revenue for Auckland DHB, Waitemata DHB and Counties Manukau DHB were projected to be US\$ 256,211/year, US\$ 88,410/year, and US\$ 134,085/year, respectively. By assuming a discount rate of 20% and a payback of 5

years, the PVs of adopting a VA recovery solution were US\$ 766,226/year for Auckland DHB, US\$ 264,402/year for Waitemata DHB, and US\$ 400,997/year for Counties Manukau DHB.

Table 5: Cost estimation of regeneration and purification simulating the *Deltazite*[®] adsorptive separation technology

	Regeneration	Purification
Process	<i>Desorption</i>	<i>Fractional distillation</i>
Total power requirement	74.07 kWh* (Includes 0.5 hour of heating up from room temperature to 100°C and 5 hours of operation at the set temperature)	15,000 kWh [†] (For a 10-hour batch process)
Cost/batch[‡]	US\$ 9	US\$ 1,800
	Approximately 25% of the saturated adsorbent weight in the canister consisted of the adsorbed volatile anaesthetics. In an ideal scenario, it can be expected to recover approximately 15.94 kg [§] of volatile anaesthetics per batch of regeneration and purification. Therefore, the equivalent regeneration and purification cost is estimated to be US\$113/kg of recovered volatile anaesthetics.	

* Estimation was based on a vessel made of stainless steel 502 with the dimensions: diameter, 1m; length, 2m; wall thickness, 0.02 m; outer surface area, 7.86 m²; total mass, 1,210 kg. The vessel can accommodate 85 canisters. This estimation considers power for heating the adsorbent, desorption vessel, and power losses to the atmosphere.

[†] The reboiler was assumed to operate at 1,500 kW.

[‡] Operating cost estimation assumed an average electricity cost of 12 cents per kWh.

[§] The estimation was based on the regeneration of 85 canisters per batch process, and each canister contains 750 g solid adsorbent.

^{||} This estimate considered the cost pertaining only to heating.

4. Perspectives

The recovery of VAs from waste anaesthetic gas is indeed a unique and challenging subject, and as far as the author understand, very few research has been done on the capture or adsorption of VAs (Ang et al., 2019). Most progresses have been made to evaluate and improve the available removal technologies, specifically finding and developing adsorbents with higher adsorption capacity. Only few works are devoted to investigate the recovery of VAs (Abrahams et al., 2017; Gargiulo et al., 2014; Jänchen et al., 1998), and none of them actually addresses the challenges associated with the downstream processing of recovered VAs. **Figure 6** shows the lifecycle of VAs from emission source and removal of the gases to downstream processing. The lifecycle of VAs can be broken down into two areas with research interest – the removal technologies and downstream processes. It should be noted that, at the initial stage of research, the utmost priority is to reduce emission of VAs to the atmosphere. Currently, only two removal technologies, namely adsorptive separation and cryogenic condensation, have been identified useful. Other potential technologies, for instance membrane separation (Tsai et al., 2002), absorption using highly efficient liquid (Lecomte et al., 2010) and photolytic destruction (Oró & Holzer, 1979) that have been proposed for removing volatile organic compounds, may be applicable. However, much consideration has to be given on whether these technologies can be technologically and economically implemented in hospitals. Besides that, societal consideration such as safety and environmental friendliness are also among the key issues not to be excluded.

Figure 6: The lifecycle of volatile anaesthetics, and the removal technologies and downstream processes leading to a greener anaesthesia practice.

Almost all the removal technologies capture VAs without deconstructing them to inert materials, where they still possess GWP when being released to the atmosphere. Therefore, downstream processes are crucial to close the loop on the polluting VAs. The captured VAs may be valorised as renewable resources like reclaimed anaesthetic agents and fluorinated feedstock, or deconstruct to inert materials using hydrothermal process (Ledesma et al., 2015). The downstream processing could be a different realm of research by itself, and would require different unit operations for each route.

Ideally, recycling the reclaimed VAs as anaesthetic agents is desired. The proposed framework assumed that the recovered VAs could be reused as anaesthetic agents. If the recovery technology could recover waste VAs at reasonable costs, the recovery technology possesses a good chance to be commercialized. From a scalability viewpoint, it is crucial to ensure there is a sufficient market size to absorb the recovered and purified products. However, the current status of reusing recovered VAs on patients is still pending approval from the US FDA due to regulatory concerns with safety and purity (Sherman & McGain, 2016), and conflict of commercial interest with the manufacturers. When it is not possible, the recovered VAs could be used as fluorinated-feedstock for another production processes. The only possible reported example in this case is the reclaimed isoflurane could be used as the raw material for desflurane production (Sivaramakrishnan et al., 2011). The commercial production of sevoflurane, desflurane and isoflurane involve photochemical chlorination followed by substitution of chlorine with fluorine (Terrell, 2008). Compared with VA production from scratch using more chlorinated- and fluorinated-substances, using reclaimed VAs in the production process appears to have less adverse effects on the environment – more energy efficient, requiring fewer resources and less waste. If none of the stated options is feasible, the recovered VAs could be deconstructed to inert materials via thermal processes. Compared to destructive disposal, recycling of VAs as either anaesthetic agents or fluorinated-feedstock creates more value. Besides, there is an indirect reduction in energy consumption through recycling and minimising waste formation.

Translating lab-scale research objectives into applicable outcomes is both challenging and intriguing where many practical issues, like the health and safety, environmental friendliness, operations and waste disposal, need to be addressed. By looking at all these alternatives, reusing the recovered VAs is appealing. However, more works have to be carried out to

overcome the challenges remain, that is to convince all stakeholders of the benefits of the proposed framework. As there is more awareness raised on the impacts of waste VAs to the triple bottom line economy (social, environmental and financial), the competitiveness of recovering VAs from waste gas stream as valuable resources can be potentially increased. Currently there is no regulation restricting the use of VAs in hospitals and the emission of these gases to the atmosphere. This case study considers only the hospitals within the DHBs; other potential emission sources include private and veterinary hospitals/clinics, which may be significant in a long run. Implementing one of the recovery technologies incurs capital and operating costs, while hospitals currently release waste VAs to the atmosphere free of charge. In contrast to industrial processes, wastes discharge to the environment incurs costly 'end of pipe' treatments, in order to meet governing regulations and to reduce contamination to the environment (Mansouri et al., 2017). When governing authorities imposes regulations on waste medical gas emissions, more hospitals will get to the resort of mitigating VA emissions. The currently high operating cost, namely the recurring service and maintenance charges, could be reduced with the development of more efficient adsorption technologies possessing better efficiencies. There may be no one ideal solution for this problem. Different scenarios would call for different solutions.

5. Conclusions

From the case study, the following barriers for implementing a VA recovery solution in hospitals were identified:

- Only limited VA recovery technologies are available, and two were identified, namely the adsorptive separation and cryogenic condensation. Of the two, the adsorptive separation technology has a TRL of 8 indicating its potential to be implemented in hospitals at full-scale.

- For the recovery technology to be applicable in hospitals, it must be adaptable to the existing anaesthetic systems and must not affect the delivery of anaesthetic agent to patients.
- Both technologies recovered VAs as a mixture in liquid form. The liquid mixture needs to be separated and purified to medical standard to be reused as anaesthetic agents.
- When recovered VAs could be marketed as anaesthetic agents like in the ideal scenario, the proposed VA recovery and purification technologies should only be carried out if the cost of implementation is less than US\$ 766,226/year for Auckland DHB, US\$ 264,402/year for Waitemata DHB, and US\$ 400,997/year for Counties Manukau DHB.
- When recovered VAs could not be recycled (i.e. $Best\ Price_{VA} = 0$), the annual net revenue for the DHBs become negative, which is contributed chiefly by the monthly service charge for operating the VA recovery technology in the hospitals. To implement the VA recovery technology, the DHBs have to pay US\$ 74,377/year, US\$ 23,375/year, and US\$ 39,959/year respectively for hospitals in Auckland DHB, Waitemata DHB and Counties Manukau DHB.

The proposed methodology and the application example addressed potential barriers associated with the implementation of VA recovery technologies in hospitals. By employing the detailed economic analysis in conjunction with techno-societal evaluation, the implementation of the recovery technology and the associated downstream processing technology may be justified and employed. The two technologies identified were tested to varying extents in laboratory settings and in hospitals. Only adsorptive separation technology has reached a maturity that allows full-scale installation in hospitals. Although the adsorptive

separation technology is promising, more work needs to be done on the downstream processes. The recycling of recovered VAs as anaesthetic agents is currently not favourable. However, the recovered VAs could be used as fluorinated feedstock in the production of related value-added products, or they could be deconstructed to inert forms and disposed of safely. Despite the different fate of recovered VAs, the ultimate aim of the recovery solution would be to reduce the emission of these greenhouse gases to the atmosphere.

References

- Abrahams, B. F., Dharma, A. D., Donnelly, P. S., Hudson, T. A., Kepert, C. J., Robson, R., Southon, P. D., & White, K. F. (2017). Tunable porous coordination polymers for the capture, recovery and storage of inhalation anesthetics. *Chemistry - A European Journal*, 23(33), 7871-7875. doi: 10.1002/chem.201700389
- Ang, T. N., Baroutian, S., Young, B. R., Hyland, M. M., Taylor, M., & Burrell, R. (2019). Adsorptive separation of volatile anaesthetics: a review of current developments. *Separation and Purification Reviews*, 211, 491-503. doi: 10.1016/j.seppur.2018.10.012
- Armstrong, F. (2009, 23 March 2009). A remedy for the operating room, Special to the Globe and Mail, *The Globe and Mail*. Retrieved from <https://www.theglobeandmail.com/report-on-business/a-remedy-for-the-operating-room/article1155719/>
- Baker, M. T. (2007). Sevoflurane: are there differences in products? *Anesthesia and Analgesia*, 104(6), 1447-1451. doi: 10.1213/01.ane.0000263031.96011.36
- Barash, P. G. (2013). Section IV: anaesthetic agents, adjuvants, and drug interaction. In P. G. Barash, B. F. Cullen, R. K. Stoelting, M. K. Cahalan, M. C. Stock & R. Ortega (Eds.),

652 *Handbook of Clinical Anesthesia*. Philadelphia, PA: Wolters Kluwer
653 Health/Lippincott Williams & Wilkins.

654 Berry, J. M., & Morris, S. (2006a). Method and apparatus for anesthetic gas reclamation with
655 compression stage: United States Patent.

656 Berry, J. M., & Morris, S. (2006b). Method of low flow anesthetic gas scavenging and
657 dynamic collection apparatus therefor: United States Patent.

658 Berry, J. M., & Morris, S. (2009). Anesthetic gas reclamation system and method: United
659 States Patent.

660 Blue-Zone Technologies Ltd. (2009). The 2009 Clean Technology ReportTM. Retrieved 14
661 February, 2018, from <https://www.bluezone.ca/The-2009-Clean-Technology-Report>

662 Brown, A. C., Canosa-Mas, C. E., Parr, A. D., Pierce, J. M. T., & Wayne, R. P. (1989).
663 Tropospheric lifetimes of halogenated anaesthetics. *Nature*, 341(6243), 635-637. doi:
664 10.1038/341635a0

665 Bucher, D., Pasel, C., Luckas, M., Bentgens, J., & Bathen, D. (2017). Adsorption of
666 inhalation anesthetics (fluranes and ethers) on activated carbons and zeolites at trace
667 level concentrations. *Journal of Chemical and Engineering Data*, 62(6), 1832-1841.
668 doi: 10.1021/acs.jced.7b00079

669 Byhahn, C., Wilke, H.-J., & Westphal, K. (2001). Occupational exposure to volatile
670 anaesthetics: Epidemiology and approaches to reducing the problem. *CNS Drugs*,
671 15(3), 197-215. doi: 10.2165/00023210-200115030-00004

672 Campbell, M., & Pierce, J. M. T. (2015). Atmospheric science, anaesthesia, and the
673 environment. *BJA Education*, 15(4), 173-179. doi: 10.1093/bjaceaccp/mku033

674 Charlesworth, M., & Swinton, F. (2017). Anaesthetic gases, climate change, and sustainable
675 practice. *The Lancet Planetary Health*, 1(6), e216-e217. doi: 10.1016/S2542-
676 5196(17)30040-2

677 Chen, T.-H., Kaveevivitchai, W., Jacobson, A. J., & Miljanić, O. Š. (2015). Adsorption of
678 fluorinated anesthetic within the pores of a molecular crystal. *Chemical*
679 *Communications*, 51(74), 14096-14098. doi: 10.1039/C5CC04885K

680 Conrow, E. H. (2011). Estimating technology readiness level coefficients. *Journal of*
681 *Spacecraft and Rockets*, 48(1), 146-152. doi: 10.2514/1.46753

682 Dayan, A. D. (2016). Analgesic use of inhaled methoxyflurane: evaluation of its potential
683 nephrotoxicity. *Human and Experimental Toxicity*, 35(1), 91-100. doi:
684 10.1177/0960327115578743

685 Delgado-Herrera, L., Ostroff, R. D., & Rogers, S. A. (2001). Sevoflurane: Approaching the
686 ideal inhalational anesthetic. A pharmacologic, pharmacoeconomic, and clinical
687 review. *CNS Drug Reviews*, 7(1), 48-120. doi: 10.1111/j.1527-3458.2001.tb00190.x

688 Fan, Y., Jia, J.-J., Wang, X., & Xu, J.-H. (2017). What policy adjustments in the EU ETS
689 truly affected the carbon prices? *Energy Policy*, 103, 145-164. doi:
690 10.1016/j.enpol.2017.01.008

691 Fradette, C. (2015). Protecting the surgical team from waste anesthetic gases during medical
692 missions. *AORN Journal*, 101(3), 370-373. doi: 10.1016/j.aorn.2014.11.011

693 Gargiulo, N., Peluso, A., Aprea, P., Hua, Y., Filipović, D., Caputo, D., & Eić, M. (2014). A
694 chromium-based metal organic framework as a potential high performance adsorbent
695 for anaesthetic vapours. *RCS Advances*, 4(90), 49478-49484. doi:
696 10.1039/c4ra05905k

697 Grodin, W. K., Epstein, M. A. F., & Epstein, R. A. (1985). Soda lime adsorption of isoflurane
698 and enflurane. *Anesthesiology*, 62, 60-64.

699 Hua, Y., Gargiulo, N., Peluso, A., Aprea, P., Eić, M., & D, C. (2016). Adsorption behavior of
700 halogenated anesthetic and water vapor on Cr-based MOF (MIL-101) adsorbent. Part

701 I. Equilibrium and breakthrough characterizations. *Chemie Ingenieur Technik*, 88(11),
702 1730-1738. doi: 10.1002/cite.201600051

703 Jänchen, J., Brückner, J. B., & Stach, H. (1998). Adsorption of desflurane from the
704 scavenging system during high-flow and minimal-flow anaesthesia by zeolites.
705 *European Journal of Anaesthesiology*, 15(3), 324-329. doi: 10.1046/j.1365-
706 2346.1998.00299.x

707 Kim, B. M., & Sircar, S. (1977). Adsorption characteristics of volatile anesthetics on
708 activated carbons and performance of carbon canisters. *Anesthesiology*, 46(3), 159-
709 165.

710 Kossick, M. A. (2014). Inhalation anesthetics. In J. J. Nagelhout & K. L. Plaus (Eds.), *Nurse*
711 *anesthesia* (pp. 85-103). St. Louis, Missouri: Elsevier Saunders.

712 Langbein, T., Sonntag, H., Trapp, D., Hoffmann, A., Malms, W., Röth, E.-P., Mörs, V., &
713 Zellner, R. (1999). Volatile anaesthetics and the atmosphere: atmospheric lifetimes
714 and atmospheric effects of halothane, enflurane, isoflurane, desflurane and
715 sevoflurane. *British Journal of Anaesthesia*, 82(1), 66-73.

716 Lecomte, F., Broutin, P., & Lebas, É. (2010). *CO₂ capture: technologies to reduce*
717 *greenhouse gas emissions*. Paris, France: Editions Technip.

718 Ledesma, B., Román, S., Sabio, E., & Álvarez-Murillo, A. (2015). Improvement of spent
719 activated carbon regeneration by wet oxidation processes. *The Journal of*
720 *Supercritical Fluids*, 104, 94-103. doi: 10.1016/j.supflu.2015.05.007

721 Mansouri, S. S., Udugama, I. A., Cignitti, S., Mitic, A., Flores-Alsina, X., & Gernaey, K. V.
722 (2017). Resource recovery from bio-based production processes: a future necessity?
723 *Current Opinion in Chemical Engineering*, 18, 1-9. doi: 10.1016/j.coche.2017.06.002

724 Mehrata, M., Moralejo, C., & Anderson, W. A. (2016). Adsorbent comparisons for anesthetic
725 gas capture in hospital air emissions. *Journal of Environmental Science and Health*.

726 *Part A, Toxic/Hazardous Substances and Environmental Engineering*, 51(10), 805-
727 809. doi: 10.1080/10934529.2016.1181438

728 Morrison, T. (2017, 30 November 2017). NZ carbon price hits highest level in more than 6
729 years. Retrieved 24 July 2018, 2018, from [https://www.nbr.co.nz/article/nz-carbon-](https://www.nbr.co.nz/article/nz-carbon-price-hits-highest-level-more-6-years-b-210621#.W1aAD6sekig.email)
730 [price-hits-highest-level-more-6-years-b-210621#.W1aAD6sekig.email](https://www.nbr.co.nz/article/nz-carbon-price-hits-highest-level-more-6-years-b-210621#.W1aAD6sekig.email)

731 Murrin, K. R. (1974). Adsorption of halothane by activated charcoal. *Anaesthesia*, 29(4),
732 458-461. doi: 10.1111/j.1365-2044.1974.tb00687.x

733 Oró, J., & Holzer, G. (1979). The photolytic degradation and oxidation of organic compounds
734 under simulated Martian conditions. *Journal of Molecular Evolution*, 14(1-3), 153-
735 160. doi: 10.1007/BF01732374

736 Ortmann, R., Pasel, C., Luckas, M., Heimböckel, R., Kraas, S., Bentgens, J., Fröba, M., &
737 Bathen, D. (2016). Adsorption and desorption of isoflurane on carbonaceous
738 adsorbents and zeolites at low concentrations in gas phase. *Journal of Chemical and*
739 *Engineering Data*, 61(1), 686-692. doi: 10.1021/acs.jced.5b00844

740 Pomerantz, J. M. (2004). Recycling expensive medication: why not? *Medscape General*
741 *Medicine*, 6(2), 4.

742 Porter, K. M., Dayan, A. D., Dickerson, S., & Middleton, P. M. (2018). The role of inhaled
743 methoxyflurane in acute pain management. *Open Access Emergency Medicine*, 10,
744 149-164. doi: 10.2147/OAEM.S181222

745 Ryan, S. M., & Nielsen, C. J. (2010). Global warming potential of inhaled anesthetics:
746 application to clinical use. *Anesthesia and Analgesia*, 111(1), 92-98. doi:
747 10.1213/ANE.0b013e3181e058d7

748 Rybicka, J., Tiwari, A., & Leeke, G. A. (2016). Technology readiness level assessment of
749 composites recycling technologies. *Journal of Cleaner Production*, 112(1), 1001-
750 1012. doi: 10.1016/j.jclepro.2015.08.104

751 Sherman, J., & McGain, F. (2016). Environmental sustainability in anesthesia: pollution
 752 prevention and patient safety. *Advances in Anesthesia*, 34(1), 47-61. doi:
 753 10.1016/j.aan.2016.07.004

754 Sivaramakrishnan, H., Upare, A. A., Satagopan, D., & Chambers, O. R. (2011). The
 755 preparation of desflurane by the vapor-phase fluorination of isoflurane. *Organic*
 756 *Process Research and Development*, 15(3), 585-592. doi: 10.1021/op100318b

757 Sulbaek Andersen, M. P., Sander, S. P., Nielsen, O. J., Wagner, D. S., Sanford Jr, T. J., &
 758 Wallington, T. J. (2010). Inhalation anaesthetics and climate change. *British Journal*
 759 *of Anaesthesia*, 105(6), 760-766. doi: 10.1093/bja/aeq259

760 Tanada, S., Kawasaki, N., Nakamura, T., & Abe, I. (1996). Adsorption properties of CFC and
 761 CFC replacements on activated carbon containing introduced ionic fluoride and
 762 chloride. *Journal of Colloid and Interface Science*, 183(1), 143-147. doi:
 763 10.1006/jcis.1996.0528

764 Terrell, R. C. (2008). The invention and development of enflurane, isoflurane, sevoflurane,
 765 and desflurane. *Anesthesiology*, 108(3), 531-533. doi:
 766 10.1097/ALN.0b013e31816499cc

767 Tsai, W.-T., Chen, H.-P., & Hsien, W.-Y. (2002). A review of uses, environmental hazards
 768 and recovery/recycle technologies of perfluorocarbons (PFCs) emissions from the
 769 semiconductor manufacturing processes. *Journal of Loss Prevention in the Process*
 770 *Industries*, 15(2), 66-75. doi: 10.1016/S0950-4230(01)00067-5

771 Udugama, I. A., Mansouri, S. S., Mitic, A., Flores-Alsina, X., & Gernaey, K. V. (2017).
 772 Perspective on resource recovery from bio-based production processes: from concept
 773 to implementation. *Processes*, 5(3), 48. doi: 10.3390/pr5030048

774 Vollmer, M. K., Rhee, T. S., Rigby, M., Hofstetter, D., Hill, M., Schoenenberger, F., &
 775 Reimann, S. (2015). Modern inhalation anesthetics: potent greenhouse gases in the

776 global atmosphere. *Geophysical Research Letters*, 42(5), 1606-1611. doi:
777 10.1002/2014GL062785

778 Williamson, R., & Beasley, J. (2011). *Automotive technology and manufacturing readiness*
779 *levels: a guide to recognised stages of development within the automotive industry*.
780 Retrieved from [https://www.smmmt.co.uk/wp-content/uploads/sites/2/Automotive-](https://www.smmmt.co.uk/wp-content/uploads/sites/2/Automotive-Technology-and-Manufacturing-Readiness-Levels.pdf)
781 [Technology-and-Manufacturing-Readiness-Levels.pdf](https://www.smmmt.co.uk/wp-content/uploads/sites/2/Automotive-Technology-and-Manufacturing-Readiness-Levels.pdf)

782 Yan, X., Zhang, X., Chen, H., Xu, Y., & Tan, C. (2014). Techno-economic and social
783 analysis of energy storage for commercial buildings. *Energy Conversion and*
784 *Management*, 78, 125-136. doi: 10.1016/j.enconman.2013.10.014

785 Yasny, J. S., & White, J. (2012). Environmental implications of anesthetic gases. *Anesthesia*
786 *Progress*, 59(4), 154-158. doi: 10.2344/0003-3006-59.4.154

787

788

Appendices

Appendix I. List of CO₂e Emission Multiplier of Volatile Anaesthetics

Table A: CO₂e emission multiplier of the volatile anaesthetics

Greenhouse gas	GWP ₁₀₀	CO ₂ e emission multiplier [*]
Carbon dioxide (CO ₂)	1	1
Sevoflurane	210	210
Isoflurane	510	510
Desflurane	1620	1620

^{*} Calculated using $(GWP_{100,VA}/GWP_{100,CO_2})$.

Appendix II. Estimation of the Monthly Service Charge of the Adsorption System

Based on the available information from the *Deltasorb*[®] application of Blue-Zone Technologies Ltd., the average operating expenses per litre of VA was estimated.

Table B: Estimation of nominal service charge for the installed adsorption system

DHB	No. of operating rooms [*]	Operating expenses (US\$/year) [†]	Volatile anaesthetics usage (L/year)	Operating expenses (US\$/L)
Auckland	39	107,673	865	125
Counties Manukau	24	66,260	456	145
Waitemata	12	33,130	292	114
Average operating expenses (US\$/L)				130

^{*} Assume there is only one unit of adsorption system in each operating room.

[†] A nominal monthly service charge of US\$ 230 (C\$ 300) per canister installed was used for the estimation.