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Methodology Case studies

Sustainable products and services
Clean technologies
Resource efficiency

A report for Defra

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Introduction

This document is part of a five piece set of reports that describe a methodology for performing a comparative valuation of a nanotechnology against an incumbent technology. The reports are entitled:

- **"A comparative methodology for estimating the economic value of innovation in nanotechnologies."** This provides a comprehensive overview of the methodology, supporting evidence and some worked examples.
- **"A working guide for determining the value of nanotechnology innovation."** This provides a simpler document designed for non-economists to make less rigorous calculation.
- **"A calculation spreadsheet for valuing nanotechnology."** This is a spreadsheet in MS Excel format that is designed to accompany the working guide.
- **"Methodology Case studies."** Provides a series of case studies that use the methodology for valuing nano-enabled products relevant to Defra
- **"Nanotechnologies relevant to Defra."** A short literature review to identify nanotechnologies that are relevant under Defra's remit.

If they are not readily available, these documents can be obtained from Oakdene Hollins Ltd.

This document accompanies a methodology that has been developed to value nanotechnology. It describes three example case studies for valuing nano-enabled products using this new methodology. These case studies have been chosen to give further guidance in the practical application of the methodology and are also relevant to Defra's remit. The reader is directed to the methodology document (*'A comparative methodology for estimating the economic value of innovation in nanotechnologies'*) for background and further guidance on the techniques described here.

The nano-enabled products chosen were those of particular interest to Defra, a document "*Nanotechnologies relevant to Defra Supplement to report on the 'Benefits of Nanotechnology'."* gives the background to this decision. The following nanotechnology areas were selected being of particular interest:

- gas sensors
- antifouling paints
- nano-zero-valent iron.

It should be noted that due to the unique properties of nanomaterials, there is a possibility that they pose a risk to human health and the environment. A large volume of research is underway, both in the UK and internationally, to improve our understanding of these risks. The calculations in this document attempt to address this evidence gap on the benefits side only. **The results can later be drawn on, in conjunction with the consideration of emerging evidence on potential risks of nano-enabled products. Such potential risks can be included within the calculation as they have been identified and monetised to allow a full cost-benefit analysis.**

1 Case studies: Gas sensors

1.1 Select nano-enabled product

Nanotechnologies have the potential to increase the sensitivity, selectivity and reliability of sensors[a]. This means that there could be improvements to sensors as well as entirely new applications. In this case study we consider industrial and domestic carbon monoxide testing using amperometric electrochemical gas sensors (AGS). The isolation of a specific application for a single gas sensor technology where the potential market is reasonably well defined, and for which data on the incumbent and the nano-enabled product are available, allows the benefits for this instance to be estimated.

Amperometric electrochemical gas sensors (AGS) can measure the presence of carbon monoxide, hydrogen sulphide or other toxic gases since their reduction on a working electrode with catalytic particles produces a small electric current between this and the two reference electrodes[b,c]. Platinum particles are catalytic for carbon monoxide (CO) and other carbon-oxygen compounds, and as well as having catalytic properties, they do not corrode in the acidic electrolyte. The benefit of nano-enabled product is that it increases the surface area of the catalyst, thereby increasing its performance per unit mass, or reducing the mass required.

CO sensors have both domestic and industrial applications. **In this case study we will explore the benefits accruing to the UK economy from emergence of nano-scale platinum as a catalyst in domestic electrochemical CO sensors**.

1.2 Define functionality

The functionality for gas sensors is the sensitivity to CO gas (ppm) per unit of platinum catalyst (milligrammes). The need for high sensitivity is capped (the level of ppm sensitivity), otherwise the sensor would give false alarms; therefore the benefit of the increase in sensitivity from nano-scale sensors comes in the form of a lower material requirement. A study by the Department for Communities and Local Government (2009) states the levels at which CO should be measured at 50ppm according to British Standard BS EN 50291:2001.

1.3 Identify incumbent

In the past, CO detectors consisted of a chemical strip that changed colour when in contact with CO. These were replaced by semiconductors which required mains power to operate. These have subsequently been replaced by the type of electrochemical sensor described above. With the cost of electrochemical sensors falling and the added convenience of them not requiring mains power, they are rapidly dominating the market. A review of the leading CO detector manufacturers' (Honeywell, Fire Angel, Kidde, BRK Dicon and Ei)[d] products shows them all to use electrochemical sensors. **Therefore in this case study we assume that the incumbent technology is an electrochemical sensor with a working electrode catalysed by platinum particles which are not on the nano-scale.**

1.4 Select scenario

The introduction of nano-scale platinum catalyst particles is a direct substitution of the existing larger-scale platinum catalyst particles. We assume that there will not be any change in market size due to the new technology since the average retail price of domestic CO sensors is relatively low at £31, and the sensor costs only

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[a] Nanotechnology Initiative Workshop, Nanotechnology Enabled Sensing, 5-7 May, 2009.
[b] Johnson Matthey, Catalysts All Around Us: Carbon Monoxide detectors, available at URL: http://resources.schoolscience.co.uk/johnsonmatthey/page25.htm (accessed 26 July 2010).
[c] Alphasense, Alphasense Application Note: Modelling Amperometric Gas Sensors, http://www.alphasense.com/pdf/AAN_111.pdf (accessed 26 July 2010).

[d] Department for Communities and Local Government (2009), Study on the Provision of Carbon Monoxide Detectors Under The Building Regulations, Product Code 09BD06095, September 2009.

£3 to the manufacturer of the unit[a]. Therefore the reduction in sensor production cost (see below) is not going to lead to a step change in price and hence **there is no increase in market size over and above the natural rate of growth**. This natural growth is occurring as a result of better awareness of the risks of CO and the fundamental technology shift to electrochemical sensors[d]. **Therefore, Scenario I will be used to value this nano-enabled product.**

1.5 Market definition

For this valuation the market definition used is for CO sensors in the UK, annually for 20 years.

1.6 Identify data requirements

The data requirements for performing a valuation under Scenario I are:

- Q_A Initial market quantity for the incumbent electrochemical sensor
- P_A Incumbent price for the electrochemical sensor
- C_A Incumbent unit cost for the electrochemical sensor
- C_N Nano-scale sensor unit cost.

1.7 Determine production costs

It has not been possible to establish the absolute production cost of the incumbent. However Alphasense estimates that nano-scale sensors lead to a cost saving of 5% to 10%, so an average of 7.5% was used. Alphasense also believe that Johnson Matthey is responsible for close to 100% of the global supply of the platinum catalyst, while 60% of CO electrochemical sensors are manufactured in the UK. Therefore we can approximate the incumbent sensor manufacturing cost to the average of Johnson Matthey's 'Environmental Technologies' division[b] which includes catalysts and catalyst components. The manufacturing cost ('cost of goods sold') to sales ratio of this division averaged 72% over the past 3 years. Given the potential for Johnson Matthey to make high margins in the business given their high market share for some products, we also calculated cost ratios for Spectris [c] and Renishaw[d], two UK manufacturers of precision testing equipment. These were 43% and 44% respectively suggesting that if anything Johnson Matthey's margins might overestimate the incumbent production cost.

Since the unit sales price of a sensor is £3 (see below), the incumbent production cost is £2.16, and the nano-enabled product unit cost is £2.00 (£2.16 x (100%-7.5%)).

1.8 Determine sales price

Alphasense state that the price of a domestic sensor is £3. According to the Methodology, the sales price of a sensor using nano-scale platinum is assumed to be the same as the incumbent at t = 0. The sales price is assumed to decline in a linear fashion to t = 20 years until the gross profit margin of the nano-scale sensor is equal to that of the incumbent.

Applying the implied gross profit margin for the incumbent of £0.84 to the nano-scale sensor unit production cost of £2.00, gives a price in 20 years of £2.84. Therefore the annual price decline is (£3.00 - £2.84)/ 20 = £0.008.

1.9 Establish market size

There is no data available on the size of the UK market. According to the Office for National Statistics there are approximately 26 million households in the UK. According to a 2009 Ipsos MORI survey conducted on behalf of the Carbon Monoxide Consumer Awareness Alliance[e], 19% of households have an audible carbon monoxide alarm. We take the average lifetime of a CO sensor to be 6 years[d]. Therefore annual replacement unit sales are 19% of 26 million/ 6 years =823,000. We assume that at t= 20, half of UK households have a carbon monoxide

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[a] Alphasense (2010), personal communication.
[b] Johnson Matthey (2010), Reports and Accounts archive, Annual report 2009 and 2010, available at URL: http://www.matthey.com/investors2004/reports.htm (accessed 26 July 2010)

[c] Spectris (2010), Financial reports, Annual report 2009 and 2008, available at URL: http://www.spectris.com/FinancialReports.aspx (accessed 26 July 2010).
[d] Renishaw (2010), Financial reports, Annual report 2009 and 2009, available at URL: http://www.renishaw.com/en/investor-relations--6430#tocTarget8 (accessed 26 July 2010).
[e] Carbon Monoxide Consumer Awareness Alliance (2009), 'Carbon Monoxide – Be Alarmed', (available at URL http://www.co-bealarmed.co.uk/wp-content/uploads/2010/01/CM_CAMPAIGN-REPORT_AW3-PANTONE-123-FINAL.pdf)

sensor, that the number of households is constant, and that the sensor lifetime remains at 6 years, giving annual replacement unit sales of 2.2 million.

The annual natural increase in UK market size needs to be calculated (the introduction of the nano-sensors does not affect this). This is calculated as (2,200,000 – 823,000)/ 20 = 68,850

Alphasense estimate the global market size for domestic CO sensors at 4 million units, although they note that this is conservative and suggest it could be multiples of this. In the United States, 23 states now require households to have CO detectors by law. According to the US Census Bureau[a] there are 115 million households in the US; therefore, by taking a simple average of the number of states that require CO detectors by law implies that 53 million households will have at least one detector. Given the average life of a sensor is 6 years, this implies annual replacement demand alone of 9 million new detectors/ sensors. **Therefore we estimate the global market to be 10 million units at present, and to grow to 40 million units in 20 years' time, made up of new and replacement demand. This would be made up of approximately 15 million each in the US and Europe, and 10 million in the rest of the world. Therefore the annual increase in global market size = (40-10)/ 20 = 1.5 million**

1.10 Determine externalities

Each sensor will require less platinum for which there will be a reduction in environmental externalities associated with platinum mining and production overseas. However, since there is no anticipated increase in the market size as a result of the nano-scale sensor (above the established natural rate), there will be no additional environmental or social benefits accruing to the UK.

With respect to the social benefit of less deaths or illness from CO poisoning, there is no additional benefit arising from the introduction of the nano-sensors. This is because it has been assumed that there is no increase in detection between the sensors, and the introduction of the nano-sensors will not affect the market size (the natural growth rate persists).

There is no reason to believe that the R&D expenditure on the nano-scale sensors is any different to the incumbent; therefore we do not assume any change and no R&D spillovers are expected.

1.11 Calculate surplus

Producer Surplus

At t=0, because the sales price is the same, the change in the producer surplus is the cost saving of the nano-scale sensors. This is £2.16 - £2.00 = £0.16 per unit. The change in producer surplus then declines in a linear fashion until at t=20 it is equal to zero.

Geography
60 per cent of the incumbent and the nano-scale sensors are produced in the UK, therefore UK industry is estimated to produce 60% of 10 million = 6 million units at t = 0, increasing to 24 million (60% of 40 million) at t= 20.

Consumer Surplus

At t=0, the change in the consumer surplus is zero as the Methodology assumes that all the cost saving is taken by the producer. However, through time this is transferred to the consumer in a linear fashion in the form of unit price declines, until in year 20, all the benefit is with the consumer.

Total Surplus

The total benefit associated with the nano-enabled product is then the sum of the consumer and producer surplus' (additional externalities were not identified and cannot be included). At t=0, the total surplus is £160,000 per year.

1.12 Estimate economic value

The product is currently on the market and therefore we assume a discount rate of 4% in-line with typical equity risk premiums outlined in the Methodology.

[a] *US Census Bureau (2010), Projections of Households by Type, available at URL: http://www.census.gov/population/projections/nation/hh-fam/table1n.txt (accessed 26 July 2010).*

As a result the benefits accruing to the UK economy are limited to the change in the producer surplus and the consumer surplus. Whilst the improvement in the consumer surplus is limited to the number of units sold in the UK, the UK's producer surplus benefits from the scale of sensor exports. The results are shown in Table 1.

Over 20 years the value of the technology may be worth £8.1 million to the UK. The net present value of the benefits accruing to the UK economy from the use of nano-scale platinum in carbon monoxide sensors is approximately £12.4 million. This is in the context of a current UK market for the incumbent product of £2.5 million, and projected market of £13 million. The current global market is estimated at £30 million, and is expected to grow to £120 million; it is the UK's share of this market which is an important factor in the scale of these benefits.

This case study does not estimate any external benefits, however there may be instances of nanotechnology being applied in gas sensors where these are realised, such as sensors of nitrous oxide. Furthermore, CO sensors are a small part of the overall gas sensor market which was estimated at approximately £1 billion in 2002, and was expected to grow over 50 percent by 2010[a]. However it is not possible to extrapolate the findings from this study to estimate the potential benefits from gas sensors in general, since the private as well as external benefits may differ.

[a] *Hooker, S. (2002), Nanoparticles 2002 Conference Proceedings, Nanomaterials Research LLC.*

Table 1: Benefits accruing to the UK economy from the use of nano-scale platinum in carbon monoxide sensors (£ million)

					Diffusion rate		Discount	
Year	**ΔCS**	**ΔPS**	**ΔE**	**ΔS**	**%**	**ΔS**	**Rate**	**MVR**
2010	-	-	-	-	0.2	-	1	-
2011	0.01	1.03	0	1.04	0.7	0.007	0.962	0.007
2012	0.02	1.10	0	1.12	2	0.022	0.925	0.021
2013	0.02	1.16	0	1.18	5	0.059	0.889	0.053
2014	0.04	1.20	0	1.24	10.9	0.135	0.855	0.115
2015	0.05	1.23	0	1.28	20.5	0.261	0.822	0.215
2016	0.06	1.24	0	1.30	34	0.443	0.79	0.350
2017	0.07	1.24	0	1.32	50	0.658	0.76	0.500
2018	0.09	1.23	0	1.32	66	0.868	0.731	0.635
2019	0.10	1.20	0	1.30	79.5	1.035	0.703	0.728
2020	0.12	1.16	0	1.28	89.1	1.137	0.676	0.768
2021	0.14	1.10	0	1.24	95	1.174	0.65	0.763
2022	0.16	1.02	0	1.18	98	1.159	0.625	0.724
2023	0.18	0.94	0	1.12	99.3	1.109	0.601	0.666
2024	0.20	0.84	0	1.04	99.8	1.035	0.577	0.597
2025	0.22	0.72	0	0.94	100	0.944	0.555	0.524
2026	0.25	0.59	0	0.84	100	0.838	0.534	0.447
2027	0.27	0.45	0	0.72	100	0.718	0.513	0.368
2028	0.30	0.29	0	0.59	100	0.585	0.494	0.289
2029	0.32	0.12	0	0.44	100	0.439	0.475	0.209
2030	0.35	0.00	0	0.35	100	0.352	0.456	0.160
							Total value over 20 years	8.14
							Net present value	12.36

2 Case studies: Antifouling paints

2.1 *Select nano-enabled product*

Antifouling paints are used to reduce the build up of organisms on the hulls of ships, minimising friction caused when the ship moves through water. The friction caused by these organisms leads to a significant reduction in fuel efficiency.

A European Framework Programme 7 project has recently been completed that set out to examine nano-enabled paints to improve the efficacy of foul release paints. Current research in this area is ongoing and although some interesting avenues of research were investigated, a commercially viable solution was not discovered. Researchers involved with the project do believe that nanotechnology will have some impact on antifouling paints. Clearly though, to investigate the potential benefit of nano-enabled paint, assumptions over the future efficacy of the paint will need to be made. Although, in this case, the valuation may be somewhat theoretical, it offers an important example of the use of the methodology in estimating the value of technologies that are still some way from commercialisation.

This case study will examine the development of nano-enabled antifouling paints. Several different approaches are being trialled, but due to the experimental nature of the work, this case study will not detail the technology. Comments from industry suggest a nano-enabled paint is between three and five years from commercialisation; this case study will assume that the product is five years from commercialisation. Clearly there are significant unknowns in the cost of production or efficacy of the final product.

The current state of the art for nano-enabled paints is not as effective as the current incumbent technology. An inferior product that may be more expensive than the incumbent is unlikely to be commercially successful therefore; this case study is using some assumptions on the future performance of the nano-enabled paints to obtain a more realistic valuation. It is important that the reader is aware of these assumptions and that they can be readily challenged. The assumptions on the efficacy of the nano-enabled antifouling paints are that:

- the product is five years from commercialisation
- the production costs associated with the nano-enabled paint are 10% higher than the incumbent
- a 1% fuel efficiency saving can be realised by using the nano-enabled paint
- the market size does not increase for the nano-enabled paint.

2.2 *Define functionality*

Anti fouling paints are designed to minimise the build up of microorganisms. The output of the antifouling paint is an improvement in fuel efficiency, or the amount of fuel consumed per kilometre travelled. Therefore the functionality will be in cost per kilometre or total transport costs. This case study includes the cost of fuel and the cost associated with the antifouling paints. Due to the diversity of vessels and distances travelled, obtaining meaningful data across the UK from a 'bottom-up' approach is impractical. However, data are available agglomerated to a national level. **Therefore the functionality will be measured on the total cost associated with using FRPs and the fuel costs associated with moving this shipping**. This is then scaled up to the UK level.

2.3 *Identify incumbent*

The nano-enabled paint replaces incumbent foul release paints. Traditionally, biocides have been used to combat the problem. These were made using toxic metal salts, which have led to problems of bioaccumulation and destruction of biodiversity within the marine environment. There is therefore a desire to move away from these biocides to less damaging alternatives; these technologies are being phased out, and therefore biocides are not taken as the incumbent for this case study.

The alternative type of antifouling paint uses surface interactions to form either a non-stick layer or a surface which is 'ambiguous' to microorganisms. These are known as Foul Release Paints (FPR). It is this technology that is taken as the current incumbent technology for the case study. It is assumed that an improvement in efficacy of the nano-enabled foul release paint leads to a reduction in fuel consumption. **Therefore, the nano-enabled paint is equivalent to the UK consumption of the incumbent FRP and the additional fuel consumption associated with the less efficient incumbent**.

2.4 Select scenario

The incumbent technology (described above) requires the combination of two products to meet the functionality of the nano-enabled paint (the incumbent paint plus the additional performance of reduced fuel consumption). Therefore, using these assumptions, **Scenario III will be used to value the nano-enabled paint, which is enhanced performance over existing products in a fixed market size**.

2.5 Market definition

Foul release paints are designed for use on ships that are continually moving. The frictional action of moving through deep water removes organisms from the hull of the ship. Therefore **the market of these products is constrained to merchant shipping**, rather than pleasure craft that spend the majority of their time moored in marinas where these paints are ineffective.

For this valuation the market definition used is for nano-enabled paints for merchant shipping in the UK, annually for 20 years.

2.6 Identify data requirements

The data requirements for performing a valuation under Scenario III are:

- Q_A Initial market quantity for the incumbent FRP
- P_A Incumbent price for the FRP
- C_A Incumbent unit cost for the FRP
- Q_B The additional fuel needed
- P_B Price of the fuel oil
- C_B Manufacturing costs of the fuel oil
- C_N Nano-enabled paint unit cost.

As noted above, due to the practicalities of the data available on the types of vessels using the paints, **data has all been agglomerated to the UK level for this particular case study**. The case study therefore compares the total costs and benefits of the incumbent and nano-enabled paints for the UK market.

2.7 Determine production costs

2.7.1 Incumbent technology

A proxy for the production cost of the paint can be made by examining the sales price of the paint and the margin achieved by manufacturers in similar business sectors. Annual report data from the Akzo Nobel coating division[a] indicates an operating profit in 2008 of 12.2%, and Nippon Paints[b] quote their COGS/Sales at 32% over the same period. An average of 22% margin will therefore be used in determining the costs of production. Based on the market size (described below), the annual costs of production of the incumbent paint total £1.79 million for the UK merchant shipping market.

The cost associated with the extra fuel consumption also needs to be taken into account. Because the products are still in their infancy, the performance differential between the nano-enabled paint and the incumbent are not yet well defined. Therefore, an arbitrary improvement in fuel efficiency of 1% compared to the incumbent technology will be used. Using the COGS data described under the Fuel Replacement Catalyst case study, (see Appendix D of the methodology), the average margin for a fuel supplier is 6.67%. Based on the sales price of the fuel saved (described below), the annual cost to produce the fuel is £504,000 for the UK merchant shipping market.

Overall the total cost of the incumbents is the sum of the paint (£1.79 m) and the additional fuel (£0.504 m) which totals £2.294 m per year.

2.7.2 Nano-enabled paints

Production figures for this technology are unavailable. The additional costs associated

[a] AkzoNobel annual report, 2008
[b] Nippon Paints annual report 2008

with the production are therefore unknown. However, conversations with experts suggest that the production of nano-enabled FRP will be more expensive than the current incumbent. For the purposes of this case study a figure of 10% will be used to illustrate this point. Based on this assumption, the production costs associated with the nano-enabled paint will be £1.97 million.

2.8 Establish market size

Because of the nature of the data available in this case study (i.e. only agglomerated at a UK level), it is useful to establish the market size ahead of determining sales prices.

The global market for antifouling paints has been reported as $4billion annually[a]. Currently, 5% of International Paints business[b] is for foul release paint. To simplify this scenario, the market size for foul release paints will assume to remain constant at 5%[c]. Assuming 5% of this is attributed to the foul release sector, this equates to £130 million. Examining the UK merchant fleet, the Central Intelligence Agency (CIA) Fact book estimates that 1.8% of all merchant shipping is registered in the UK[d]. Using this figure, the UK represents a market of £2.3 million.

2.9 Determine sales price

2.9.1 Incumbent

It has been reported that antifouling paints reduce fuel consumption by approximately 40%[e]. This saves an estimated 120 million tonnes of fuel oil annually, which is priced at approximately $300 per tonne[f]. Assuming the nano-enabled paint leads to a 1% increase in fuel efficiency, $900 million annually will be saved by the global shipping industry. Based on the UK shipping fleet (1.8%) and the size of the FRP market (5%), £525,000 will be saved by UK shipping per year.

2.9.2 Nano-enabled paint

Under Scenario III, the sales price of the nano-enabled paint (when not known) is the sum of the individual components. Therefore, the initial sales price of the nano-enabled paint is assumed to be the same as the sum of the sales price of the incumbent paint (£2.3 million) and that associated with the additional cost of the fuel oil (£0.525 million). This equates to £2.825 million. Over time, the sales price of the nano-enabled paint is assumed to fall so that the producer makes the industry standard margin for the paint (calculated above at 22%). Therefore, using the costs derived above at year 20, the sales price of the nano-enabled FRP will be £ 2.403 million for the UK merchant shipping market per year.

2.10 Determine externalities

The shipping industry consumes 300 million tonnes of fuel oil per year. This is equivalent to emitting 960 million tonnes of CO_2 and 9 million tonnes of SO_2. Based on the market data described above for FRPs in the UK, the shipping fleet emits 864,000 tonnes of CO_2 and 8,100 tonnes of SO_2. A 1% reduction through the use of a nano-enabled product would result in a saving of 8,640 tonnes of CO_2 and 81 tonnes of SO_2 per year. These are values using data supplied in Appendix B of the methodology.

2.11 Calculate surplus

The calculation of these values are summarised in Table 2.

Producer Surplus

The Producer Surplus for the nano-enabled FRP is equivalent to the difference in the margin of the nano-enabled FRP and the margin on the incumbent FRP plus the additional margin on the fuel savings from the increased efficacy of the nano-enabled paint.

PS = nano-enabled paint - (FRP+margin on fuel)

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[a] *Coatings World, May 2009*
[b] *Personal communication with David Williams International paints.*
[c] *This is clearly a simplification. Any improvement in efficiency will lead to a change in the market structure, additionally, the market is relatively immature for foul release paints and is expected to grow over time.*
[d] *https://www.cia.gov/library/publications/the-world-factbook/fields/2108.html*
[e] *An Experimental Study into the Effect of Foul Release Coating on the Efficiency, Noise and Cavitation Characteristics of a Propeller. First International Symposium on Marine Propulsors, Trondheim, Norway, June 2009*
[f] *The benefits of foul release coatings. Shipbuilding technology, ISST 2007.*

This falls from a surplus of £340,000 to -£74,997 due to a linear drop in overall sales price of the nanotechnology.

Geography
The UK has a strong market lead in the production of both the incumbent and the nano-enabled paints. International Paints, based in the North East of England, is a world leader in this area. Although the company is now a subsidiary of Akzo Nobel, based in The Netherlands, the R&D and manufacturing operations are primarily based in the UK. This methodology assumes that this situation persists for the nano-enabled paint, and can be justified because International Paints are actively involved in this research. The model will therefore assume that UK-based shipping will use UK manufactured paint.

Consumer Surplus

At t=0, it is assumed that the producer collects all the surplus of migrating to the new technology, meaning that the consumer surplus is zero. Over time, the sales price of the nano-enabled paint decreases leading to an increase in the consumer surplus equalling £398,000 per annum.

Total surplus

Summing the consumer surplus, producer surplus and the externalities associated with reductions in emissions, the total surplus equates to £894,294 per annum, which increases to just over £1 million in 2030.

2.12 Estimate economic value

Additional modifiers to the final calculation are needed to take into account the diffusion of the new technology (set at 8 years for half penetration) and that the technology is at least 5 years from commercialisation. A higher discount rate of 8% is also applied to account for the risk associated with a new technology entering a marketplace. The results of these modifications are presented in Table 2.

One aim of this case study was to demonstrate the ability of the model to value technologies that are not currently commercially available. Under this scenario, assumptions were made during the calculation on the time to market, production costs, efficacy and sales price. The unknowns surrounding the sales price and efficacy are two areas which could have the largest impact on the value of the nano-enabled paint.

Based on the data entered above, this technology could be worth a relatively modest net present value of £4.7 million compared to the incumbent technology and valued at £2.3 million over 20 years. This figure, however, does not include the additional global sales of the product which could be significant if the technology is developed in the UK. Although a simplistic assumption for illustration purposes, if the technology was developed and patented in the UK (which is plausible given the UK's position in this area), and the profits from the sale of the product accrued in the UK, this technology could be worth £143 million in exports over a 20 year period (Table 3)

Table 2: The calculated MVA (£/annum) for nano-enabled foul release paint

	Surplus				Diffusion Rate			Discounted
Year	ΔCS	ΔPS	ΔE	ΔS	%	ΔS	Discount rate	MVA
2010	0	0	0	0	0	0	0.926	0
2011	0	0	0	0	0	0	0.857	0
2012	0	0	0	0	0	0	0.794	0
2013	0	0	0	0	0	0	0.735	0
2014	0	0	0	0	0	0	0.681	0
2015	0	324,000	570,294	894,294	0	1,789	0.630	1,127
2016	19,950	304,050	570,294	894,294	1	6,260	0.583	3,653
2017	39,900	284,100	578,934	902,934	2	18,059	0.540	9,757
2018	59,850	264,150	587,574	911,574	5	45,579	0.500	22,801
2019	79,799	244,201	596,214	920,214	11	100,303	0.463	46,460
2020	99,749	224,251	604,854	928,854	21	190,415	0.429	81,666
2021	119,699	204,301	613,494	937,494	34	318,748	0.397	126,579
2022	139,649	184,351	613,494	937,494	50	468,747	0.368	172,357
2023	159,599	164,401	622,134	946,134	66	624,448	0.340	212,600
2024	179,549	144,451	630,774	954,774	80	759,045	0.315	239,283
2025	199,499	124,501	639,414	963,414	89	858,402	0.292	250,559
2026	219,449	104,551	648,054	972,054	95	923,451	0.270	249,580
2027	239,398	84,602	656,694	980,694	98	961,080	0.250	240,509
2028	259,348	64,652	665,334	989,334	99	982,409	0.232	227,636
2029	279,298	44,702	673,974	997,974	100	995,978	0.215	213,685
2030	299,248	24,752	682,614	1,006,614	100	1,006,614	0.199	199,970
							Value over 20 years	2,298,222
							terminal value	4,797,843

Table 3: Possible producer surplus for the UK if the nano-enabled foul release paint is developed in the UK

World wide sales	Diffusion Rate			
DPS/0.018	**%**	**DS**	**Year**	**MVA**
77,000,000	0	-	1	-
75,891,674	0	-	2	-
74,783,348	0	-	3	-
73,675,022	0	-	4	-
72,566,696	0	-	5	-
71,458,370	0.2	142,917	6	90,062
70,350,044	0.7	492,450	7	287,340
69,241,718	2	1,384,834	8	748,183
68,133,391	5	3,406,670	9	1,704,183
67,025,065	10.9	7,305,732	10	3,383,968
65,916,739	20.5	13,512,932	11	5,795,465
64,808,413	34	22,034,861	12	8,750,346
63,700,087	50	31,850,044	13	11,711,195
62,591,761	66	41,310,562	14	14,064,637
61,483,435	79.5	48,879,331	15	15,408,804
60,375,109	89.1	53,794,222	16	15,702,021
59,266,783	95	56,303,444	17	15,217,073
58,158,457	98	56,995,288	18	14,263,015
57,050,131	99.3	56,650,780	19	13,126,669
55,941,805	99.8	55,829,921	20	11,978,209
54,833,479	100	54,833,479	21	10,892,986
		Value over 20 years		**143,124,155**
		Terminal value		**279,286,476**

3 Case studies: Nano-zero-valent iron

3.1 *Select nano-enabled product*

Zero-valent iron nanoparticles (nZVI) technology is becoming an increasingly popular choice for the treatment of hazardous and toxic wastes, and for remediation of contaminated sites. The size of the iron nanoparticles helps to foster effective subsurface dispersion whereas their large specific surface area corresponds to enhanced reactivity for rapid contaminant transformation. Recent advances in nano-particles synthesis and production have resulted in substantial cost reductions and increased availability of nZVI for large scale applications[a].

nZVI particles rapidly transform many environmental contaminants to benign products. Their nanoscale size and increased reactivity enables them to be more effective than granular zero-valent iron that is already in use for contaminant remediation in soil and groundwater aquifer[b]. Permeable reactive barriers (PRB) using granular zero-valent iron were first introduced as an *in situ* treatment method. Whilst granular zero-valent iron has been used at numerous sites it is still considered semi-experimental and has a very small market. Its major drawback is that it can only address contaminants that flow through it. nZVI promises to be more effective than granular iron, with reaction rates 25-30 times faster and an adsorption capacity which is much higher than with granular iron, due to its large reactive surface area. nZVI particles have surface areas that are up to 30 times greater than larger size powders or granular iron. Thus nZVI is 10 to 1,000 times more reactive.

nZVI has been demonstrated to effectively reduce chlorinated organic contaminants (e.g. PCB, TCE, PCE, TCA, pesticides, solvents) and also inorganic anions (perchlorate). It/the particles can even be used to recover or remove dissolved metals from solution[c,d].

[a] *Li et al., Zero-Valent Iron Nanoparticles for Abatement of Environmental Pollutants: Materials and Engineering Aspects, Critical Reviews in Solid State and Materials Sciences, 31:111–122, 2006.*

[b] *Cook SM, Assessing the Use and Application of Zero-Valent Iron Nanoparticle Technology for Remediation at Contaminated Sites, Report prepared for US EPA, 2009.*

3.2 *Define functionality*

nZVI is primarily used for the remediation of contaminated land and ground water. Field tests have been demonstrated for a wide variety of contaminants, but some of the most promising have been in the remediation of localised, concentrated contamination with chlorinated volatile organic solvents from ground water. The remediation of a cubic meter of soil, containing a particular contaminant, is the most appropriate functional unit. However because each site is different, the effectiveness and circumstance of individual contaminated site causes complications in quantifying this value. Therefore, comparisons of particular sites, where nZVI and the incumbent were assessed, will be used as a proxy and then scaled-up to account for viable treatment sites across the UK.

3.3 *Identify incumbent*

Currently in the UK, the two most common methods for treating contaminated land involve removal of soil to a landfill site or containing the contaminants onsite with a capping layer. Disposal to landfill is becoming more expensive as the number of sites that are permitted to accept hazardous material has fallen, whereas containing the hazardous material leaves legacy issues and can limit land development. Indeed neither treatment is effective against historical water pollution, where treatment is currently focused at the point of abstraction, colloquially known as ‘pump and treat’. **This case study will compare the costs of pump and treat (the incumbent) with the application of nZVI.** It is possible to choose granular iron as the incumbent, but due to its semi-experimental nature and small market it was decided that pump and treat represented the more suitable choice for the incumbent.

[c] *ObservatoryNANO, Report on Nano zero-valent iron – THE solution for water and soil remediation?, 2010.*

[d] *Observatory Nano, Report on Nanotechnology in the Technology Sector: Environment, 2009*

In addition to the costs associated with pump and treat, the additional costs of under-utilisation of land will be taken into account, which can be a significant burden because such remediation techniques can take decades to completely clean a site.

As mentioned in a previous section, the functionality is difficult to define due to variance between contaminated sites. Therefore, costs and associated benefits will be determined based on case studies that compare the incumbent with the nano-enabled product.

3.4 Select scenario

Although there are several proposed methods for treating contaminated groundwater, due to costs, these are not generally in use and the current incumbent (treatment at abstraction) does not adequately represent the overall functionality of the nano-enabled product. In addition, the under-utilisation of the land needs to be accounted as part of the calculation. The current market size of the incumbent is somewhat limited by costs and feasibility. **Based on these factors, Scenario IV (increased utility and increased market size) appears to be the most appropriate scenario for nZVI remediation of ground water**.

It is important to identify the consumer and producer within this scenario. The model assumes that the producer is the land remediation company whereas the consumer is a construction company wishing to develop the land for residential accommodation, enabling a valuation of the land.

3.5 Market definition

For this valuation the market definition used is for nZVI remediation in the UK, annually for 20 years.

3.6 Identify data requirements

The data requirements for performing a valuation under Scenario IV are:

- Q_A Initial market quantity for possible remediation by the nZVI
- P_A Incumbent price for the incumbent treatment
- C_A Incumbent unit cost for the incumbent treatment
- Q_B Initial market quantity of land, which is not needed because land is not 'made'.
- P_B Incumbent price for the remediated land
- C_B Incumbent unit cost for land which is not needed because the land is not 'made'
- C_N nZVI unit cost
- β Elasticity of demand.

3.7 Determine production costs

3.7.1 Incumbent technology

Data available from the Buildings.co.uk website[a] suggests that contractors within this industry make an average of 4% profit. Based on the price of the incumbent technology of £1.3 million, (described below) the average production costs of the incumbent are £1,250,000. In this case study the additional product is the underutilisation of land. Land itself does not have an additional production cost associated with it but there are additional costs to the end consumer that must be accounted for. This is addressed under the sales price (i.e. the cost to the consumer) of the incumbent technology but is not included as a production cost or used in the calculation of the producer surplus.

3.7.2 Nano-enabled product

The intellectual property associated with nZVI resides outside the UK, therefore only the costs associated with the set-up of the remediation technology are likely to result in benefits accruing the UK-based companies. Based on *Figure* 1, approximately half of the overall sales price can be attributed to costs associated with nZVI. It is therefore reasonable to assume that approximately half of the costs are associated with 'non-specialist' production, i.e. production that is necessary for the deployment of nZVI in remediation, but does not itself use any proprietary technology. Based on an average sales price of £140,000, £70,000 accrues to UK business. From the industry standard of a 4% margin, production costs in the UK equate to £67,300 per site.

[a] *Cost model: Land remediation, 27/11/09, accessed from www.buildings.co.uk website 15/07/10*

Figure 1: Costs associated with the treatment of four contaminated land sites in the USA

	Hunters Point Study #1	Hunters Point Study #2	NAS Jacksonville	NAES Lakehurst
	$31,000 - Mobilization		$28,000 - Mobilization	
	$62,000 - Labor/Drilling for injection		$52,000 - Monitoring Well Installation	$24,400 - Monitoring Well Installation
	$100,000 ($32,500 of which are for ZVI) - Equipment/Supplies for injection:	$770,000 – Treatability study field effort	$67,000 ($37,000 of which are for NZVI) - Injection/Circulation Events	$154,600 - NZVI Treatment
	$96,000 – Monitoring, IDW disposal, and miscellaneous costs	$452,000 – Monitoring, sampling, and analysis	$112,000 – Monitoring and investigation-derived waste (IDW) disposal, miscellaneous costs	$58,400 – Sampling and Analysis
		$168,000 – Project management, data management, and reporting	$153,000 - Project Management, Work Plan, Bench-Scale Study	$18,100 - Reporting
Demonstration Total:	**$289,000**	**$1,390,000**	**$412,000**	**$255,500**
Treatment Volume (yd^3):	**1,683**	**27,778**	**967**	**9,500**
Cost per yd^3 of Soil Treated:	**$172**	**$50**	**$426**	**$27**

Source: Cost and performance report nanoscale zero-valent iron technologies for source remediation. Naval Facilities Engineering Service Center, 2005.

3.8 Determine sales prices

3.8.1 Incumbent technology

A relatively old study (2001) performed by the US EPA[a] suggested that the median pump and treat costs across a diverse series of sites was approximately $2 million (£1.3 million). The high cost associated with the incumbent technology is partly due to the longer timescale needed to remediate the land.

The study also estimated the average time for pump and treat to be 6 years, compared to less than one year with the nano-enabled product. It also limits the use of the land (and therefore its value) over this period. To evaluate this, an estimation of the lost value of the land can be determined through discounting the present value of uncontaminated land at the point where the remediation process is complete for the incumbent (after 6 years based on EPA data). Thus:

Lost land value = current land value – discounted land value after 6 years

The Valuation Office Agency estimates the value of residential land in UK cities at approximately £2 miliion per hectare[b]. A comparative study (used below to determine the sales price on nano-enabled product) examined 0.2 hectares of land. If this is normalised to the EPA data the average remediation site is worth approximately £200,000. Using a discount rate of 4%, and the equation below:

$$D_t = \frac{1}{(1+\delta)^t}$$

the discounted value of the remediated site after 6 years is £158,000 and the lost value of the site is £42,000.

Based on the figures derived for the pump and treat remediation technology and the value of land depreciation, the total sales price of a

[a] *Cost Analyses for Selected Groundwater Cleanup Projects:Pump and Treat Systems and Permeable Reactive Barriers, USA EPA, 2001*

[b] *Property market report: Residential Building Land, January 2010, Valuation Office Agency*

pump and treat system is therefore £1.34 million.

3.8.2 Nano-enabled product

Although the study of the clean-up of contaminated groundwater is still in its infancy, several studies of the associated costs have been performed on nZVI. However, as stated above, the variance due to site specific costs makes direct comparison difficult. Comparative data is available from a remediation site in New Jersey conducted by Pars Environmental Inc.[a]. The data should be used with some caution because the comparison is part of the company's promotional material. Three technologies were assessed in the study (Table 4). This data has been normalised to the average cost of remediation provided by the 2001 EPA study.

Table 4: Comparative costs associated with remediating a test site

Remediation approach	Estimated costs ($)	Normalised to EPA Data
Pump and treat	4,160,000	2,000,000
Reactive barrier	2,200,000	1,057,000
NZVI	450,000	216,000

Based on this the 'average' treatment costs of nZVI is approximately $216,000 (£140,000). Approximately half these costs are associated with production, supply and injection of nZVI; the remainder are largely associated with overhead costs associated with 'traditional' activities such as monitoring the site and drilling bore holes. It is unlikely that significant additional savings will be made on these activities and the focus will be on the reductions in cost associated with the scale-up in production of nZVI.

Indeed, the majority of the savings associated with the nZVI have already been realised by the significant reduction in costs to the end user. Therefore, in this study, over the projected 20 year lifetime of the product, further decreases in Sales Price are not expected to be realised. This is clearly a simplification because the processing costs associated with the production of nZVI are likely to reduce over this timescale.

[a] http://www.parsenviro.com/nanofeaw-1.html

3.9 Establish market size

Approximately 10% of contaminated land sites are suitable for nZVI remediation.[b] Currently approximately 380 sites are being controlled through the Environment Agency's reporting regime suggesting that at the current market size approximately 40 sites per year could undergo treatment with nZVI. This figure is an underestimation because it does not take into account remediation practice undergone through the planning process.

This case study is based on Scenario IV, where a decrease in costs increases the market share for the nano-enabled product. The expanded market size of the nano-enabled productivity can be determined using the equations below:

$$Q_t = \alpha {P_t}^{\beta}$$

Where P_t is the price of the nano-enabled product (£140,000), β is the price elasticity of demand (assumed to be -1) and Q_t is the new market size. α can be determined using the equation below:

$$\alpha = Q_0 \cdot {P_0}^{-\beta}$$

Where Q_0 is the current market size of the technology (10% of the total, 35 sites) and P_0 is the current market price (£1.6 million). Based on these equations and figures, the new market size of the nano-enabled product can be calculated at 400 sites.

Although the market size is small and could in theory grow, some caution must be taken to ensure that there is a large enough market to support any increase in use due to a limit on the number of sites suitable for remediation using this technology. There are a wide range of estimates on the number of sites which will need remediation from 75,000[c] to 300,000[d] sites. In the UK, this is likely to be a moving target as further brownfield sites from decommissioned industry increase the number

[b] *ObservatoryNANO focus report 2010 Nano zero valent iron – THE solution for water and soil remediation?, 2010*
[c] *London Hazard Centre Factsheet. http://www.lhc.org.uk/members/pubs/factsht/43fact.htm*
[d] *Potential health effects of contaminants in soil, Defra, 2009*

of viable areas for remediation. Therefore the market for nZVI is likely to be in excess of 10,000 sites in the UK (taking a conservative view from the 75,000-300,000 range, multiplied by 10%).

3.10 Determine externalities

Surprisingly, the results of a major literature review on the health effects associated with contaminated land, conducted for Defra[a], were inconclusive. The report found no compelling evidence that linked contamination with human health problems, nor did it find evidence that contaminated land was safe. Under such circumstances, a potential health benefit cannot be attributed to faster decontamination offered by the nZVI and will therefore be omitted from the study.

Clearly there is some difference between the processing methods performed through 'pump and treat' and nZVI, however, data over the environmental impacts of the processes themselves are unknown. Therefore, under this scenario, because the majority of the benefits accrue to the producer or consumer, no additional externalities will be considered. As further data on the processing costs are known, as well as the human health impact of contaminated land and the controlled release of nanoparticles into the environment, this section can be revisited.

3.11 Calculate surplus

As is described above, this technology follows scenario IV, where a decrease in sales price results in an increase in the market size for the product. Currently, the use of nZVI leads to a significant reduction in the cost of remediation, which is reflected in the model. Difficulties in identifying exact costs of the incumbent and the nanotechnology meant that it was not possible to define further reductions in the sales price of the nanotechnology over the life time of this study. To account for this, only the initial drop in the sales price of the nanotechnology and the corresponding increase in the market size are modelled. In practice, this is equivalent to having an initial drop in sales price of the nanotechnology (with a resulting increase in market size) in the first year followed by same sale price for all subsequent years. Hence, in Table 5, the consumer surplus and consumer surplus remain unchanged over the twenty year model.

Producer Surplus

The producer surplus is equivalent to the difference between the margin of the nanoenabled product and the margin of the incumbent pump and treat technology. Due to the significant reduction in costs, this results in a net loss of approximately £365,000 per unit year.

Geography
This case study will examine the benefit to the UK. Current incumbent remediation technologies are performed by both UK and internationally based companies. Although there is likely to be some intellectual property surrounding the use of the incumbent, on average, the majority of the benefit is likely to reside with companies based in the UK.

Conversely, the majority of the patents and companies offering nZVI are based in the USA, meaning that a portion of the overall benefit will migrate outside the UK. Based on a study conducted by the USA Navy[b], approximately 50% of the sales price of nZVI remediation are associated with the patented nano-enabled product and are likely to accrue to the company that holds the patent portfolio (which is outside the UK).

Therefore:

The producer surplus $= 0.5 \times \Delta PS_{t,0} - 0.5 \times PS_0$

where $\Delta PS_{t,0}$ is the difference in the producer surplus between the nano-enabled product and the incumbent at time, t and PS_0 is the producer surplus for the incumbent.

$\Delta PS_{t,0}$ can be defined thus:

$$\Delta PS_{t,0} = PS_{t,N} - PS_0$$

[a] *Potential health effects of contaminants in soil, Defra, 2009*

[b] *Cost and performance report nanoscale zero-valent iron technologies for source remediation, Naval Facilities Engineering Service Center, 2005*

By substituting the two equations above:

Producer surplus = $0.5 \times PS_{t,N} - PS_0$

Determining the producer surplus is difficult because calculating the unit costs requires commercially sensitive data which is generally unavailable. This is even more acute for nano-enabled products where comparable costs are not well established, reducing the accuracy of any proxy used. In this case study, this situation has been mitigated because the term 0.5 X PS relates to 'traditional' technology. This means that the production costs associated with nano-enabled products can be ignored and proxies can be developed based on traditional remediation technologies.

Consumer Surplus

The significantly reduce costs associated with the use of nZVI means that there is a large positive consumer surplus associated with its use. The consumer surplus is equivalent to the difference between the sales price of nZVI and the pump and treat technology (with the associated land value cost). This equates to £1.46 per site.

Total surplus

Based on the values described above and the increase in the total market size for the technology, a total surplus of £124 million per year for nZVI can be determined.

3.12 Estimate economic value

Table 5 describes the calculation to determine the MVA. This takes into account a diffusion rate of 8 years to half adoption and uses a discount rate of 4% as the product is already on the market.

On sensitivity the relative sales price of the incumbent versus the nano-enabled product is the largest factor in determining the overall value of the technology. More robust data is probably needed in order to ensure that the figures quoted here are correct, possibly attained through independent trials and comparative cost analysis between the different technologies.

Over a 20 year lifespan, nZVI could be worth approximately £1 billion to the UK with a net present value of £2.4 billion. The vast majority of this is realised by the consumer in reductions in sales price. Overall, due to the largely foreign owned intellectual property and reduction in operating costs, there is a loss to UK producers (which is smaller than the benefit which accrues to consumers). Currently, data are unavailable on the health and environmental benefits of faster remediation; further evidence is needed before further modification to this case study is possible

Table 5: The MVA for nZVI compared to pump and treat

	Surplus totals				Diffusion rate		Discount	
Year	**ΔCS**	**ΔPS**	**ΔE**	**ΔS**	**%**	**ΔS**	**Rate**	**MVR**
2010	136422523	-11695000	0	124727523	0.2	249455	1.000	249,455
2011	136422523	-11695000	0	124727523	0.7	873093	0.962	839,512
2012	136422523	-11695000	0	124727523	2	2494550	0.925	2,306,352
2013	136422523	-11695000	0	124727523	5	6236376	0.889	5,544,116
2014	136422523	-11695000	0	124727523	10.9	13595300	0.855	11,621,319
2015	136422523	-11695000	0	124727523	20.5	25569142	0.822	21,015,971
2016	136422523	-11695000	0	124727523	34	42407358	0.790	33,515,151
2017	136422523	-11695000	0	124727523	50	62363762	0.760	47,391,333
2018	136422523	-11695000	0	124727523	66	82320165	0.731	60,150,538
2019	136422523	-11695000	0	124727523	79.5	99158381	0.703	69,667,363
2020	136422523	-11695000	0	124727523	89.1	111132223	0.676	75,076,948
2021	136422523	-11695000	0	124727523	95	118491147	0.650	76,969,590
2022	136422523	-11695000	0	124727523	98	122232973	0.625	76,346,354
2023	136422523	-11695000	0	124727523	99.3	123854431	0.601	74,383,761
2024	136422523	-11695000	0	124727523	99.8	124478068	0.577	71,882,983
2025	136422523	-11695000	0	124727523	100	124727523	0.555	69,256,766
2026	136422523	-11695000	0	124727523	100	124727523	0.534	66,593,044
2027	136422523	-11695000	0	124727523	100	124727523	0.513	64,031,773
2028	136422523	-11695000	0	124727523	100	124727523	0.494	61,569,013
2029	136422523	-11695000	0	124727523	100	124727523	0.475	59,200,974
2030	136422523	-11695000	0	124727523	100	124727523	0.456	56,924,013
Total value over 20 years								**1,004,536,332**
Net present value								**2,427,387,212**

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