SOME EXAMPLES OF THE ECONOMIC EFFECT OF NANOMATERIALS PRODUCED BY THE CHEMICAL INDUSTRY

Gary Thayer, J. Fred Roach, Lori Dauelsberg, Los Alamos National Laboratory

INTRODUCTION

The production of nanomaterials by the chemical industry is projected to surpass $1B by 2007 and reach $35B by 2020.[1] These nanomaterials will find uses in a wide range of applications and industries. Because of their widespread use, their economic impact will not be confined to the chemical industry alone but will be felt throughout the whole economy. This study looks at a few examples of the economic impact of nanomaterials out of the literally thousands of applications available. This study also examines examples from three areas of nanotechnology applications: catalysts, coatings, and membranes. These three areas represent about $4B, or ~10%, of the $35B projected 2020 market for nanomaterials.[1] The examples in this study are only a few of the many possible applications for nanomaterials in these three areas. For each of the examples, this study not only examines the direct impact of the nanomaterials on the production costs for the application but it also develops an estimate of their impact over the whole economy as the cost savings associated with their use propagate through the economy.

Because this study is a projection into the future and because of the lack of specific information on industry-wide effects, the numbers given in this report have a large uncertainty associated with them. In general, where we have obtained estimates from references we have not associated an uncertainty with that number and have used the point estimate in subsequent calculations. However, we have tried to indicate the uncertainty associated with the final numbers by choosing ranges for the values that we estimate, such as what percent of the particular industrial applications could economically use the nanomaterials.

METHODOLOGY

The initial step in the analysis is to find information on the quantitative effects (i.e., cost savings) of using a nanomaterial in an application. Generally, this information is available for a particular instance of the use for the nanomaterial, such as the fuel savings measured on a particular ship. The results of this particular instance are then extrapolated to the entire sector, such as the US maritime fleet.

Once the reduction in production costs for the sector is determined, it is input into the demonstration model of REMI,[2] an economic model that calculates the impact of these cost savings over the whole economy. The information was also entered into another national economic model, the RIMS II model (Bureau of Economic Analysis).[3] The resulting economic impacts calculated from the RIMS II model are similar to the cumulative 3-year impact calculated by the REMI. Because the REMI model is more applicable to the type of problem encountered in this study, we decided to report the 3-year cumulative economic impact as calculated by REMI. However, because REMI allows for adjustments within the economy through time for these types of technology-driven cost savings, the long-term cumulative impacts may be significantly less than those seen in the earlier years.

The nanomaterial application examples (13) that were examined include the following industries:

Chemical Industry

- Reduction in feedstock requirements and energy use due to the ability of nanomaterials to improve the selectivity of catalysts
- Reduction in precious metal usage in catalysts
- Reductions in energy use due to incorporating advanced separations processes based on membrane nanotechnology in the production of chemicals

Petroleum Refining

- Reduction in crude oil and processing requirement to produce gasoline due to the ability of nanomaterials to improve the selectivity of catalysts used
- Reduction in precious metal requirements for petroleum-refining catalysts
- Reduction in energy use by using advanced separations technology based on membrane nanotechnology

Automotive Industry

- Reduction in precious metal requirements for automobile catalysts
- Reduction in tool and die requirements since nanomaterials can produce more durable hard coatings on tool and dies

Trucking Industry

- Reductions in diesel fuel use by using nanomaterial combustion catalysts as a fuel additive

Maritime Industry

- Reduced fuel usage due to nanomaterial coatings that reduce ship bottom fouling thereby reducing drag
- Reductions in maintenance requirements due to nanomaterial coatings that provide longer wear characteristics on wear surfaces

Manufacturing Industry

- Reductions in tool and die requirements since nanomaterials can produce more durable hard coatings on tool and dies

Natural Gas Supply Industry

- Cost savings in removing N_2 and CO_2 from natural gas by using nanomaterial membranes

The benefits of using nanomaterials given in the examples above can be grouped into four general categories that cut across the various industries:

- Nanomaterials that can increase the selectivity and activity of catalysts because of the ability to control pore size and particle characteristics using nanotechnology
- Nanomaterials that reduce the precious metals requirements for catalysts because of the larger surface area presented by nano-sized particles. Also the possibility exists that cheaper nanomaterials, having the same catalytic effect as precious metals, could be substituted for precious metals.
- Nanomaterials that can produce more wear-resistant hard coatings and eliminate the need for chromium electroplating
- Nanomaterial membranes that can remove unwanted molecules from gasses or liquids or enable separations of different molecules because of the ability to control pore size and membrane characteristics using nanotechnology.

CATALYST USE IN THE CHEMICAL INDUSTRY

Three effects of using nanomaterials in catalysts in the chemical industry were identified: (1) more efficient catalysts produced through nanotechnology, (2) a reduction in the amount of precious metals required to produce the same catalytic effect, and (3) membranes used to effect the separation of various chemicals.

The basis for the cost reductions in the chemical industry due to more efficient nanomaterial catalysts was a report by PNNL[4] that examined the possible cost savings in producing the top 50 chemicals thanks to improved catalysts. In discussions with a catalyst expert at LANL,[5] it was determined that the primary effect of nanomaterial use in chemical production catalysts would be an improvement in the selectivity of the catalysts.

Table 1 presents the list of the top 50 chemicals. Those processes that don't use catalysts are highlighted in yellow. Using the expert's opinions,[5] the catalysts that could benefit from nanomaterials were identified. In Table 1 those catalysts that would not benefit from nanomaterials employment are highlighted in green. This leaves the unhighlighted chemicals as the processes using catalysts that could benefit from the use of nanomaterials. Table 1 gives the present selectivity of the catalyst in terms of a percentage of the maximum theoretical selectivity. The high end of the possible savings was calculated as follows:

- Assume that using nanomaterials would increase the catalyst's selectivity half of the difference between the present selectivity and the maximum theoretical selectivity (the values used for the new selectivity are shown in Table 1 as a percent of maximum theoretical efficiency).
- The cost savings for this assumed selectivity improvement for the top 50 chemicals were then calculated using a program supplied as part of the PNNL report.
- The cost savings due to improved selectivity also resulted in reduced feedstock requirements and reduced energy usage.
- The dollar savings themselves were subsequently calculated using the above reductions, present-day prices for the feedstocks,[6] and the chemical industry average energy cost.[6]

The results of these calculations are presented in Table 1. Extrapolations of the savings for the 50 top chemicals to industry-wide savings were computed as follows:

- The cost savings for the top 50 chemicals due to reduced energy use and reduced need for feedstock chemicals were about 1% of the total revenue from the top 50 chemicals.
- The total annual revenue from the chemical industry is ~ $400B per year.
- Assume that the 1% cost savings for the top 50 chemicals can be extrapolated to the whole industry.

This then produces a reduction of $4B per year in production costs for the chemical industry.

The PNNL program found the energy savings for the top 50 chemicals, assuming a 50% improvement in selectivity, was ~0.08 quad. The top 50 chemicals represent about 20% of the total chemical sales. Therefore, linearly extrapolating the energy savings from the top 50 chemicals to the entire chemical industry gives a savings of ~0.4 quad.

The low end of the savings range was calculated using the same methodology but with the assumption that the catalyst selectivity improved only 25% of the distance from the present selectivity to the theoretical selectivity. This resulted in a low-end estimate for the savings in the chemical industry of $2.5B in industry-wide savings and 0.2 quads in energy savings.

The reduction in the precious metal requirement for chemical industry catalysts could save an additional $22M per year, assuming that the anticipated 20% reduction in precious metal usage[7] in catalysts is achieved by using nano-size materials.[8]

It has been reported that if more efficient separations processes are utilized, the potential for energy savings in the chemical industry is ~1.2 X 10^{14} Btu per year.[9] One way to create a more effective separation process is to use membranes. These membranes would most likely be designed using nanotechnology and would probably contain nanomaterials. If we estimate that up to 25% of the potential energy savings could be realized using nanomaterial membranes, the cost savings to the chemical industry would be $70M per year.

The total savings for the chemical industry in these examples amounted to $2.5B to $4B per year. The energy savings for the entire chemical industry due to better catalytic selectivity and membrane use was estimated to be 2 X 10^{14} to 4 X 10^{14} Btu.

The REMI model, which translates direct economic changes into total impacts within the nation, was used to determine the probable impacts of the savings identified above on output, income, and employment. The REMI model used a reduction of $2.5B to $4B per year in the production costs for the chemical industry to arrive at total impacts. After just three years, the model calculated that $10B to $15B would be added to the total gross domestic product (GDP) due to these cost reductions in the chemical industry. Employment would increase by 150,000 to 240,000 jobs, and personal income would increase by $9B to $14B in these same three years

Table 1. TOP 50 CHEMICALS CATALYST IMPROVEMENT CALCULATIONS (Assuming a 50% Improvement in Selectivty)

🟨 Processes that do not use catalysts
🟩 Processes where nanotechnology would not improve catalyst performance

Chemical	Produced Using Catalyst?	Nanotech Increases Selectivity?	Old Selectivity (% of Theoretical)	New Selectivity (% of Theoretical)	Base Feedstock Losses from Theoretical (M lb/yr)	Feedstock Losses w New Selectivty (M lb/y)	Feedstock Cost ($/lb)	Feedstock Cost Savings ($M/yr)	Base Energy Loss from Theoretical (Q/yr)	Energy Loss w New Selectivity (Q/yr)	Net Energy Savings (Q/yr)
Sulfuric acid	Yes	Yes	99.5	99.75	476	320	0.115	18	0.0008	0.0006	0.0002
Nitrogen	No	-									0
Oxygen	No	-									0
Ethylene	No	-									0
Ammonia	Yes	Yes	99	99.5	625	601	0	0	0.2944	0.2919	0.0025
Lime	No	-									0
Phosphoric acid	No	-									0
Sodium hydroxide	No	-									0
Propylene	Yes	Yes	95	97.5	0	0	0	0	0.143	0.126	0.017
Chlorine	No	-									0
Sodium carbonate	No	-									0
Urea	No	-									0
Nitric acid	Yes	No	95								0
Ethylene dichloride	Yes	Yes	99	99.5	261	237	0.315	8	0.0203	0.0188	0.0015
Ammonium nitrate	No	-									0
Vinyl chloride	yes	No	98								0
Benzene	Yes	Yes	N/A								0
Ethylbenzene	Yes	Yes	99	99.5	29	15	0.315	4	0.0042	0.0032	0.001
MTBE	Yes	Yes	100	100							0
Carbon dioxide	No	-									0
Styrene	Yes	Yes	90	95	693	160	0.33	176	0.02	0.0173	0.0027
Methanol	Yes	Yes	99	99.5	155	116	0	0	0.0367	0.0362	0.0005
Formaldehyde	Yes	Yes	91	95.5	736	351	0.068	26	0.0061	0.0029	0.0032
Xylene	Yes	Yes	N/A								0
Toluene	Yes	Yes	N/A								0
Hydrochloric acid	No	-									0
p-Xylene	yes	Yes	70	85	841	0	0.33	278	0.0936	0.0648	0.0288
Terephthalic acid	Yes	Yes	90	95	660	660	0.35	0	0.0078	0.0061	0.0017
Ethylene oxide	Yes	No	80								0
Ethylene glycol	Yes	No	99								0
Ammonium sulfate	No	-									0
Cumene	Yes	No	99								0
Potash	No	-									0
Phenol	Yes	No	97								0
Acetic acid	Yes	No	99								0
Butadiene	Yes	Yes	90	95	1588	1331	0.34	87	0.0806	0.0704	0.0102
Carbon black	No	-									0
Acrylonitrile	Yes	Yes	66.5	83.25	654	71	0.3	175	0.0235	0.0096	0.0139
Propylene oxide	Yes	No	90								0
Vinyl acetate	Yes	No	90								0
Titanium dioxide	No	-									0
Acetone	Yes	Yes	90	95	N/A				0.0081	0.0075	0.0006
Cyclohexane	Yes	Yes	100	100	4	4	0.143	0			0
Aluminum sulfate	No	-									0
Sodium silicate	No	-									0
Adipic acid	Yes	No	90								0
Calcium chloride	No	-									0
Caprolactam	Yes	No	95								0
Sodium sulfate	No	-									0
Isobutylene	Yes	No	99								0
Total								**772**			**0.0838**

CATALYST USE IN THE REFINING INDUSTRY

A petroleum refinery is a highly integrated process producing a spectrum of products. This means that an increase in production of one particular product will probably result in the decreased production of others, especially where the effect of nanomaterial usage in the catalysts is the improvement of selectivity for a product. This study assumes that the refinery operation is optimized to produce gasoline. Therefore, if gasoline production of a refinery can be increased by use of better catalysts, the refinery would reduce its throughput so that the same amount of gasoline is produced.

Cost savings were achieved in the refining industry by improving the catalysts through the use of nanomaterials, by reducing the precious metal requirements for refinery catalysts when nanomaterials are utilized in the catalysts, and by using membranes to effect the separation of gas molecules for gas recovery.

Two effects of improved catalysts were examined: the reduction in temperature needed for catalytic processes and an increase in the production of gasoline from a barrel of crude. The savings for the reduced energy requirements because of reduced temperatures in catalytic processes were calculated as follows:

If the activity of a catalyst can be increased, this will allow a reduction in the temperature for the catalytic process and will keep the same output. A rough rule of thumb for the increase in activity for refinery catalytic processes is that the activity doubles for every 10°C increase in temperature.[5] Thus, if a catalyst can be designed to have twice the activity rate, the process temperature for the catalytic processes in a refinery can be lowered by 10°C and still have the same output. The savings in the refinery energy usage due to lower temperatures allowed by nanomaterial use in catalysts that results in catalysts with increased activity was calculated as follows:

- Assume that nanomaterials can increase the catalyst activity for refineries in the range of 50% to 100%. This would allow the catalytic processes to be run at temperatures 5°C to 10°C lower than present.
- The energy savings from the temperature reduction is assumed to be the energy required to raise the temperature of crude 5°C to 10°C, or 2,650 Btu/bbl to 10,750 Btu/ bbl.[10]
- The annual volume of material flowing through the various refinery catalytic processes is shown below for a total throughput for catalytic process of 8 X 10^9 bbl/year[11]:
  Catalytic Cracking - 1.9 X 10^9 bbl/year

Deep Catalytic Cracking –0.4 X 10^9 bbl/year
Catalytic Reforming –1.3 X 10^9 bbl/year
Hydrotreatment -- 3.9 X 10^9 bbl/year
Isomerization – 0.15 X 10^9 bbl/year
Esters Production – 0.08 X 10^9 bbl/year

- Assuming that the energy saved by the use of lower temperatures in catalytic processes all come from the consumption of crude oil at an energy content of 6 X 10^6 Btu/bbl,[10] the crude oil saved is 3.5 X 10^6 to 15 X 10^6 bbl per year or 2 X 10^{13} to 8 X 10^{13} Btu per year

Assuming a price of $60 per bbl of crude, the cost savings to the refinery industry of the reduced temperatures are $210M to $880M per year.

The savings gained by increasing the amount of gasoline from a barrel of crude due to better catalysts were computed as follows:

- Assume that the use of nanotechnology catalysts with better selectivity is projected to increase the amount of gasoline obtained from a barrel of crude by 2%.[12]
- This additional gasoline would result in a net savings of $0.30 to $0.50 per gallon when the costs associated with not producing alternative products are considered[13]
- About 8.8 billion gallons of gasoline are produced each year in US refineries.[11]

The combination of these assumptions then results in a $50M to $90M annual savings for the production of gasoline. Associated with this cost savings is an annual energy savings of 0.6 X 10^{14} to 1.2 X 10^{14} Btu, a reduction in wastewater production of 150 to 300 million gallons per year, and a reduction in toxic chemical emissions of 1 to 2 million pounds per year.[11]

The use of nano-sized particles in precious metal catalysts was estimated to result in a 20% reduction in the amount of precious material used in catalysts.[7] The 20% reduction in material use results in an annual savings of $10M.[8] If all the precious metal catalyst material could be replaced by “normal” material, a savings up to $50M could be realized in the refining industry.

The use of membranes for gas recovery could result in a potential energy savings of 1 X 10^{13} Btu per year.[9] Again, if we assume that this energy in a refinery was supplied by crude oil at $60 per barrel, the cost savings to the refinery industry would be $100M per year.

The total benefits identified with the use of nanomaterials in catalysts by the refining industry is $0.4B to $1.1B per year, with an additional annual reduction of 0.8 X 10^{14} 1.3 X 10^{14} Btu of energy usage, an annual wastewater reduction of 100 to 300 million gallons per year, and an annual toxic chemical emission reduction of 1 to 2 million tons.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $0.4B and $1.1B per year in the production costs for the refinery industry. After just three years, the model calculated that $0.8B to $2.2B would be added to the total GDP due to these cost reductions in the petroleum refining industry. Employment would increase by 10,000 to 30,000 jobs in these same three years, and personal income would increase by $0.9B to $2.2B.

AUTOMOBILE PRODUCTION COST SAVINGS

Two examples of savings in automobile production costs were identified: the reduction in precious metals required for automobile catalysts and the reduction in tool and die requirements due to improvements in hard coatings that use nanomaterials.

General Motors estimates that precious metal loadings on automobile catalysts can be reduced by 20% over the next few years largely through the use of nanomaterials.[7] This would result in a production savings for the US auto industry of $230M per year.[8] If automobile catalysts could be designed so as not to require precious metals at all, this savings could increase to $1.1B per year.[8]

The annual tool and die spending by the automobile industry is approximately $100M per year.[14] Nanomaterials used as hard coatings have the potential to double the tool and die lifetime.[15] If this can be realized, the result would be a $50M annual savings in the production costs for the automobile industry.

The combined savings for the automobile production industry would be $280M to $1,100M per year depending upon the amount of precious metal reduction.

There are many other applications of nanomaterials that can be used by the automobile industry, from better paints and plastics to tires. Freedonia projects a $800M per year market for nanomaterials in the automobile production industry.[1] Some of these other additional applications will result in better products while others will result in cost savings; therefore, the cost impact will be substantially larger than is presented here.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $280M to $1,100M per year for the automobile production industry. After just three years, the model calculated that $1.3B to $5B would be added to the total GDP due to these cost reductions. Employment would increase by 20,000 to 79,000 jobs in these same three years, and personal income would increase by $1.2B to $4.7B.

TRUCKING INDUSTRY COST SAVINGS

Tests using nanomaterials as combustion catalysts in diesel engines have indicated that in addition to reducing the amount of smoke that is emitted in diesel engines, it also results in improved diesel engine efficiency. The fuel efficiency can come from more efficient fuel combustion characteristics or by allowing the diesel engine to run leaner without exceeding EPA NOx standards.[16] The savings from this improved efficiency were computed as follows:

- Assume that the efficiency improvements for trucks will be 3% to 10% as has been reported.[17]
- Approximately $37B of diesel fuel is sold per year.[18]
- Assuming that 40% to 60% of this fuel is consumed by trucks that could use the nanomaterial catalyst, the result would be a cost reduction to the trucking industry of approximately $0.4B to $2B per year. Use of the nanomaterial catalyst would also result in an energy savings of 0.06 to 0.3 quads of energy per year.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $0.4B and $2B per year in the production costs for the trucking industry. After three years, the model calculated that $1.5B to $7.9B would be added to the total GDP due to these cost reductions. Also, in the same three years, employment would increase by 25,000 to 126,000 jobs, and personal income would increase by $1.3B to $7B.

MARITIME INDUSTRY SAVINGS

One of the problems ships encounter is that plant and animal life attach themselves to the bottom of the vessels, creating a rough surface that increases drag and consequently fuel usage. The coating used at present has a short half-life and some coatings are facing restrictions on their use because of environmental problems. The use of nanomaterial antifouling coatings can significantly reduce the amount of plant and animal life that attaches itself to the bottom of the ship. Nanomaterial coatings do not have the environmental issues present coatings are encountering. The savings from use of nanomaterial coatings were constructed as follows:

- The Navy has estimated that using antifouling coatings on naval vessels can save one million dollars per year per ship in fuel costs.[19]
- Using the 2002 price of fuel oil, this translates into an energy savings of about 2.0 X 10^{11} Btu per ship per year.
- Approximately 350 Navy ships are of the size that could achieve this level of benefit from the use of the

nanomaterial antifouling coating.[20] This would result in a savings to the Navy of approximately $350M per year in fuel costs. In addition, the Navy would see energy usage reductions of 7 X10^{13} Btu . The use of the nanomaterials for antifouling coatings also could save the Navy $46M in pollution abatement costs.[19]

Also, a study has determined that using nanomaterials to hard-coat propeller shafts on minesweepers (class/size of 900 to 1400 tons[20]) could result in an annual savings of a million dollars per ship.[21] This would result in an additional annual savings for the Navy of $350M.

Studies on the fuel savings on commercial ships have also been reported. These studies were used to calculate the savings to the maritime industry as follows:

- Commercial studies on antifouling coatings have indicated that about a 5% fuel savings can be realized by using these coatings.[22]
- Approximately 1.4 X 10^{15} Btu of fuel is supplied to the water freight sector of the economy[23] each year and it is approximately divided between 2.9 X 10^{14} Btu for diesel and 1.1 X 10^{15} Btu for heavy fuel oil.
- By using present prices[24] of these two fuels, a fuel savings of $340 million per year, or 7.5 X 10^{13} Btu per year could be potentially realized. Also, if the US Navy's experience holds, the US civilian maritime industry could reduce its pollution abatement costs up to $460M per year.

The maritime industry, as was the case for the US Navy, can also benefit from employment of nanomaterial hard coatings. The potential savings were calculated in a similar manner as above:

- There are approximately 3,800 US-flag cargo-carrying vessels over 1,000 gross tons.[25]
- Assuming that these ships could receive one-quarter to one-half ($250,000 to $500,000 per ship) of the cost reduction that the Navy anticipates for hard-coating minesweepers, the maritime industry as a whole could reduce its maintenance costs by $950M to $1,900M per year.

By summing these cost effects, an approximate $1.7B to $2.6B per year in cost savings would accrue for the US maritime industry.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $1.7B and $2.6B per year in the production costs for the maritime industry. After just three years, the model calculated that $4.3B to $6.7B would be added to the total

GDP due to these direct cost reductions. In addition, over these same three years, employment would increase by 73,000 to 110,000 jobs, and personal income would increase by $4.6B to $7.0B.

MANUFACTURING COST SAVINGS

The use of nanomaterials in hard coatings is predicted to reduce the need for chrome electroplating while simultaneously producing a coating on wear surfaces that has the potential to last twice as long as the current chrome electroplating. A cost-benefit analysis of using nanomaterials for hard coatings on the landing gear of C-130s indicated that the direct cost of using nanomaterials was slightly less expensive than the traditional electroplating, resulting in an annual savings of $100 per C-130 in the U.S. military fleet.[26] However, there are additional benefits not analyzed in that study. The parts that had been hard coated with nanomaterials had a significantly longer lifetime and eliminated the toxic emissions associated with the chromic acid used presently in the hard-coating process.

The cost savings to the manufacturing sector consist of two parts: the reduction in the need for chromic acid for electroplating and the increased lifetime of the tools and dies used in manufacturing.

The cost savings due to the reduced need for chromic acid were calculated as follows:

- Hard-coated parts examined in the cost-benefit study normally required 13,000 lb of chromic acid a year. Using nanomaterials eliminated the need for this chromic acid and also saved $200,000 per year.[26]
- This translates to a savings of $1.54 per pound of chromic acid that was normally used for electroplating
- Approximately 52,600 tons of chromic acid is produced per year, 22% of which is used for electroplating.[27]
- Assuming 50% to 100% of the chromic acid demand could be eliminated, the result would be a $175M to $350M savings within the manufacturing industry as a whole for the reduced need for chromic acid.

Hard coating is used extensively in the production of cutting tools and in tool and dies. Cost savings would be seen in the manufacturing industry when nanomaterials were used to hard-coat these tools and dies because nanomaterial hard coating is projected to last twice as long as the normal coating, thereby doubling the lifetime of the tools and dies. The industry savings from employment of the nanotechnology coatings in the tools and dies was calculated as follows:

- The total market for cutting tools is $5B per year[28] and $8B for tool and dies per year.[29]
- Assume that nanomaterials can double the lifetime of cutting tools and tool and dies.

- Also assume that 25% to 50% of the cutting tools and tool and dies could use nanomaterials.

Using these assumptions results in the reduction of the manufacturing sector's costs for cutting tools and tools and dies by 12.5% to 25%. This would then result in a savings to the manufacturing sector of $1.6B to $3.2B per year. This dollar savings, plus the reduction in cost from not using chrome electroplating, would reduce manufacturing costs by $1.7B to $3.5B per year.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $1.7B and $3.5B per year in the production costs for the manufacturing industry. After just three years, the model calculated that between $10B and $21B would be added to the total GDP due to these cost reductions. Employment would increase by 150,000 to 310,000 jobs after the same three years, and personal income would increase by $14B to $19B.

NATURAL GAS SUPPLY SAVINGS

Approximately 22% of the natural gas produced in the United States requires the removal of CO_2 or N_2, or both before it can be distributed through pipelines.[30] The use of membranes incorporating nanomaterials is estimated to allow the removal of these two contaminates at a reduced cost from the present methods.

The cost savings for removing N_2 from natural gas were computed as follows:

- Subtract the cost of removing N_2 using nanomaterial membranes from the cost of removing N_2 using present technology.

The cost of removing N_2 using present technology was estimated in the following manner:

- Some natural gas wells are not operated because the cost of removing N_2 from the gas plus the production cost is greater than the price for the natural gas.[30]
- Assume the present removal technology costs at various sites for removing N_2 from the natural gas from contaminated wells are distributed linearly from 0 to the point at which cleaning the gas is not economic.
- Using this assumption, the average price of removing N_2 would then be one-half of the difference between the selling price and the production cost.
- The selling price of natural gas minus the cost of production is $2.28 per thousand cu ft.[31,32]

- With the above assumptions, the present cost of removing N_2 is approximately $1.14 per thousand cu ft.

The cost savings for removing N_2 using nanomaterial membranes can then be determined as follows:

- The cost of N_2 removal using nanomaterial membranes is $0.28 per thousand cu ft.[30]
- The savings for removing N_2 from natural gas using nanomaterial membranes can then be estimated to be $1.14 minus $0.28, or $0.86 per thousand cu ft.

To obtain the costs of removing CO_2 from natural gas using present technology, the following assumptions and procedures were used:

- The present cost of removing CO_2 is less than the cost of removing N_2.[30]
- Because the removal cost for CO_2 is lower than for N_2, the average cost of removing CO_2 is less than the halfway point described above for N_2.
- Considering the previous statements, we assume that today's cost of removing CO_2 is 25% to 50% of the difference between the production cost and the selling price.
- Further, the selling price of natural gas minus the cost of production is approximately $2.28 per thousand cu ft.[31,32]
- This then results in an average cost estimate of $0.57 to $1.14 per thousand cu ft using present technology to remove CO_2.

The cost savings for removal of CO_2 using nanomaterial membranes were determined using the following information and assumptions:

- The cost of CO_2 removal using nanomaterial membranes is $0.18 per thousand cu ft.[30]
- The savings for removing CO_2 from natural gas using nanomaterial membranes can then be estimated to be $0.57 to $1.14 minus $0.18, or $0.39 to $0.96 per thousand cu ft.

Using the above assumptions, the industry-wide savings accrued from using nanomaterial membranes to remove CO_2 and N_2 from natural gas can be calculated as follows:

- Removing CO_2 would yield an estimated savings of $0.39 to $0.96 per thousand cu ft
- Removing N_2 would yield an estimated savings of $0.86 per thousand cu ft.
- For natural gas that contains both N_2 and CO_2, the savings would be the present cost of removing N_2 ($1.14 per thousand cu ft) minus the cost of removing both N_2

and CO_2 ($0.28 plus $0.18 per thousand cu ft), resulting in a cost savings of $0.68 for removing both contaminates.

- About 8.8 X 10^9 thousand cu ft of natural gas is produced in the United States per year.[31]
- Approximately 11% of the natural gas supply is contaminated with N_2 and approximately 22% is contaminated with CO_2.[30]
- If none of the natural gas is contaminated with both N_2 and CO_2, the annual savings would be $1.6B to $2.7B per year. If all of the natural gas contaminated with N_2 is also contaminated with CO_2, the annual cost saving would be $1.0B to $1.6B per year. Thus, the range of annual cost savings for using nanomaterial membranes would be $1.0B to $2.7B per year.

The REMI model was used to determine the total economic impact of the savings identified above: a reduction of $1.0B and $2.7B per year in the production costs for the natural gas supply. After just three years, the model calculated that $2.1B to $5.8B would be added to the total GDP due to these cost reductions in this portion of natural gas supply. In the same three years, employment would increase by 31,000 to 85,000 jobs, and personal income would increase by $2.2B to $5.9B.

SUMMARY

This report has examined some examples of the possible cost savings that could be achieved by using nanomaterials in catalysts, coatings, and membranes. Table 2 presents a summary of these results. Obviously, there are many more examples where the use of nanomaterials will result in production cost savings, and the total impact on the economy of using nanomaterials would be considerably larger than is represented in these few examples.

Table 2 Summary of Results of Nanomaterial Savings

Example	Cost Savings ($B per Year)	GDP Increase after 3 Years (Billions of $)	Employment Increase after 3 Years (000's of Jobs)	Personal Income Increase after 3 Years (Billions of $)	Energy Savings (Quads per Year)	Waste Reduction per Year
Chemical Catalysts Selectivity Increase	2.5 to 4.0	10 to 15.	150 to 240	9 to 14.	0.2 to 0.4	
Chemical Catalysts Precious Metal Reductions	0.02				--	
Chemical Use of Membranes for Separations	0.07				0.03	
Refinery Catalysts Precious Metal Reductions	0. 01 to 0.05	0.8 to 2.28	10 to 30	0.9 to 2.2	--	100 to 300M gal. of wastewater 1 to 2M tons toxic emissions
Refinery Process Temperature Reductions	0.2 to 0.9				0.02 to 0.08	
Refinery Catalysts Selectivity Increases	0.05 to 0.09				0.06 to 0.12	
Refinery Use of Membranes for Gas Separation	0.08				0.001	
Automobile Catalysts Precious Metal Reductions	0.3 to 1	1.3 to 5	20 to 80	1.2 to 5	--	
Trucking Industry Fuel Combustion Catalysts	0.4 to 2	1.5 to 8	25 to 130	1.3 to 7	0.06 to 0.3	
US Navy Antifouling Coating Fuel & Pollution Abatement Savings	0.7				0.07	$46M in pollution abatement costs
US Navy Nanomaterial Hard-Coating Savings	0.35				--	
US Shipping Industry Antifouling Coating Fuel & Pollution Abatement Savings	0.8	4 to 7	70 to 110	5 to 7	0.08	Up to $460M in pollution abatement costs
US Shipping Industry Nanomaterial Hard-Coating Savings	1 to 2				--	6,000 to 12,000 tons of chromic acid
Manufacturing Industry Hard-Coating Savings	2 to 3.5	10 to 20	150 to 300	14 to 20		
Natural Gas N_2 and CO_2 Removal by Membranes	1 to 3	2 to 6	30 to 85	2 to 6	--	

REFERENCES

1. Hayes, T. L., Richardson, M. B., Bayrer, R. L., Lent, J. J., and Mushenheim, A. "Industry Study 1677 NANOMATERIALS," The Freedonia Group, Inc., Cleveland, OH, 2003.
2. REMI Policy Insight (version 5.5), Regional Economic Models, Inc., copyright 1982, 1987-2000.
3. US data from the RIMS II model (Bureau of Economic Analysis) using 1997 data.
4. Tonkovich, A. L. Y. and Gerber, M. A.,"The Top 50 Commodity Chemicals: Impact of Catalytic Process Limitations on Energy, Environment, and Economics," Pacific Northwest Laboratory, PNL-10684, Richland WA, August 1995.
5. Kevin Ott, Los Alamos National Laboratory, personal communication, July 2004.
6. "Chemical Marketing Reporter," ICIS Publication, Jan. 10, 2005. Vol. 267 No. 2 pp20-22
7. Stundza, T., "GM to Reduce Platinum Use in Autocatalysts by 17%," *Purchasing*, **131(20)**, 164B(Dec, 12, 2003).
8. Platinum 2004 (available URL: http://www.platinum.matthey.com/publications/1084795390.html).
9. Oak Ridge National Laboratory, GCS, Incorporated, "Materials for Separation Technologies: Energy and Emission Reduction Opportunities" (Draft) Dec. 13, 2004.
10. Gains, L. L. and Wolsky, A. M., "Energy and Materials Flows in Petroleum Refining," Argonne National Laboratory, ANL/CNSV-10, Feb. 1981.
11. Energetics Inc., "Energy and Environmental Profile of the U.S. Petroleum Refining Industry," prepared for the US Department of Energy Office of Industrial Technologies, December 1998.
12. Engelhard Corp., "NaphthaMax® Catalysts Overview" (available URL: http://www.engelhard.com/Lang1/xDocIDD9A2D6D5B8324FDDAD74C7406476F852/xDocTable_Product/Tab_Overview/TechnologyClassIDD2F7DE9A40BC413291D99F3AFC95BC19/MarketID0/TechnologyID0/ApplicationID56D278D1549D4BFD9B633E1B1CC9D451/up1/SubSiteID0).
13. David DePaoli, Oak Ridge National Laboratory, & Members of Vision 2020 committee, personal communication April 2005.
14. US Census Bureau, "Motor Vehicle Metal Stamping: 2002," 2002 Economic Census, Manufacturing, Industry Series, August 2004.
15. Sartwell, B. D., Natishan, P. M., and Singer, I. L., Naval Research Laboratory, Legg, K. O. Rowan Catalyst, Inc., Schell, J. D., GE Aircraft Engines, and Sauer, J.

P., Metcut Research Inc., "Replacement of Chromium Electroplating Using HVOF Thermal Spray Coatings."

16. Prof. Nigel Clark, Department of Mechanical and Aerospace Engineering, University of West Virginia, personal communication, Feb. 2005.
17. Leavitt, W., "Show and Tell for Skeptics," *Fleet Owner*, **98(8)**. 80 (Aug. 2003).
18. US Census Bureau, "Petroleum Refineries: 2002," 2002 Economic Census, Manufacturing, Industry Series, Sept. 2004.
19. Paul, R., Wolfe. J., Hebert, P., and Sinkula, M., "Investing in Nanotechnology, *Nature Biotechnology*, **21(10),** Oct 2003.
20. Jane, F. T., *Jane's Fighting Ships 2003*-2004, Commodore S. Saunders Ed., Jane's Information Group, Alexandra, VA
21. Frost and Sullivan, " Nanotechnology Industry Impact Research Service, D254." Research Report
22. "2003: Antifouling product and technology guide," *Propeller International*, Issue 15, Akzo Nobel, Jan. 2003
23. Davis, S. C and Diegel, S. W., "Transportation Energy Data Book: Edition 22," Oak Ridge National Laboratory, ORNL-6967, Sept. 2002.
24. US Department of Energy, Energy Information Agency, "Receipts and Average Delivered Cost of Petroleum by Type of Purchase, Fuel Type, Census Division and State, 2000" (available URL: http://www.eia.doe.gov/cneaf/electricity/cq/t8p1.html).
25. US Maritime Administration, "US-Flag Cargo Carrying Fleet by Area of Operation"(available URL: http://www.marad.dot.gov/MARAD_statistics/USCCF_7-02.htm).
26. Sartwell, B. D., Legg, K. O., Schell, J. Sauer, and J. Natishan, P., "Validation of HVOF WC/Co Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear," Naval Research Lab, NRL/MR/6170-04-8762, Washington, DC, March 2004.
27. Chemical Marketing Reporter, "Chromic Acid" (available URL: http://www.the-innovation-group.com/ChemProfiles/Chromic%20Acid.htm).
28. US Census Bureau, "Machine Tool (Metal Cutting Types) Manufacturing: 2002," 2002 Economic Census, Manufacturing, Industry Series.
29. US Census Bureau, "Special Die and Tool, Die Set, Jig, and Fixture Manufacturing; 2002," 2002 Economic Census, Manufacturing, Industry Series.
30. Daiminger, U. and Lind, W., "Adsorption Processes for Natural Gas Treatment, A Technology Update," Engelhard Corp. (available URL: http://www.engelhard.com/Lang1/xDocID1B2748B565B140CA9F708C089C524D46/xDocTable_Product/Tab_Overview/Technolog

yClassIDF9D47DC8D3154D468EC1C25264275960/MarketID0/TechnologyIDAD428B04AA3741F68373A7430ABBEEB7/ApplicationIDE3475C2AD2C140AA89FFE3317549E58C/up1/SubSiteID0).

31. US Department of Energy, Energy Information Administration, “Table 12. Average Prices, Sales, and Production in Oil and Natural Gas for FRS Companies 2002-2003” (available URL: http://www.eia.doe.gov/emeu/perfpro/tab12.html)
32. US Department of Energy, Energy Information Administration, “Table 11. Income Components and Financial Ratios in Oil and Natural Gas Production for FRS Companies, 2002-2003 ” (available URL: http://www.eia.doe.gov/emeu/perfpro/tab11.html)