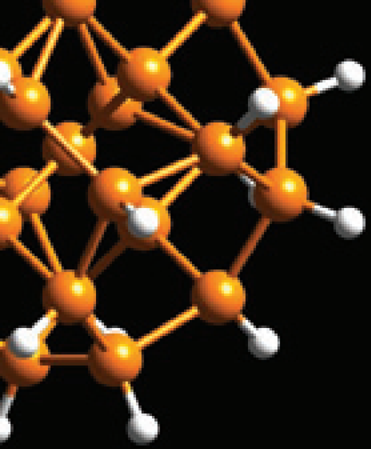

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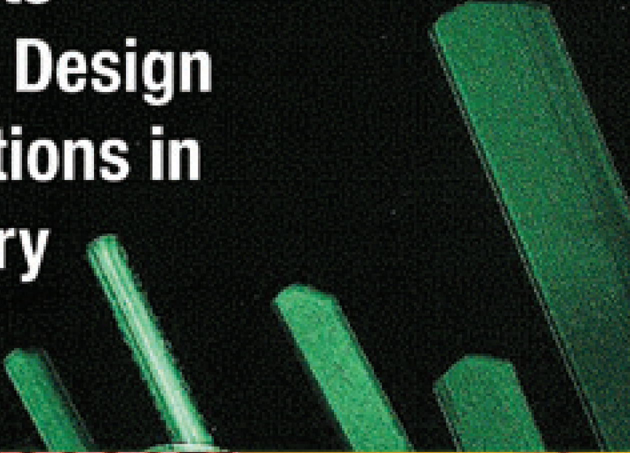

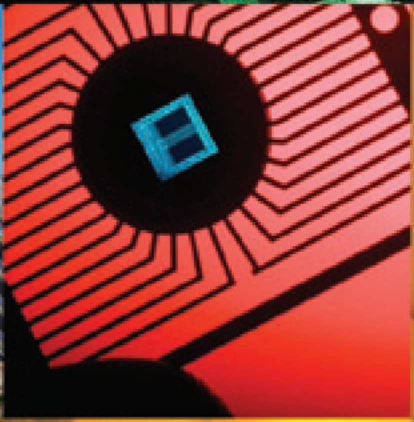

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ESTIMATED ENERGY SAVINGS AND FINANCIAL IMPACTS OF NANOMATERIALS BY DESIGN ON SELECTED APPLICATIONS IN THE CHEMICAL INDUSTRY

March 2006

Prepared by:
Los Alamos National Laboratory

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Chemical Industry Vision2020
Technology Partnership

U.S. Department of Energy
Industrial Technologies Program

**Approved and Issued by the
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Foreword

This study was commissioned by the Chemical Industry Vision 2020 Technology Partnership to supplement the December 2003 roadmap, *Chemical Industry R&D Roadmap for Nanomaterials By Design: From Fundamentals to Function.* This document provides information useful for prioritizing nanotechnology R&D by estimating some of the potential impacts that nanotechnology could have on energy efficiency, economic competitiveness, waste reduction, and productivity, for the chemical and related industries.

This study was carried out by Los Alamos National Laboratory (LANL), which is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. Much of the information contained in this report has been published in the LANL report: Gary Thayer, J. Fred Roach, and Lori Dauelsberg, "Some Examples of the Economic Effect of Nanomaterials Produced by the Chemical Industry" Los Alamos LA-UR-05-1150, April 2005. Funding for the project was provided by the Chemicals Plus Program of the Industrial Technologies Program in the DOE Office of Energy Efficiency and Renewable Energy.

The study was guided by input from the Research Focus Working Group of the National Nanotechnology Initiative Chemical Industry Consultative Board for Advancing Nanotechnology (NNI-ChI CBAN). The NNI-ChI CBAN was established in March 2004 by the National Nanotechnology Initiative (NNI), the Council for Chemical Research (CCR), and Chemical Industry Vision2020. The goals of this partnership include planning and support of collaborative activities in key R&D areas, identifying and promoting new R&D for exploratory areas, and expanding nanotechnology R&D. NNI-ChI CBAN has chartered two working groups: a Research Focus area working group, and an Environmental Safety and Health (ESH) working group. These working groups have broad participation from industry, government researchers, NNI, and other groups.

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Executive Summary

The production of nanomaterials by the chemical industry is projected to surpass $1B by 2007 and to reach $35B by 2020.[1] These nanomaterials will find uses in a wide range of applications and industries. Because of the widespread use of nanomaterials, this economic impact will not be confined to the chemical industry, but will be felt throughout numerous other industries. This study considers a few examples of the economic impact of three types of nanomaterials: catalysts, coatings, and membranes in selected applications. These areas represent about $4B, or roughly 10%, of the $35B projected 2020 market for nanomaterials.[1] Selected applications were considered in seven of the largest expected target industries for these materials – energy (petroleum refining and natural gas supply), transportation (automotive, trucking and maritime), manufacturing, and chemicals production.

This study provides a preliminary analysis of the potential impact that nanotechnology could have on energy efficiency, economic competitiveness, waste reduction, and productivity, in the chemical and related industries. It semi-quantitatively estimates the potential benefits to the U.S. economy of products manufactured by the chemical industry using nanoscale technologies, and through the use of nano-derived products by the chemical industry and its customers. The projected technical impact and market penetration of each application was estimated, and an established economic model was employed to estimate the value created.

This restrictive study indicates that adoption of nanoscale technologies in the U.S. chemical industry can be expected to generate significant benefits. For the limited set of evolutionary applications considered in this study, value creation is estimated to be $10-20 billion/year, and energy savings are estimated to be 0.5 to 1.1 X 10^{15} Btu/year. While there is significant uncertainty in any projection, these values may be seen as representative of the magnitude of the potential impact of nanotechnology research on the chemical industry. It is probable that the total impact will be considerably larger because there are many more potential applications of nanotechnology than the examples considered in this study.

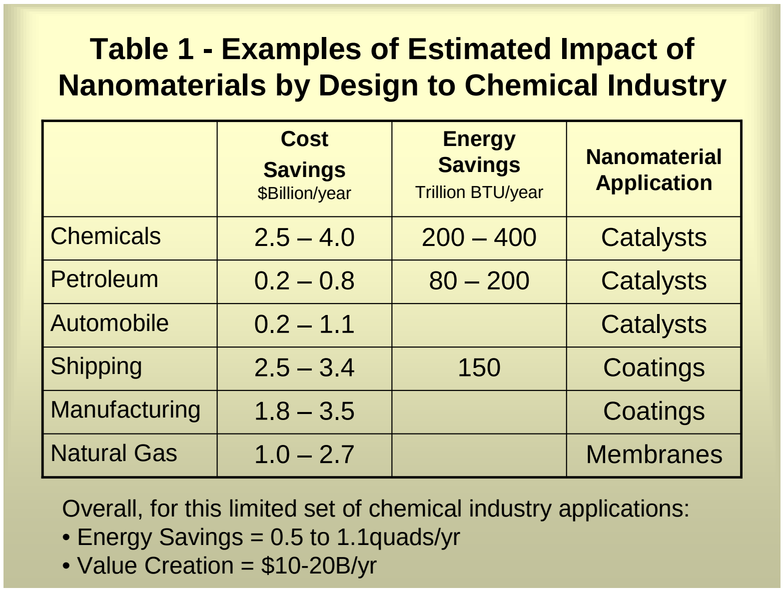

Table 1 - Examples of Estimated Impact of Nanomaterials by Design to Chemical Industry

	Cost Savings $Billion/year	**Energy Savings** Trillion BTU/year	**Nanomaterial Application**
Chemicals	2.5 – 4.0	200 – 400	Catalysts
Petroleum	0.2 – 0.8	80 – 200	Catalysts
Automobile	0.2 – 1.1		Catalysts
Shipping	2.5 – 3.4	150	Coatings
Manufacturing	1.8 – 3.5		Coatings
Natural Gas	1.0 – 2.7		Membranes

Overall, for this limited set of chemical industry applications:
- Energy Savings = 0.5 to 1.1quads/yr
- Value Creation = $10-20B/yr

1. Introduction

Nanoscale materials present a tremendous opportunity for U.S. industry to introduce a host of new products that could energize our economy, solve major societal problems, revitalize existing industries, and create entirely new businesses. In particular, the chemical industry represents a major prospect for substantial, near-term adoption of nanoscale technologies with sustained benefits. The U.S. chemical industry generates more than 70,000 diverse products ranging from everyday items to materials used in high-technology industries such as electronics, biotechnology, and pharmaceuticals. Products of the chemical industry are essential to key industries, including health care, communications, food, clothing, housing, energy, electronics, and transportation. Importantly, the chemical industry employs materials and processes particularly suited to improvement through application of nanoscale technologies.

The scope of this study is based upon the *Chemical Industry R&D Roadmap for Nanomaterials By Design: From Fundamentals to Function* and through subsequent input and review of the Research Focus working group of the NNI-ChI CBAN (National Nanotechnology Initiative-Chemical Industry Consultative Board for Advancing Nanotechnology). The applications of nanomaterials in catalysts, coatings, and membranes in seven industries were examined. Based on data available in the literature for the technical impact of nanotechnologies, both costs and energy savings were calculated in a variety of processes in selected industries. The REMI Policy Insight Model was used to estimate the impact of these cost and energy savings on changes in GDP (Gross Domestic Product), employment and personal income three years after adoption.

Since this study projects into the future, and because of the lack of specific information on industry-wide effects, the numbers given in this report have a large degree of uncertainty associated with them. In general, for input estimates obtained from references, point estimates without uncertainties were used in calculations. In some cases, the uncertainty associated with the final numbers is indicated by a range in estimated values, such as what percent of the particular industrial applications could economically use the nanomaterials.

2. Methodology

The first step in this study was to gather quantitative information on the cost or energy impacts of applications of nanotechnology in specific industries. The types of savings found in these specific applications were then extrapolated to broader applications both within and between industries. For example, estimates of the fuel savings expected from nanomaterial coatings on specific naval vessels were used to estimate savings for other classes of naval vessels, and then for the U.S. maritime fleet.

This analysis found the following 16 examples in seven industries of nanomaterial applications:

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 use in catalysts
- Reduction in energy use due to the incorporation of advanced separations processes based on membrane nanotechnology in the production of chemicals

Petroleum Refining

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

Automotive Industry

- Reduction in precious metal requirements for automobile catalysts
- Reduction in tool-and-die requirements, because nanomaterials can produce more durable hard coatings on these components

Trucking Industry

- Reduction in diesel fuel use from using nanomaterial combustion catalysts as fuel additives

Maritime Industry

- Reduced fuel use due to nanomaterial coatings that reduce fouling on ship bottoms, thereby reducing drag in both the U.S. Navy and the U.S. shipping industry
- Reductions in maintenance requirements due to nanomaterial coatings that provide longer wear characteristics on wear surfaces in both the U.S. Navy and the U.S. shipping industry

Manufacturing Industry

- Reduction in tool-and-die requirements, because nanomaterials can produce more durable hard coatings on these components

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 three general categories that cut across the various industries:

- Catalysts with increased selectivity and activity, developed through enhanced fundamental understanding of catalytic mechanisms and the anticipated capability for molecular-level control of catalyst structure (e.g., pore size, surface functionalization, etc.). Such catalysts developed through the application nanoscale science may reduce or eliminate the precious metals requirements for catalysts.
- Nanoscale materials that can produce more wear-resistant hard coatings and eliminate the need for chromium electroplating, or that can produce antifouling coatings to improve performance of marine vessels.
- Nanomaterial membranes that can remove unwanted molecules from gases or liquids or enable separation of different molecules because of the ability to control pore size and membrane characteristics using nanotechnology.

During the analysis, other opportunities for waste reduction, such as decreased wastewater or process chemical use, resulting from the use of nanomaterials were also tabulated. No economic value was assigned to these non energy-saving applications of nanomaterials.

Cost reductions estimated from the applications of nanomaterials for each industry were then input into the demonstration model of REMI,[2] an economic model that calculates the impact of these cost savings on the entire U.S. economy. REMI calculates cumulative impacts on GDP, employment, and personal income three years after initial savings are incurred. 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. More information on the REMI model and a list of organizations that have used REMI are provided in Appendix A.

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 REMI. Since the REMI model is more applicable to the type of problem encountered in this study, the 3-year cumulative economic impacts as calculated by REMI are reported.

3. Nanomaterials Use in the Chemical Industry

Three examples of beneficial use of nanomaterials in the chemical industry were identified: more efficient catalysts produced through nanotechnology, a reduction in the amount of precious metals required to produce the same catalytic effect, and membranes used to effect the separation of various chemicals.

3.1 Catalysts for Increasing Selectivity

Estimates of cost reductions in the chemical industry due to more efficient nanomaterial catalysts are based on a report by Pacific Northwest National Laboratory (PNNL)[4] that examined the possible cost savings in producing the top commodity 50 chemicals via the use of improved catalysts. Discussions with a catalyst expert at Los Alamos National Laboratory (LANL),[5] determined that the primary effect of nanomaterial use in chemical production catalysts would be an improvement in the selectivity of the catalysts.

Table 2 lists the top 50 chemicals and the present selectivity of the catalyst used for producing each one 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 by 50% of the difference between the present selectivity and the maximum theoretical selectivity. (The values used for the new selectivity are shown in Table 2 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 with the PNNL report.
- The cost savings due to improved selectivity also resulted in reduced feedstock requirements and reduced energy use.
- The dollar savings themselves were subsequently calculated using the above reductions, present-day prices for the feedstocks,[6] and the average energy cost for the chemical industry.[6]

The results of these calculations are presented in Table 2. The majority of the potential savings lies in the production of styrene, p-xylene, butadiene, and acrylonitrile. 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 generated.

The total annual revenue from the chemical industry is ~$400B per year. If the 1% cost savings for the top 50 chemicals can be extrapolated to the whole industry, a reduction of $4B per year in production costs for the chemical industry is possible.

The PNNL program found that the energy savings for the top 50 chemicals, assuming a 50% improvement in selectivity, were ~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 by only 25% of the difference between present selectivity and 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 quad in energy savings.

3.2 Catalysts for Reducing Precious Metal Use

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 use[7] in catalysts is achieved by using nanoscale materials.[8]

3.3 Membrane Use in Separations

If more efficient separations processes are utilized, the potential for energy savings in the chemical industry is around 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% (0.03 quad) of the potential energy savings could be realized using nanomaterial membranes, the cost savings for the chemical industry would be $70M per year.

3.4 Overall Impact of Nanomaterials in the Chemical Industry

The total savings for the chemical industry in the above examples amounted to $2.5B to $4B per year. The energy savings for the entire chemical industry from better catalytic selectivity, reduced use of precious metal in catalysts, and membrane use were estimated to be 0.2 to 0.4 quad.

The REMI model was used to determine the probable impacts of the savings in the chemicals industry (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 3 years, the model calculated that $10B to $15B would be added to the total 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 3 years.

Table 2. Catalyst Improvement Calculations for Top 50 Chemicals (Assuming a 50% Improvement in Selectivity)

🟨 Processes that do not use catalysts ☐ Processes where nanotechnology can improve performance

🟩 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 with New Selectivity (M lb/yr)	Feedstock Cost ($/lb)	Feedstock Cost Savings ($M/yr)	Base Energy Loss from Theoretical (Q/yr)	Energy Loss with 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

Table 2. (continued))

🟨 Processes that do not use catalysts

⬜ Processes where nanotechnology can improve performance

🟩 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 with New Selectivity (M lb/yr)	Feedstock Cost ($/lb)	Feedstock Cost Savings ($M/yr)	Base Energy Loss from Theoretical (Q/yr)	Energy Loss with New Selectivity (Q/yr)	Net Energy Savings (Q/yr)
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**			**0.084**

4. Nanomaterial Use in the Refining Industry

A petroleum refinery is a highly integrated process producing a spectrum of products from the same feedstock. Cost savings are expected to be achieved in the refining industry by improving the activity of catalysts through the use of nanomaterials both by the reduction in temperature needed for catalytic processes, and by an increase in the production of gasoline from a barrel of crude. These savings can be achieved by reducing the precious metal requirements for refinery catalysts when nanomaterials are utilized in the catalysts, and by using membranes to effect improved separation of gas molecules for gas recovery.

4.1 Catalysts for Reducing Process Temperature

The savings from reduced energy use resulting from reduced temperature requirements in catalytic processes were calculated as follows.

An increase in the activity of a catalyst will allow a reduction in the temperature for the catalytic process while maintaining 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^{o}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^{o}C and still have the same output.

Assuming that nanomaterials can increase the catalyst activity for refineries in the range of 50 to 100%, nanomaterials will allow the catalytic processes to be run at temperatures 5 to 10^{o}C lower than those presently used.

The energy savings from the temperature reduction are assumed to be the energy required to raise the temperature of crude by 5 to 10^{o}C, or 2,650 to 10,750 Btu/bbl.[10]

The annual volume of material flowing through the various refinery catalytic processes is shown below and amounts to a total throughput for the 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 comes 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 $45 per barrel of crude, the cost savings for the refinery industry from reduced temperatures are $160M to $660M per year. Recent increases in crude oil prices will increase the magnitude of these savings.

4.2 Catalysts for Increasing Selectivity

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

- Assume that nanotechnology catalysts with better selectivity will 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 is produced each year in U.S. refineries.[11]

Based on these combination of assumptions, annual savings of $50M to $90M for the production of gasoline can be expected. Associated with this cost savings is an annual energy savings of 0.06 X 10^{15} to 0.12 X 10^{15} 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]

4.3 Catalysts for Reducing Precious Metal Use

The use of nanosized 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, up to $50M in savings could be realized in the refining industry.

4.4 Membranes in Gas Recovery

The use of membranes for gas recovery could result in a potential energy savings of 0.01 X 10^{15} Btu per year.[9] Again, if we assume that this energy in a refinery was supplied by crude oil at $45 per barrel, the cost savings to the refinery industry would be $75M per year.

4.5 Overall Impact of Nanomaterials in the Refining Industry

The total benefits identified from the application of nanomaterials in catalysts and membrane separation in the refining industry is $0.3B to $0.9B per year, with an additional annual reduction of 0.08 to 0.13 quad 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 determined the total economic impact in the production costs for the refinery industry to be savings of $0.3B and $0.9B per year. After just 3 years, the model calculated that $0.6B to $2B would be added to the total GDP due to these cost reductions in the petroleum refining industry. Employment would increase by 8,000 to 25,000 jobs in these same 3 years, and personal income would increase by $0.7B to $2B.

5. 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.

5.1 Catalysts for Reducing Precious Metal Use

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 U.S. auto industry of $230M per year.[8] If automobile catalysts could be designed so that no precious metals were required, this savings could increase to $1,100M per year.[8]

5.2 Hard Coatings for Improving Die Casting

The tool-and-die spending by the automobile industry is approximately $100M per year.[14] The use of nanomaterials as hard coatings has 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.

5.3 Overall Impact of Nanomaterial Use in Automobile Production

The combined savings for the automobile production industry would be $280M to $1100M per year, depending upon the amount of precious metal reduction.

Many other applications of nanomaterials can be used by the automobile industry, from better paints and plastics to tires. Freedonia projects a market of $800M per year for nanomaterials in the automobile production industry.[1] Some of these 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 determined the total economic impact for the automobile production industry to be savings of $280M to $1,100M per year. After just 3 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 3 years, and personal income would increase by $1.2B to $4.7B.

6. 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 by diesel engines, such use also results in improved diesel engine efficiency. The fuel efficiency can result from achieving more efficient fuel combustion characteristics, or by allowing the diesel engine to run leaner without exceeding U.S. Environmental Protection Agency (EPA) NO_x standards.[16]

6.1 Catalysts for Improved Combustion

The savings from this improved efficiency were computed as follows:

- Assume that the efficiency improvement for trucks will be 3 to 10%, as has been reported.[17]
- At present, approximately $37B worth 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 quad per year.

6.2 Overall Impact of Nanomaterial Use in the Trucking Industry

The REMI model determined the total economic impact for the trucking industry to be savings of $0.4B and $2B per year in the production costs. After 3 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 3 years, employment would increase by 25,000 to 126,000 jobs, and personal income would increase by $1.3B to $7B.

7. Maritime Industry Savings

One of the problems ships encounter is that plant and animal life attaches to the bottom of the vessels, creating a rough surface that increases drag and consequently, fuel use. Current vessel coatings have 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 material that attaches to the bottom of the ship. Nanomaterial coatings do not have the same environmental problems as current coatings.

7.1 Antifouling Coatings

The savings from the use of nanomaterial coatings were computed as follows:

- The Navy has estimated that using antifouling coatings on naval vessels can save 1 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 savings for the Navy of approximately $350M per year in fuel costs. In addition, the Navy would realize energy use reductions of 0.07 X 10^{15} Btu. Furthermore, the use of nanomaterials for antifouling coatings could save the Navy an additional $46M in pollution abatement costs.[19]

Studies on fuel savings for 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 each year, [23] and it is divided (approximately) between 0.29 X 10^{15} Btu for diesel and 1.1 X 10^{15} Btu for heavy fuel oil.
- By using present prices of these two fuels,[24] a fuel savings of $340 million per year, or 0.075 X 10^{15} Btu per year, could be potentially realized. Also, if the U.S. Navy's experience holds, the U.S. civilian maritime industry could reduce its pollution abatement costs up to an additional $460M per year.

7.2 Hard Coatings

A study has also 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 1 million dollars per ship.[21] This would result in an additional annual savings for the Navy of $350M.

As was the case for the U.S. Navy, the maritime industry can also benefit from use of nanomaterial hard coatings. The potential savings were calculated in a similar manner as for antifouling coatings:

- There are approximately 3,800 U.S.-flag cargo-carrying vessels that exceed a weight of 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 $0.95B to $1.9B per year.

7.3 Overall Impact of Nanomaterial Use in the Maritime Industry

Excluding pollutions abatement savings, the REMI model determined the total economic impact to be a reduction of $1.7B to $2.6B per year in the production costs for the maritime industry. After just 3 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 3 years, employment would increase by 73,000 to 110,000 jobs, and personal income would increase by $4.6B to $7.0B.

8. 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 the use of nanomaterials for hard coatings on the landing gear of C-130 aircrafts indicated that the direct cost of using nanomaterials was slightly less than that of the traditional electroplating, resulting in an annual savings of $100 per C-130 aircraft 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 presently used in the hard-coating process.

8.1 Hard Coatings

The cost savings in 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 resulting from 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 $15.40 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 that 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 as a result of 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 use of the nanotechnology coatings in the tools and dies were calculated as follows:

- The total market for cutting tools is \$5B per year,[28] and that for tools and dies is \$8B per year.[29]
- Assume that nanomaterials can double the lifetime of cutting tools and tools and dies.
- Assume also that 25 to 50% of the cutting tools and tools and dies could use nanomaterials.

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

8.2 Overall Impact of Nanomaterial Use in the Manufacturing Industry

The REMI model determined the total economic impact to be a savings of \$1.7B to \$3.5B per year in the production costs for the manufacturing industry. After just 3 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 3 years, and personal income would increase by \$14B to \$19B.

9. 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 contaminants at a reduced cost compared with that achieved via the present methods.

9.1 Membranes for Separations

The cost savings for removing N_2 and CO_2 from natural gas were computed as follows:

- Subtract the cost of removing the gas using nanomaterial membranes from the cost of removing the gas 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 that the present costs of removing N_2 from the natural gas from contaminated wells at various sites 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 cubic feet.[31,32]
- With the above assumptions, the present cost of removing N_2 is approximately $1.14 per thousand cubic feet.

The cost savings for removing N_2 using nanomaterial membranes is determined by:

- The cost of N_2 removal using nanomaterial membranes is $0.28 per thousand cubic feet.[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 cubic feet.

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 that for N_2, the average cost of removing CO_2 is less than the halfway point described above for N_2.

- Considering these lower costs, 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.
- The selling price of natural gas minus the cost of production is approximately \$2.28 per thousand cubic feet.[31,32]
- This then results in an average cost estimate of \$0.57 to \$1.14 per thousand cubic feet 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 nanomaterials is \$0.18 per thousand cubic feet.[30]
- The savings for removing CO_2 from natural gas using nanomaterial membranes is then \$0.57 to \$1.14 minus \$0.18, or \$0.39 to \$0.96 per thousand cubic feet.

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 cubic feet.
- Removing N_2 would yield an estimated savings of \$0.86 per thousand cubic feet.
- Due to the generally much lower cost of CO_2 removal, the average cost today to remove both gases from natural gas is roughly the same as the average cost to remove N_2 from gas contaminated with N2 alone. Therefore, for natural gas that contains both N_2 and CO_2, the savings would again be approximately half of the difference between the present sales and production prices (\$1.14 per thousand cubic feet) minus the cost of removing both N_2 and CO_2 (\$0.28 plus \$0.18 per thousand cubic feet), resulting in a cost savings of \$0.68 for removing both contaminants.
- About 8.8×10^9 thousand cubic feet 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.

9.2 Overall Impact of Nanomaterial Use in Natural Gas Supply Industry

The REMI model determined the total economic impact to be a reduction of \$1.0B to \$2.7B per year in the production costs of the natural gas supply. After just 3 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 the natural gas supply. In the same 3 years, employment would increase by 31,000 to 85,000 jobs, and personal income would increase by \$2.2B to \$5.9B.

10. Conclusion

This report has examined some examples of the possible cost savings that could be achieved by using nanomaterials in catalysts, coatings, and membranes. Table 4 presents a summary of these results categorized by selected industries of application. Obviously, there are many more examples where the use of nanomaterials will result in production cost savings. Thus, the total impact on the economy of using nanomaterials could be considerably larger than is represented in the examples outlined in this report.

Based on the examples in this study, the primary financial impact of development of nanomaterials will come from their application in catalysts (annual savings estimates of $3B-$8B) and coatings (annual savings estimates of $4B-$7B), rather than in membranes (annual savings estimates of $1B-$3B) as shown in Figure 1.

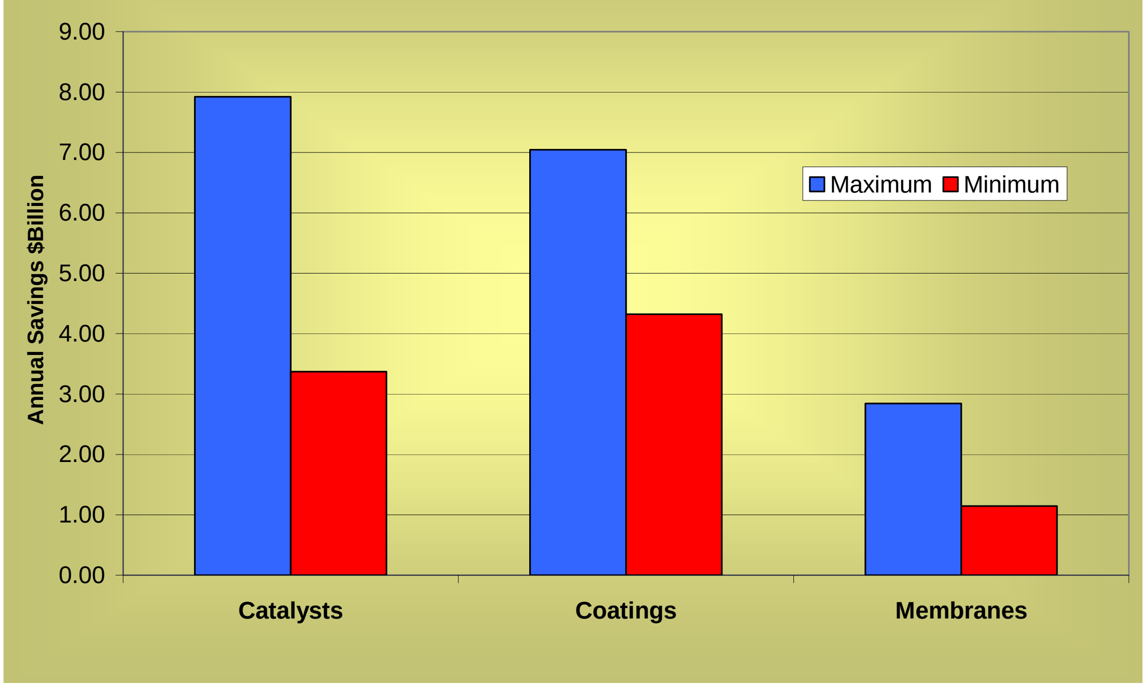

Figure 1 - Some Potential Cost Savings by Process

The greatest cost savings identified to date will be in the chemical industry itself where annual savings could range from $2.5B to $4B (Figure 2).

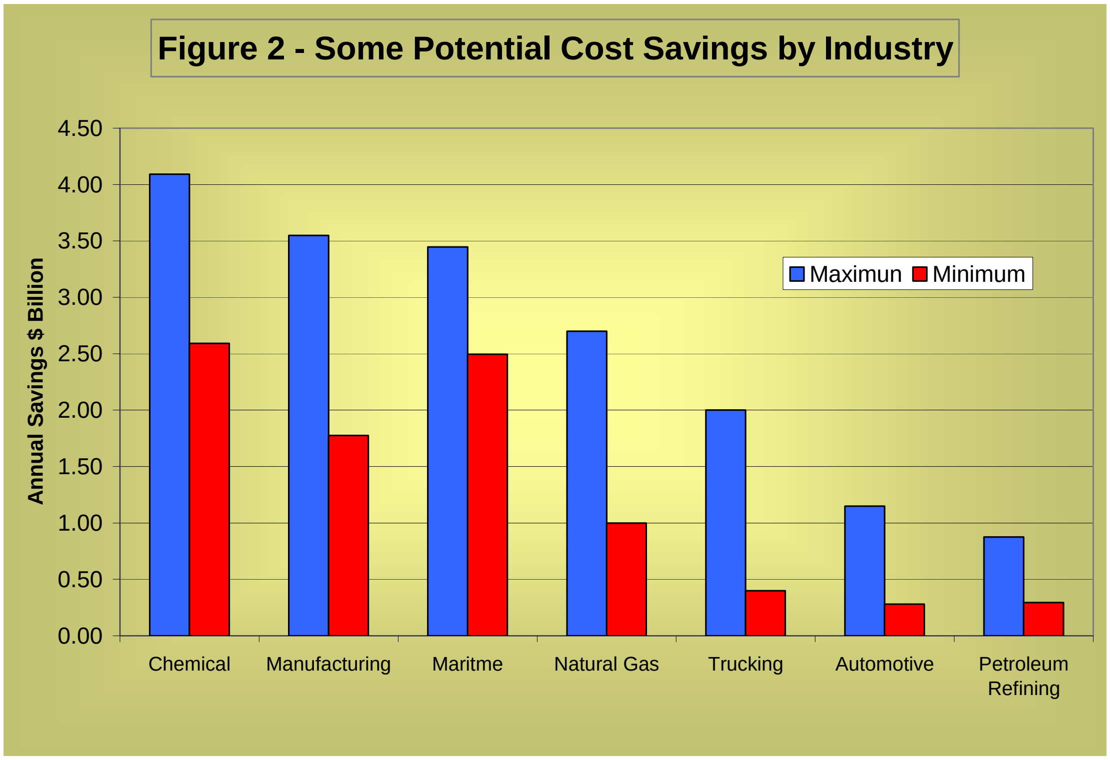

Figure 2 - Some Potential Cost Savings by Industry

Improved catalysts, primarily in the chemicals industry and for improved diesel engine combustion in the trucking industry, provide the most significant opportunities for energy reduction in the processes examined in this study (Figure 3).

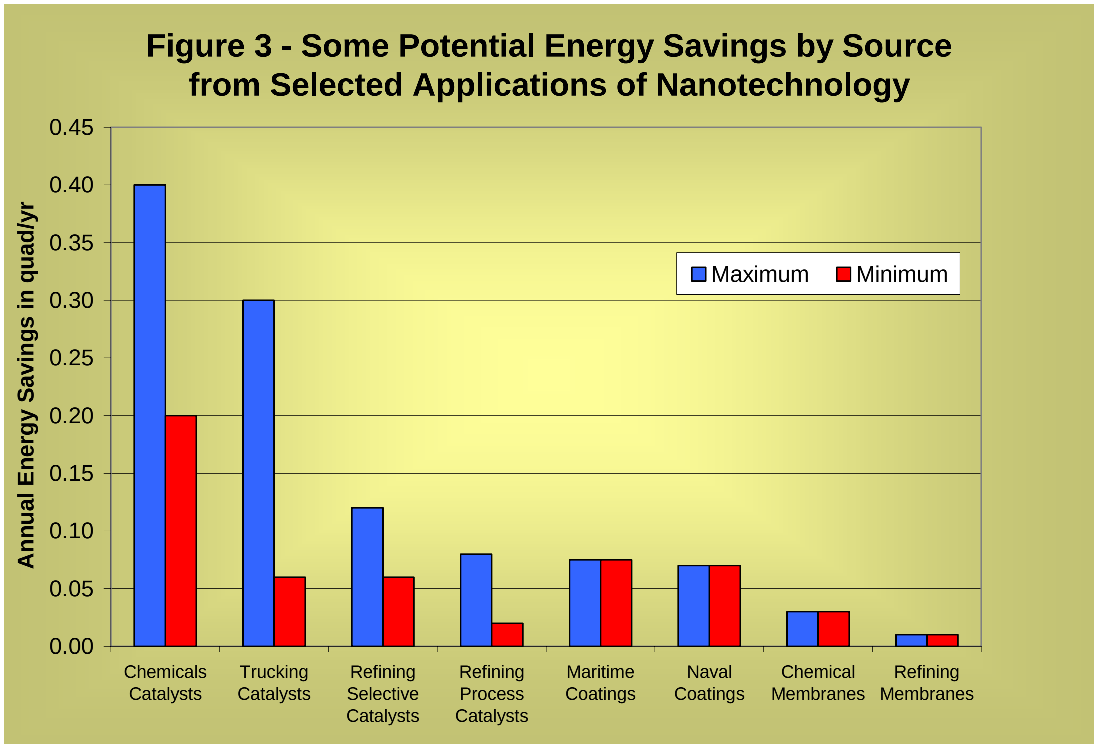

Figure 3 - Some Potential Energy Savings by Source from Selected Applications of Nanotechnology

Implementation of nanotechnologies will have positive impacts beyond energy savings in waste reduction (Table 3). The use of more selective catalysts in refining will reduce the production of wastewater and toxic emissions. The use of improved hard coatings can lead to elimination of the substantial amounts of chromic acid currently used. In the shipping industry more environmentally friendly antifouling coatings can eliminate pollution abatement costs for both commercial and military vessels.

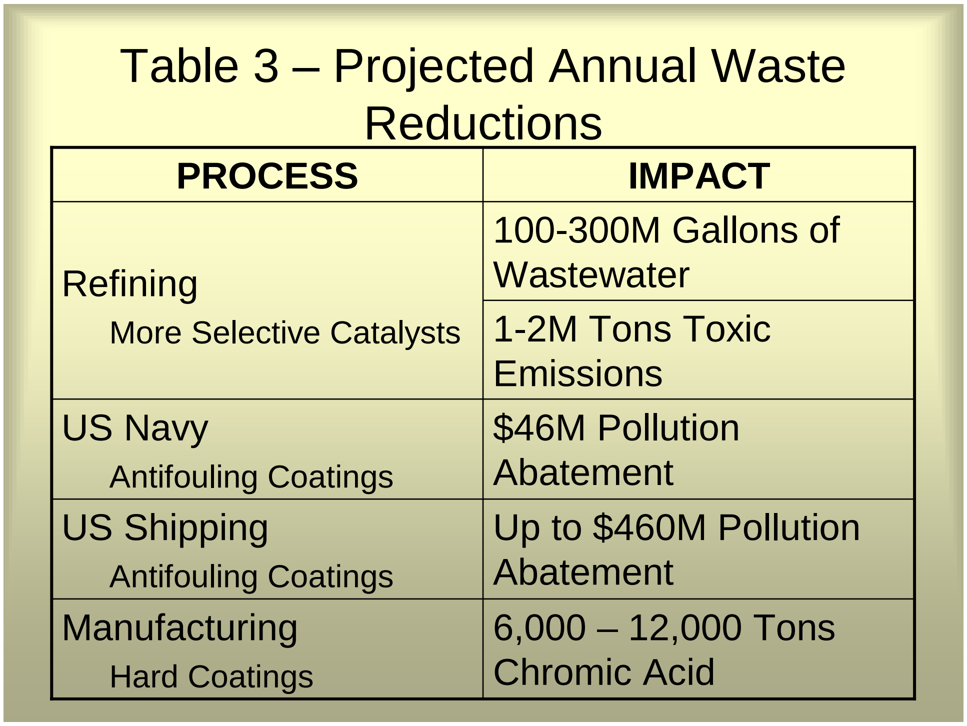

Table 3 – Projected Annual Waste Reductions

PROCESS	IMPACT
Refining More Selective Catalysts	100-300M Gallons of Wastewater
	1-2M Tons Toxic Emissions
US Navy Antifouling Coatings	$46M Pollution Abatement
US Shipping Antifouling Coatings	Up to $460M Pollution Abatement
Manufacturing Hard Coatings	6,000 – 12,000 Tons Chromic Acid

Table 4. Summary of Results for Selected Applications of Nanotechnology

Industry	Application	Process	Cost Savings (10^9 \$/YR) Min	Cost Savings (10^9 \$/YR) Max	Energy Savings Quad/YR Min	Energy Savings Quad/YR Max	GDP Increase (10^9 \$) @ 3 YR	Employment Increase (10^3 Jobs) @ 3 YR	Personal Income Increase (10^9 \$) @ 3 YR
Chemical	Catalysts Selectivity Increase	Catalysts	2.500	4.000	0.200	0.400			
Chemical	Catalysts Precious Metal Reductions	Catalysts	0.022	0.022					
Chemical	Membranes for Separations	Membranes	0.070	0.070	0.030	0.030			
Chemical Total		**Subtotal**	2.592	4.092	0.230	0.430	10 to 15	150 to 240	9 to 14
Petroleum Refining	Process Temperature Reductions	Catalysts	0.160	0.660	0.020	0.080			
Petroleum Refining	Catalysts Selectivity Increase	Catalysts	0.050	0.090	0.060	0.120			
Petroleum Refining	Catalysts Precious Metal Reductions	Catalysts	0.010	0.050					
Petroleum Refining	Membranes for Gas Separation	Membranes	0.075	0.075	0.010	0.010			
Petroleum Refining Total		**Subtotal**	0.295	0.875	0.090	0.210	0.6 to 1.8	8 to 25	0.7 to 1.8
Automotive	Precious Metal Reductions	Catalysts	0.230	1.100					
Automotive	Hard Coatings	Coatings	0.050	0.050					
Automotive Total		**Subtotal**	0.280	1.150			1.3 to 5	20 to 80	1.2 to 5
Maritime	U.S. Navy Antifouling Coating	Coatings	0.396	0.396	0.070	0.070			
Maritime	U.S. Navy Hard-Coating Savings	Coatings	0.350	0.350					
Maritime	U.S. Shipping Antifouling Coating	Coatings	0.800	0.800	0.075	0.075			
Maritime	U.S. Shipping Hard-Coating Savings	Coatings	0.950	1.900					
Maritime Total		**Subtotal**	2.496	3.446	0.145	0.145	4 to 7	70 to 110	5 to 7
Trucking	Fuel Combustion Catalysts	Catalysts	0.400	2.000	0.060	0.300	1.5 to 8	25 to 130	1.3 to 7
Manufacturing	Hard-Coating Savings	Coatings	1.775	3.550			10 to 20	150 to 300	14 to 20
Natural Gas	N_2 and CO_2 Removal by Membranes	Membranes	1.000	2.700			2 to 6	30 to 85	2 to 6
Total			8.838	17.813	0.525	1.085	29 to 63	450 to 970	33 to 61

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Appendix A: Additional Information about REMI

(The information about REMI contained in this appendix is adapted with permission from the REMI Web page[1] and from material supplied to the authors by REMI.[2] Please refer to the Web page for additional information.)

Selection of REMI for Use in This Study

REMI Policy Insight is the economic model that was selected for this study. The use of REMI makes it possible to accurately evaluate the economic effects of the use of nanomaterials in selected industries, including the potential effects throughout the entire economy. The model's structure allows users to outline potential technological applications to be evaluated and then assists in interpreting the predicted economic and demographic effects of any given technological change. Although the model is calibrated to accommodate analysis and forecasting for subnational areas, only the national-level model is used in this study.

REMI Policy Insight is widely used by government agencies (including most U.S. state governments), consulting firms, nonprofit institutions, universities, and public utilities. A study performed by K. R. Polenske et al. at MIT evaluated REMI and other socioeconomic models and concluded that REMI "has been used by a large number of users under diverse conditions and has proven to perform acceptably." Several specific advantages of REMI outlined by Polenske proved useful for this study: REMI "combines several different kinds of analytical tools," "allows users to manipulate an unusually large number of input variables" and "gives forecasts for an unusually large number of output variables." Furthermore, the model provides flexibility in allowing users to specify forecast periods.[3]

The two-step process using the available baseline forecast as input made it possible to generate output data predicting the overall economic impact of the implementation of nanotechnology in specific industries. After the direct economic impacts of the use of nanotechnology in the various chemical industries are determined, REMI generates estimates of the corresponding increases in the gross national product, the number of jobs created, and personal income for the 3-year forecast period selected for this study.

Structure and Application of the Model

REMI facilitates the use of policy variables (in this case, changes resulting from implementation of nanotechnology) and enables users to track the effects of such changes on all variables in the model. The five blocks in Figure A.1 show the underlying structure of the REMI model. The interaction both within and between blocks is shown via lines and arrows. The core of the model is the block labeled "Output." An input-output structure represents the interindustry and final demand linkages. The interaction between block 1 and the rest of the model is extensive. Predicted outputs drive labor demand, which in-turn affects wages. Wages determine relative profitability and, ultimately, market shares. The market shares represent the endogenous demands in block 1 (consumption, investment, demands of state and local government), as well as the export demand that the regional production fulfills.

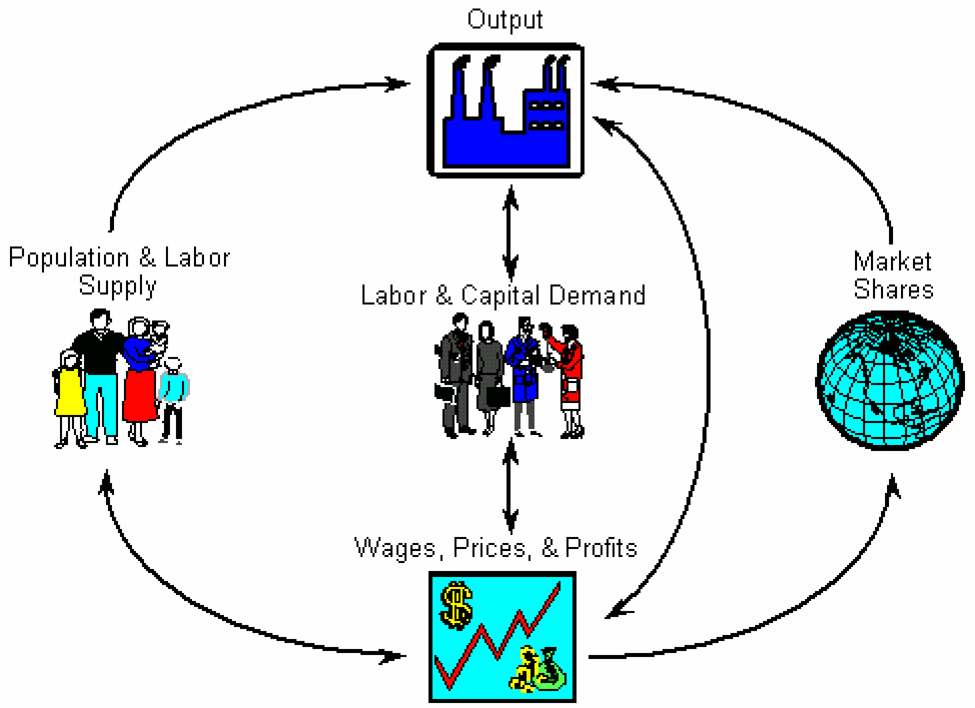

Figure A.1: Underlying Structure of REMI Model

As shown in Figure A.2, the REMI model is a two-step process. First, the model generates a baseline forecast to be used as one of the inputs to the model. Next, the direct impacts of a policy change (i.e., implementation of nanotechnology) are input into the model to generate a forecast for a specified region (i.e., the United States) when the policy change is implemented. The latter is referred to as an alternative forecast. The difference between the baseline and alternative forecasts represents the total effects of the policy change.

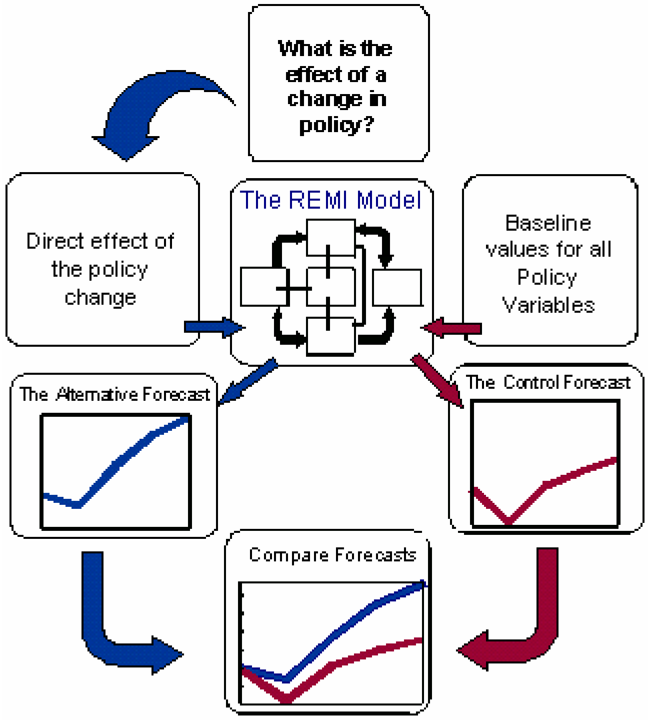

Figure A.2: REMI Process

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