



NASF SURFACE TECHNOLOGY WHITE PAPERS
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3rd Quarterly Report
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AESF Research Project #R-121

Development of a Sustainability Metrics System
and
a Technical Solution Method for Sustainable Metal Finishing

by
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Editor's Note: This NASF-AESF Foundation research project report covers the third quarter of project work (October-December 2020) at Wayne State University in Detroit.

Overview

It is widely recognized in many industries that sustainability is a key driver of innovation. Numerous companies, especially large ones that made sustainability as a goal, are achieving clearly more competitive advantage. The metal finishing industry, however, is clearly behind others in response to the challenging needs for sustainable development.

This research project aims to:

1. Create a metal-finishing-specific sustainability metrics system, which will contain sets of indicators for measuring economic, environmental and social sustainability,
2. Develop a general and effective method for systematically sustainability assessment of any metal finishing facility that could have multiple production lines, and for estimating the capacities of technologies for sustainability performance improvement,
3. Develop a sustainability-oriented strategy analysis method that can be used to analyze sustainability assessment results, identify and rank weaknesses in the economic, environmental, and social categories, and then evaluate technical options for performance improvement and profitability assurance in plants, and
4. Introduce the sustainability metrics system and methods for sustainability assessment and strategy analysis to the industry.

This will help metal finishing facilities to conduct a self-managed sustainability assessment as well as identify technical solutions for sustainability performance improvement.

Progress Report (Quarter 3)

1. Student participation

Since September 2020, Abdurrafay Siddiqui, a newly hired Ph.D. student, has been guided by the P.I. to work on the project. His research activities are reflected in Section 3 of this report.

2. Scheduled project tasks for Quarter 3

The main technical tasks for this quarter are listed below:

1. Identification of the parameters needed for quantifying the indicators in Sets A and B.
2. Development of new sustainability indicators based on the 12 newly added inspects.
3. Initiation of the development of a mathematical method using an enhanced sustainability metrics system (for both conventional and advanced sustainability assessments).



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3. Project activities and progress

3.1 Identification of the parameters needed for quantifying the indicators in Sets A and B

The 2nd Quarterly Report listed 53 sustainability indicators that were divided into two sets, Set A (called the minimum set) and Set B (called the extended set). The classification of these indicators is summarized in Table 1.

Table 1 - Summary of sustainability indicators in different categories.

Sustainability Category	# of Indicators in Set A	# of Indicators in Set B
Economic	12	8
Environmental	12	7
Social	7	7
Total	31	22

In sustainability assessment, each sustainability indicator needs to be evaluated by usually using more than one type of parameter data. These parameters could be divided into at least six types: (1) plant design data, (2) operational data, (3) production and product data, (4) EHS (environmental, health and safety) data, (5) cost/accounting data and (6) business and management data.

3.1.1 Parameterization of indicators in Set A.

The parameterization of 31 indicators in this set is summarized in **Section 4, Tables 2 to 4**. In each table, there is a column named "Parameter". The parameters listed for evaluation of each specific indicator are only those not appearing in the parameters already listed for the preceding indicators, in order to avoid repeat listing. For instance, the parameter, "Revenue from sales of products before tax", is already listed for indicator E-1-1. Although this parameter is also needed for indicator E-1-3, it is not shown for this indicator.

3.1.2 Parameterization of indicators in Set B

The parameters needed to evaluate 22 indicators in Set B are listed in **Section 4, Tables 5 to 7**. Note that many indicators in this set are very similar to those in Set A, except for the difference in evaluation basis. For instance, E-1-5 in Set B is evaluated per direct employee; V-1-4 in Set B counts per dollar of product sales rather than per value added for V-1-1 in Set A. It is possible that some plants may select some indicators in Set B rather than Set A, or possibly both.

3.1.3 Development of new sustainability indicators based on the 12 newly added inspects

The COVID-19 pandemic has ushered in various unprecedented challenges and severely disrupted economic and social systems worldwide. In the U.S., one of the hardest-hit segments by the pandemic is the manufacturing industry, especially small businesses like the metal finishing industry. Health risks, demand reduction, supply chain disruption, etc. have slowed numerous manufacturing facilities to a standstill. After one year of pandemic outbreak, it is still unpredictable today when the coronavirus will die down. The metal finishing industry, like other manufacturing industries, needs to look beyond the fog of uncertainty towards long-term changes and develop strategies for more sustainable and resilient development in the future. Therefore, extended sustainability assessment is needed for the industries.

In the last report, the PI reported his initial research on how to make sustainability assessment more comprehensive, and described 12 new aspects that need to be added to more traditional metrics systems. The research was published in a special issue on "Smart and Sustainable Manufacturing in the Post COVID-19 Manufacturing Era" by *ASTM journal - Smart and Sustainable Manufacturing Systems* (Huang, 2020). In this quarter, a number of sustainability indicators covering the 12 new aspects are identified, which are listed in **Section 4, Tables 7 to 10**. Note that these indicators need to be refined in the following months. Possibly, additional indicators will be introduced.

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3.1.4 Initiation of the development of a mathematical method using the enhanced sustainability metrics system

The indicators selected from the tables in the last section will be used to assess sustainability performance of a company or even the electroplating sector. Figure 1 shows a spider chart to be used as a scheme to present the results of indicator evaluations, where all indicator values are normalized to the range of 0 to 1, with 1 the best. This type of result presentation can provide a visually clear comparison of the system under different conditions.

To aggregate assessment results by individual indicators, we will use the following three formulas:

$$E = \frac{\sum_{i=1}^{N_E} a_i E_i}{\sum_{i=1}^{N_E} a_i}, \quad V = \frac{\sum_{j=1}^{N_V} b_j V_j}{\sum_{j=1}^{N_V} b_j} \quad \text{and} \quad L = \frac{\sum_{k=1}^{N_L} c_k L_k}{\sum_{k=1}^{N_L} c_k} \quad [1]$$

where E , V and L are the evaluation results of the economic, environmental and social sustainability, respectively; E_i , V_j and L_k are individual normalized indicators in different sustainability categories; N_E , N_V and N_L are the total numbers of selected indicators in different sustainability categories; a_i , b_j and c_k are weighting factors associated with different indicators, taking values between 1 and 10, with 10 as the most important and 1 as the least.

The overall sustainability performance of a plant or even an industrial sector, S , will be evaluated using the composite indices, E , V and L , i.e.,

$$S = \frac{\|(\alpha E, \beta V, \gamma L)\|}{\|(\alpha, \beta, \gamma)\|} \quad [2]$$

where α , β and γ are weighting factors in the range of 1 to 10. Because E , V and L are normalized, S is also normalized between 0 (completely unsustainable) and 1 (completely sustainable).

Note that the above formulas contain a large number of weighting factors that reflect the different relative importance versus other indicators as well as other sustainability categories. With few exceptions, the values of weighting factors cannot be scientifically and uniquely determined. Note that different weighting factor values will generate different assessment results, some of which could be misleading. Thus, weighting factor selection has been a major challenge in sustainability assessment.

Our comprehensive literature survey has led to identification of a scientific method, namely the Analytic Hierarchy Process (AHP) method, which was developed by Thomas Saaty, a member of US National Academy of Engineering (Saaty, 1980, 2008). This method has been widely used in industries for decision making in complex scenarios. In this method, Saaty introduced a rating scale. Decision-making participants can use the scale to give weights for key factors based on their own experience and judgement. Then a scientifically rigorous mathematical method is employed to calculate a consistency ratio to measure how consistent the judgements have been relative to large samples of purely random judgements. Under the PI's guidance, the Ph.D. student working on this project has been initially successful in determining weighting factors for a group of sustainability indicators (Siddiqui, 2020). An internal report on this progress is under review. We will formulate the weighting factor determination process, and test it using some case study problem. If successful, we plan to report this research work in the next quarterly report.

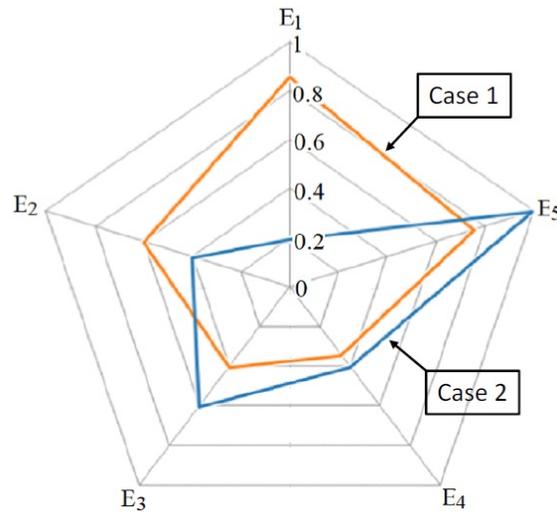


Figure 1 - Spider chart to present the economic sustainability assessment results by five individual indicators for two cases.

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4. Tables 2 thru 10

Table 2 - Economic sustainability indicators and parameterization in Set A.

Sub-category	Indicator	Parameter
E-1: Profit, Value and Tax	E-1-1: Value added (\$/yr)	<ul style="list-style-type: none"> Revenue from sales of products before tax Manufacturing cost (including direct production cost, fixed charges and plant overhead cost)
	E-1-2: Net profit margin (%/\$)	<ul style="list-style-type: none"> Net income (profit) Production cost
	E-1-3: Tax paid as percent of NIBT (%)	<ul style="list-style-type: none"> Total tax paid annually
	E-1-4: Return on average capital employed (%/yr)	<ul style="list-style-type: none"> Total financial assets Short-term financial obligations
E-2: Investments	E-2-1: Percentage increase in capital employed (%/yr)	<ul style="list-style-type: none"> Capital employed in the current year Past 5-year average of total financial assets
	E-2-2: Investment for employee's education/training	<ul style="list-style-type: none"> Funds spent for employee (re)training/(re)education Total number of employees
	E-2-3: Investment on new technology (\$/yr)	<ul style="list-style-type: none"> Spending for new technology development
E-3: Technology Advancement	E-3-1: Production increment percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Production rate increased after implementing each new technology Amount invested on each new technology
	E-3-2: Product quality improvement percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Final product off-specification rate decreased after implementing new technologies Intermediate product quality off-specification rate decreased after implementing each new technology
	E-3-3: Waste reduction percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Amount of wastewater reduced after implementing each new technology Amount of chemical consumption reduced after implementing each new technology
E-4: Production and Product Quality	E-4-1: Percentage of product delivered on time (%)	<ul style="list-style-type: none"> Total amount of products produced Products delivered on time
	E-4-2: Product return rate after shipment (%)	<ul style="list-style-type: none"> Product rejection rate

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Table 3 - Environmental sustainability indicators and parameterization in Set A.

Sub-category	Indicator	Parameter
V-1: Materials (excluding fuel and water)	V-1-1: Chemical use in production per value added (lb/\$)	<ul style="list-style-type: none"> Type and amount of chemicals used in production Value added (same as E-1-1)
	V-1-2: Chemical use in waste (pre)treatment per value added (lb/\$)	<ul style="list-style-type: none"> Type and amount of chemicals used in waste (pre)treatment
	V-1-3: Plating solution use per value added (lb/\$)	<ul style="list-style-type: none"> Type and amount of plating solutions used
V-2: Water	V-2-1: Fresh water use in production per dollar of product sales (lb/\$)	<ul style="list-style-type: none"> Amount of fresh water consumed in production lines Annual income from sales of products
	V-2-2: Used water reused in production before treatment (%)	<ul style="list-style-type: none"> Amount of used water reused in production before treatment Amount of fresh water consumed
V-3: Energy	V-3-1: Electricity use per value added (kW/\$)	<ul style="list-style-type: none"> Total amount of electricity used in plant
	V-3-2: Clean energy use among all energy (%)	<ul style="list-style-type: none"> Total amount of energy used in plant from green or environmentally neutral sources
	V-3-3: Non-production energy among all energy consumption (%)	<ul style="list-style-type: none"> Total amount of energy used in plant Total amount of energy used in production lines
V-4: Waste Generation and Effluents	V-4-1: Spent solutions per value added (lb/\$)	<ul style="list-style-type: none"> Total amount of spent solutions generated in production lines
	V-4-2: Wastewater generated in production per value added (lb/\$)	<ul style="list-style-type: none"> Total amount of wastewater generated in production lines
	V-4-3: Wastewater treatment sludge per value added (lb/\$)	<ul style="list-style-type: none"> Total amount of sludge generated in wastewater treatment facility
	V-4-4: Hazardous waste generated per value added (lb/\$)	<ul style="list-style-type: none"> Type and amount of hazardous waste generated

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Table 4 - Social sustainability indicators and parameterization in Set A.

Sub-category	Indicator	Parameter
L-1: Workplace	L-1-1: Benefits as percentage of payroll expense (%)	<ul style="list-style-type: none"> Total benefits for employees Total labor cost
	L-1-2: Work related reeducation and/or training (%)	<ul style="list-style-type: none"> Funds spent for employees' re-education and retraining
L-2: Safety and Health	L-2-1: Number of accidents in workplace (/yr)	<ul style="list-style-type: none"> Type and number of accidents in workplace (in production lines and other areas of a plant) Number of employees' health problems (including casualty) caused by accidents
	L-2-2: Chemical leakage in plant (/yr)	<ul style="list-style-type: none"> Type and amount of chemicals emitted in plant and forms Number of employees' health problems (including casualty) caused by chemical leakage
L-3: Society	L-3-1: Number of complaints from local community (/yr)	<ul style="list-style-type: none"> Number of complaints from local community
	L-3-2: Number of complaints from customers (/yr)	<ul style="list-style-type: none"> Number of complaints from customers
	L-3-3: Number of legal actions per value added (/yr)	<ul style="list-style-type: none"> Number of legal issues and actions of a company

Table 5 - Economic sustainability indicators and parameterization in Set B.

Sub-category	Indicator	Parameter
E-1: Profit, Value and Tax	E-1-5: Value added per direct employee (\$/yr)	<ul style="list-style-type: none"> Number of direct employees of a company Value added (same as E-1-1)
	E-1-6: Net profit per direct employee (\$/yr)	<ul style="list-style-type: none"> Net income (profit)
E-2: Investments	E-2-4: Percentage of new employees (%/yr)	<ul style="list-style-type: none"> Number of new employees hired Total number of employees
	E-2-5: Percentage of training vs payroll expense (%)	<ul style="list-style-type: none"> Total expense for workforce training/education
E-3: Technology Advancement	E-3-4: Production increment percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Production rate change after implementing more effective or advanced technology Investment for technology improvement
	E-3-5: Product quality improvement percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Final product quality change after implementing more effective or advanced technology Intermediate product quality change after implementing more effective or advanced technology
	E-3-6: Waste reduction percentage per dollar investment in new technology (%/\$-new tech)	<ul style="list-style-type: none"> Intermediate product quality change after implementing more effective or advanced technology Post-process waste generation change after implementing more effective or advanced technology
E-4: Production and Product Quality	E-4-3: Product defect rate during production (%)	<ul style="list-style-type: none"> Total amount of products produced Products delivered on time
	E-4-2: Product return rate after shipment (%)	<ul style="list-style-type: none"> Product quality problems identified before shipment

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Table 6 - Environmental sustainability indicators and parameterization in Set B.

Sub-category	Indicator	Parameter
V-1: Materials (excluding fuel and water)	V-1-4: Chemical use in production per dollar of product sales (lb/\$)	<ul style="list-style-type: none"> Type and amount of each chemical used in production Income from product sales
	V-1-5: Plating solution use per dollar of product sales (lb/\$)	<ul style="list-style-type: none"> Type and amount of plating solutions used
	V-1-6: Other material use per dollar of product sales (lb/\$)	<ul style="list-style-type: none"> Spending on materials other than those directly used in production
V-2: Water	V-2-3: Fresh water use in production per dollar of product sales (lb/\$)	<ul style="list-style-type: none"> Amount of fresh water consumed in each production line
	V-2-4: Fraction of water recycled within plant (%)	<ul style="list-style-type: none"> Total amount of water recycled including that after waste (pre)treatment
V-3: Energy	V-3-4: Electricity use per dollar of sales (kW/\$)	<ul style="list-style-type: none"> Total amount of electricity used in plant
	V-3-5: Natural gas and oil use per dollar of sales (MMBtu/\$)	<ul style="list-style-type: none"> Total amount of natural gas and oil used in plant
V-4: Waste Generation and Effluents	V-4-5: Non-hazardous waste generated per value added (lb/\$)	<ul style="list-style-type: none"> Type and amount of non-hazardous waste generated in plant

Table 7 - Social sustainability indicators and parameterization in Set B.

Sub-category	Indicator	Parameter
L-1: Workplace	L-1-3: Employee turnover (resigned and redundant vs total employed) (%)	<ul style="list-style-type: none"> Number of resigned employees Number of redundant employees Total number of employees
	L-1-4: Promotion rate (promotions / employed) (%)	<ul style="list-style-type: none"> Number of promotions among employees
	L-1-5: Working hours lost as percent of total hours worked (%)	<ul style="list-style-type: none"> Total number of working hours lost per year Total number of working hours
L-2: Safety and Health	L-2-3: Number of process safety review (/yr)	<ul style="list-style-type: none"> Number of comprehensive reviews of process safety conducted
	L-2-4: Human health burden (carcinogenic) per value added (/ \$)	<ul style="list-style-type: none"> Number of carcinogen-related health cases among employees Number of carcinogen-related cases in local community
L-3: Society	L-3-4: Number of stakeholder meetings (/yr)	<ul style="list-style-type: none"> Number of stakeholder meetings held
	L-3-5: Indirect community benefit (\$/yr)	<ul style="list-style-type: none"> Type of indirect community benefits converted to dollars

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Table 8 - Non-traditional economic sustainability indicators.

Sub-category	Indicator	Note
EA-1: New Technologies	EA-1-1: Number of new technologies developed and/or adopted	• Non-traditional technologies, specifically for mitigating negative impacts on manufacturing caused by unexpected major disruptions
	EA-1-2: Investment in new technologies	• Plan for spending on the development or adoption
EA-2: Supply Chain	EA-2-1: Robustness of job orders	• Focus on stability and flexibility
	EA-2-2: Stability and flexibility of other supplies	• Especially chemicals
EA-3: New Market Development	EA-3-1: Type of new market developed	• Different market opportunities
EA-4: Green Employment	EA-4-1: Number of green jobs created	• Positions created for substantially preserving or restoring environmental quality

Table 9 - Non-traditional environmental sustainability indicators.

Sub-category	Indicator	Note
VA-1: XR Initiative	VA-1-1: Implementation and effectiveness of 3R	• 3R - reduce, reuse, and recycle
	VA-1-2: Initiative of additional R's	• For instance, "redesign" of some processes for cleaner and safer production, "recover" of chemicals, "reintegration" of certain processes
VA-2: Renewable Resources	VA-2-1: Type of renewable energy used	• For instance, solar energy and biofuels
	VA-2-2: Percentage of energy supply	• As compared to total energy consumption
VA-3: Exchange Networks	VA-3-1: Type of green business connections	• Networks with other companies for exchanging used/waste materials and energy
VA-4: Regulation Compliance	VA-4-1: Effectiveness of regulation compliance	• Annual report on the effectiveness and action taking for regulation compliance

Table 10 - Non-traditional social sustainability indicators.

Sub-category	Indicator	Note
LA-1: Preparedness for Major Disruption	LA-1-1: Response time to major disruption	• Time spent for taking action, as compared with other companies
	LA-1-2: Types and effectiveness of actions	• Effectiveness can be reflected by the damage reduced due to quick actions
LA-2: Labor Conditions	LA-2-1: Preparedness of health risk prevention	• Action plans for health risk prevention
LA-3: Advanced Training	LA-3-1: Types of nontraditional training offered	• Training arranged for employees to effectively use new equipment, devices, and technologies
	LA-3-2: Quality of guidelines developed	• Preparation and annual review of guidelines
LA-4: Customer Services	LA-4-1: Types of special services provided	• Effective communications with and services to customers during a disruption period

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5. Plan for the 5th quarter of the project (1/1/21 – 3/31/21)

The sustainability indicators in Sets A and B will be continuously refined. However, the most important factor is to have industrial experts engaged in the review process. Thus, in the next quarter, the PI will develop a document about the sustainability metrics system and a guideline for the evaluation of the metrics system. In addition, the PI will seek collaboration with some electroplating facilities who may provide case studies for testing the metrics system.

As planned, the PI's team will formally initiate the development a sustainability assessment method. The primary focus will be on the development of an AHP-based methodology to systematically determine weighting factors associated with indicators. Case studies will be used to test the method.

6. References

1. Huang, Y., "Reinforcing Sustainability Assessment and Reshaping Technology Innovation for Highly Sustainable Manufacturing in the Post-COVID-19 Era", *Smart and Sustainable Manufacturing Systems*, 4 (3), 341-345 (2020).
2. T.L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, New York, 1980.
3. T.L. Saaty, T. L., "The analytic hierarchy and analytic network measurement processes: applications to decisions under risk," *European J. of Pure and Applied Mathematics*, 1 (1), 122-196 (2008).
4. A. Siddiqui, *Sample Calculations for the Overall Sustainability of an Electroplating Company by the Analytic Hierarchy Method*, Internal Progress Report, Laboratory for Multiscale Complex Systems Science and Engineering, Department of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI, Dec. 26, 2020.

7. Past project reports

1. Quarter 1 (April-June 2020): Summary: *NASF Report in Products Finishing; NASF Surface Technology White Papers*, 84 (12), 14 (September 2020); Full paper: <http://short.pfonline.com/NASF20Sep1>
2. Quarter 2 (July-September 2020): Summary: *NASF Report in Products Finishing; NASF Surface Technology White Papers*, 85 (3), 13 (December 2020); Full paper: <http://short.pfonline.com/NASF20Dec1>

8. About the author



Dr. Yinlun Huang is a Professor at Wayne State University (Detroit, Michigan) in the Department of Chemical Engineering and Materials Science. He is Director of the Laboratory for Multiscale Complex Systems Science and Engineering, the Chemical Engineering and Materials Science Graduate Programs and the Sustainable Engineering Graduate Certificate Program, in the College of Engineering. He has ably mentored many students, both Graduate and Undergraduate, during his work at Wayne State.

He holds a Bachelor of Science degree (1982) from Zhejiang University (Hangzhou, Zhejiang Province, China), and M.S. (1988) and Ph.D. (1992) degrees from Kansas State University (Manhattan, Kansas).

He then joined the University of Texas at Austin as a postdoctoral research fellow (1992). In 1993, he joined Wayne State University as Assistant Professor, eventually becoming Full Professor from 2002 to the present. He has authored or co-authored over 220 publications since 1988, a number of which have been the recipient of awards over the years.

His research interests include multiscale complex systems; sustainability science; integrated material, product and process design and manufacturing; computational multifunctional nano-material development and manufacturing; and multiscale information processing and computational methods.

He has served in many editorial capacities on various journals, as Co-Editor of the *ASTM Journal of Smart and Sustainable Manufacturing Systems*, Associate Editor of *Frontiers in Chemical Engineering*, Guest Editor or member of the Editorial Board, including the *ACS Sustainable Chemistry and Engineering*, *Chinese Journal of Chemical Engineering*, the *Journal of Clean*



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Technologies and Environmental Policy, the *Journal of Nano Energy and Power Research*. In particular, he was a member of the Editorial Board of the AESF-published *Journal of Applied Surface Finishing* during the years of its publication (2006-2008).

He has served the AESF and NASF in many capacities, including the AESF Board of Directors during the transition period from the AESF to the NASF. He served as Board of Directors liaison to the AESF Research Board and was a member of the AESF Research and Publications Boards, as well as the Pollution Prevention Committee. With the NASF, he served as a member of the Board of Trustees of the AESF Foundation. He has also been active in the American Chemical Society (ACS) and the American Institute of Chemical Engineers (AIChE).

He was the 2013 Recipient of the NASF William Blum Scientific Achievement Award and delivered the William Blum Memorial Lecture at SUR/FIN 2014 in Cleveland, Ohio. He was elected AIChE Fellow in 2014 and NASF Fellow in 2017. He was a Fulbright Scholar in 2008 and has been a Visiting Professor at many institutions, including the Technical University of Berlin and Tsinghua University in China. His many other awards include the AIChE Research Excellence in Sustainable Engineering Award (2010), AIChE Sustainable Engineering Education Award (2016), the Michigan Green Chemistry Governor's Award (2009) and several awards for teaching and graduate mentoring from Wayne State University, and Wayne State University's Charles H. Gershenson Distinguished Faculty Fellow Award.