NIST GCR 16-008

Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing

Roll-to-Roll Manufacturing

August 2016

Prepared for—

Economic Analysis Office
National Institute of Standards and Technology
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Gaithersburg, MD 20899

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August 2016

U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Contents

Figures

Number **Page**

Tables

Executive Summary

Within the past decade there has been a resurgence of interest in roll-to-roll (R2R) manufacturing methods. The potential to use this familiar, continuous production method to print multilayered products with sophisticated attributes and small feature sizes is driving innovation. Advanced R2R production methods are currently used for several different types of products, including optical films like light diffusers, but the potential to apply it to produce entirely new products is driving innovation. Emerging product segments like flexible electronics are pushing technological boundaries.

Further development and widespread adoption of this manufacturing technology will require resolving key technical challenges in standards, metrology, and technology platforms. This report, commissioned by the National Institute of Standards and Technology (NIST), explores perspectives from industry and academia on the needs for new technology infrastructure supporting R2R manufacturing and the potential economic impact of meeting these needs.

We estimate that the economic benefit of an improved technology infrastructure supporting R2R manufacturing would be at least $353 million per year. This estimate is conservative because it reflects the small size of the market today and does not take into consideration the impacts associated with market transformation, earlier introduction of novel products and services, benefits to consumers, or other types of benefits. The estimate is simply the potential impact using known information.

Many companies face barriers in adopting or developing R2R technologies because of R2R’s hard and soft costs and the associated learning curve. Missing from the marketplace are many standards, technology platforms, and other fundamental pieces of technology, making technology adoption more costly and difficult than it needs to be (Figure ES-1). Because firms cannot profit from developing these public-good technologies, they do not develop them, which in turn discourages innovation and undermines American competitiveness. Public-sector support of relevant technology infrastructure will help lessen, if not outright, remove many barriers.

The research supporting this report was informed by in-depth interviews with individuals representing manufacturers, university-based research centers, and manufacturing engineering consultancies. It was apparent from these interviews that addressing these critical needs has the potential to help the industry be more competitive in the marketplace, be more cost competitive, improve quality, and hasten the introduction of new products with novel functionality.

ES.1 SCOPE OF THE ANALYSIS

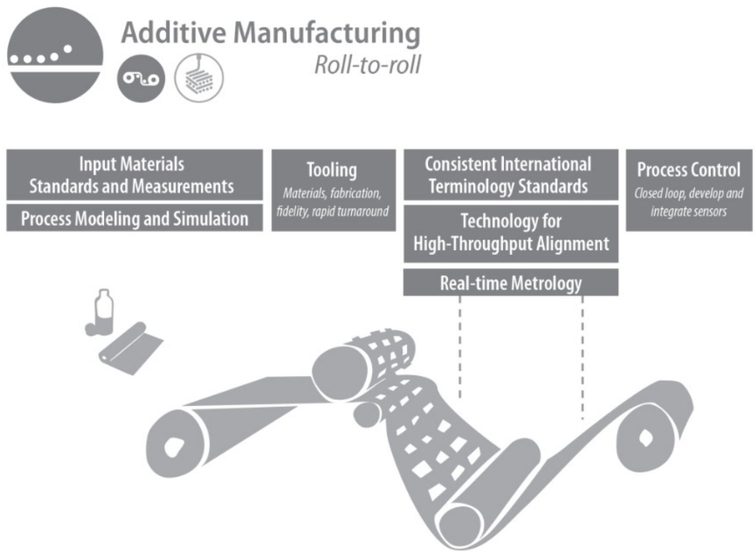
This study is a collaborative effort among multiple units within NIST to determine technology infrastructure needs to support advanced manufacturing. It presents findings of an economic analysis of the technology infrastructure, which includes standards, measurement, and general-purpose technology, and the role of this infrastructure in the efficient development and adoption of advanced R2R manufacturing in the United States.

The objectives of this strategic planning study were to

- identify current and emerging trends;
- identify technology infrastructure needs to support the development and adoption of R2R manufacturing technology;
- document the challenges and barriers that inhibit the development of technology infrastructure;
- estimate the economic benefit of meeting these technology infrastructure needs; and
- assess potential roles for NIST in meeting technology infrastructure needs.

Ultimately, the purpose of the study is to provide NIST with information on industries' technology infrastructure needs to help inform NIST's strategic planning.

Figure ES-1. Technology Infrastructure Needs for R2R Additive Manufacturing



ES.2 ANALYSIS APPROACH

We conducted in-depth interviews with industry executives, university faculty members, and independent researchers and consultants representing a cross section of the R2R research and manufacturing community. Many more informal conversations were held with individuals at conferences and industry events.

We specifically focused on sectors in which there is significant relevant industry activity and research:

- optical films,
- flexible electronics,
- biomedical applications,
- energy technologies, and
- environmental technologies.

These stakeholder engagement and interview activities were complemented with an extensive review of the relevant literature, issue briefs, and industry reports. The combined results of these activities built our knowledge base of R2R technology, key industries and application areas, and the barriers and pitfalls in R2R manufacturing that are preventing it from being fully optimized.

Quantitative information about interviewees' expectations of increased productivity, R&D efficiency, decreased production cost, and improved product quality was combined publicly available data on the manufacturing sector in economic models of the R2R manufacturing sector. Because these models used existing industry data, and did not project or speculate about future market size, our impact estimates are conservative.

ES.3 ANALYSIS OF TECHNOLOGY INFRASTRUCTURE NEEDS

Stakeholders' perspectives on technology infrastructure needs fell into the following areas (Table ES-1):

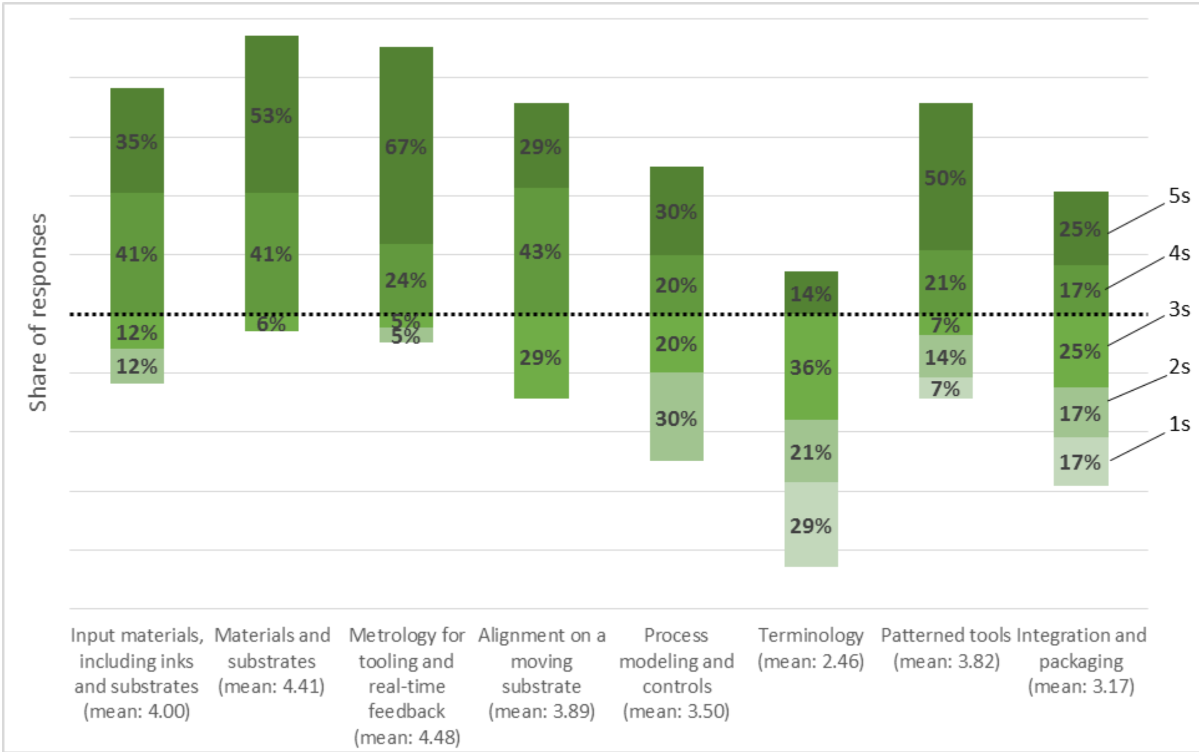
- standards and measurement technology for input materials
- new materials and substrates
- patterned tools
- metrology for tooling and real-time feedback
- technology for alignment and registration on a moving web
- process modeling and controls
- consistent international terminology

Using a Likert scale, interviewees rated the importance of addressing the needs from "very important" to "not at all important" (Figure ES-2). Metrology for tooling and feedback was identified to be the most important technology infrastructure need, followed by the development of new materials and substrates and measurement and standards for those materials.

Table ES-1. Technology Infrastructure Needs for R2R Manufacturing

Infrastructure Need	Technologies	Potential Impacts
Standards and measurement technology for input materials	Reference materials and quality standards Standard protocols and best practices to improve repeatability and materials quality validation	Improve reliability and increase reproducibility Improve robustness of results and increase yields Simplify design by reducing or removing defect-tolerant design criteria Lower R&D costs, shorter and fewer R&D cycles
Metrology for tooling and real-time feedback	Advanced analytical tools and sensors for probing a moving surface and metrology that extends beyond optical resolution Large-area metrology Metrology for obtaining measurement on a moving, reflective, and/or optically transparent web In-line flexible-substrate metrology for mechanical reliability, thermal effects, positional accuracy and reliability across a wide surface, processing on a fast-moving web	Point defect detection to eliminate additional processing for defective parts, lowering scrap rates and costs Catastrophic defect detection to eliminate portions of costly batch-level destructive testing at end of production run Quickly identify unit operation and quality issues during production runs Increase production speed
Technology for alignment and registration on a moving substrate	Technology to enable high throughput alignment	New products and decreased costs of existing products
Process modeling and controls	Process control (move to closed loop, develop and integrate sensors) Automated design flows Process simulation tools	Integration of smart manufacturing processes to support predictive understanding of frequency and source of errors, reducing both production scale-up time and machine downtime As scale increases, design for manufacturing becomes more important as do integrated sensors to support metrology
Terminology	Consistent international standards for nomenclature	Reduce uncertainty, lower transactions costs
Tooling for seam-free fabrication, including cylindrical masters that are seamless and have nanoscale fidelity	Removing the barriers that impede product size or length, thereby expanding product portfolios Removing the need to create molds from masters, which would greatly lower turnaround times, decrease wastage, and greatly decrease cost of goods	Removing the barriers that impede product size or length, thereby expanding product portfolios Removing the need to create molds from masters, which would greatly lower turnaround times, decrease wastage, and greatly decrease cost of goods
New materials and substrates	New materials formulations, especially for high-conductivity applications	Enable mass-produced flexible electronics, opening new markets. Reduced substrate defects would greatly lower costs and support product innovation

Figure ES-2. Interviewees' Rating of Importance of Technology Infrastructure Needs



Note: Respondents rated each need on a scale of 1 (not at all important) to 5 (very important). Shares of responses of 5 or 4 are indicated above the dotted line; shares of responses of 3, 2, or 1 are indicated below the dotted line.

ES.3.1 Standards and Measurement Technology for Input Materials

Interviewees regarded standards and measurement methods for input materials as one of the most important needs to address. Challenges in reliability and reproducibility are the primary reasons why companies incur excessive costs in validating the quality of their input materials and substrates. Despite the presence of industry associations, a robust standards infrastructure has not emerged because the proper combination of objectivity, funding, timelines, and knowledge has not been present to focus and sustain the effort.

The challenges related to standards and measurement technology for materials are emblematic of many fundamental barriers that bring about the failure of markets to provide essential technology. Standards and measurement technologies are not only challenging to develop but they also require buy-in from entire communities in order for them to have the desired effect. Although there is an incentive for firms to participate in standards development, standards must be developed by neutral, independent, and objective third parties or associations. Thus, stakeholders saw a clear role for NIST in the provision of standards and measurement technology for input materials and substrates.

ES.3.2 New Materials and Substrates

Several manufacturers noted that a primary barrier to flexible electronics is the lack of materials that can hold up to the thermal and mechanical stresses of the production process. Another barrier is that many metal-based inks oxidize very quickly, so separating the raw materials from humidity and environmental impurities is essential to maintaining the structural integrity of a product. New materials formulations, especially for metal inks, that can withstand processing conditions and support desired product characteristics are a critical gap. Likewise, substrate materials that are alternatives to PET, which suffers from variabilities, were mentioned as a critical need.

Development of precompetitive formulations and concepts for metal inks and substrates was a priority area. NIST is positioned to advance the science of printing, especially via building the knowledge base of how to make ink formulations and substrates compatible. The private sector is not generating and publishing this fundamental knowledge because they are unlikely to be able to capture any profits from their efforts, which in turn inhibits the technology's advancement.

ES.3.3 Patterned Tools

The technical and patent literature is replete with methods and concepts for making rolls for low-resolution applications; however, this body of work does not address the unique requirements of the formation of a continuous, high-fidelity patterned film demanded by industry.

Feedback across the range of manufacturers and R&D professionals pointed to the desire for cylindrical tooling with the following qualities, few of which are available today: submicron fidelity, seamless, long life (preferring metal tools over polymer), reduced cycle times, and tooling-specific metrology.

Our interviewees revealed that improvement in tooling would be significant for companies operating in thin-film manufacturing, as well as those with advanced electrical circuitry requirements. Like with standards and measurement technologies, the fundamental knowledge for the production of seam-free masters requires sustained, long-term focus and investment coupled with the scientific and technical knowledge that is beyond the near-term investment horizon of the young firms that constitute the industry.

ES.3.4 Metrology for Tooling and Real-Time Feedback

Manufacturers emphasized the need for metrology to detect defects before or during manufacturing for quality control, monitor the deposition of functional materials, and ensure correct alignment and registration, which is discussed further below. Real-time metrology tools would also help advance the R2R process and applications by analyzing data across numerous production runs. Metrology methodologies from traditional semiconductor industries are being applied, but adequate solutions do not yet exist.

The economic benefits of realizing such a metrology portfolio are expansive and include the following:

- midstream defect detection to eliminate additional processes for defective parts
- point defect determination to lower scrap rate
- characterization of the substrate's quality before using it
- real-time feedback of tooling and other additive printing processes to quickly identify unit operation issues during manufacture
- smaller data sets to increase process speed
- catastrophic defect detection for active devices to eliminate costly quality assurance/quality control testing of the end product
- elimination of destructive, batch-level quality control processes, such as cross-sectioning

As with metrology for input materials, metrology for tooling and real-time feedback were viewed by respondents as a classic role for NIST and areas in which market failure persists.

ES.3.5 Technology for Alignment and Registration on a Moving Web

It is difficult to achieve precise overlay and long-range placement accuracy in R2R because of the tendency of the flexible substrate to deform during processing; therefore, many potential high-value applications that require the precise and accurate placement of multiple levels of materials await improvements in metrology and control technologies. Single-level structures, used in applications such as optical films and controlled-energy surfaces, do not require such precision and were thus the first products developed using R2R.

Alignment and registration greatly affect the quality and yield of a product. The extent to which NIST could bring together sensing technologies and measurement systems to demonstrate manufacturing strategies for alignment and registration on a moving web would be valuable for flexible electronics manufacturers. Addressing this need requires a unique combination of multidisciplinary expertise and specialized facilities to solve a problem for an industry that does not have the requisite breadth of expertise and lab facilities in-house.

ES.3.6 Process Modeling and Controls

In close combination with metrology, real-time diagnostics complements the development of process modeling and control methods. R2R process models enable an improved, predictive understanding of frequency and source of errors in the manufacturing process. If reliable, modeling offers high return at low labor and materials costs. Although this modeling will not replace metrology and quality processes, it can improve the quality of the manufacturing process and reduce downtime and failure rates to reduce overall costs. Modeling also is the first step in scaling from a bench-scale or pilot system to a large production factory.

ES.3.7 Consistent International Terminology

R2R methods address a very diverse set of markets and products and include a multitude of unit operations. Defining these operations in terms that are well understood and characterized by industry, with industry-wide consensus, is crucial to support further development in the field. Currently, inconsistent process definitions, classifications, and taxonomies are applied across R2R platforms. These inconsistencies make it challenging to analyze the industry as a whole, as well as provide roadmaps and consensus.

Although some interviewees noted that consistent nomenclature and other like standards can be helpful for the industry, they are not a barrier. Several respondents during interviews characterized consistent terminology need as "nice to have" but not critically important. The extent to which NIST can support efforts that drive toward consistent terminology would be advantageous to manufacturers, but they would prefer that NIST allocate a marginal dollar to critical issues in standards and measurement technology.

ES.4 SUMMARY OF ECONOMIC IMPACTS

We estimate that the economic benefit of an improved technology infrastructure supporting R2R manufacturing would be at least $353 million per year (Table ES-2). This benefit, which is based on interview data and current costs of manufacturing for those industry sectors in which R2R is most used today, equates to approximately 15% of the total cost of goods sold (COGS) for R2R manufacturers in 2015.[1]

Table ES-2. Economic Impact of Meeting Technology Infrastructure Needs in R2R Manufacturing

	Estimated 2015 Expenditure			
Cost Category	$ Million	% of Total	Impact of Improved Technology Infrastructure[a]	Potential Cost Savings (Benefit)
Capital	153	6%	−8%	$12 million
Labor	574	24%	−25%	$144 million
Energy	44	2%	−7%	$3 million
Materials	1,621	68%	−12%	$194 million
Total	2,391	100%		$353 million

[a] Represents the mean estimated percentage change in the costs of production of meeting all technology infrastructure needs described by interviewees (see Section 4), holding production quantity constant. As described elsewhere in this report, meeting technology infrastructure needs is expected to de-risk advanced R2R manufacturing methods and thereby crowd in capital investment and expand R2R manufacturing activity, all else held equal.

[1] Total COGS for R2R manufacturing companies is estimated to be 51% of $4.7 billion in U.S. sales, or about $2.4 billion. Reducing the COGS by $353 million results in 14% savings.

Meeting critical technology infrastructure needs would de-risk the application of R2R manufacturing technologies and encourage, or “crowd in,” further investment by the private sector. Other key impacts noted by interviewees include improved quality, reduced timelines for product development, lower scrap rates, and increased system utilization and production yields (Table ES-3).

A potential overall production cost savings of 15% is significant, and it is clear that solving critical technology infrastructure barriers facing R2R manufacturers holds the prospect of greatly enhancing firms’ viability and competitiveness. Ultimately, R2R manufacturers’ competitiveness is closely related to their tooling and production process; increasing the accuracy, reliability, quality, and utilization of production lines would free resources for R&D, product development, and other activities.

Table ES-3. Impact on Common Performance Indicators

Indicator	Potential Impact
Product development and R&D cycle time	−17%
Quality control and inspection time	−25%
System utilization	+22%
Scrap rate	−23%
Sales revenue	+25%

1 Introduction

There has been a resurgence of interest in roll-to-roll (R2R) manufacturing methods because of the potential to print, essentially, large volumes of a product at high resolution inexpensively. R2R production methods are currently used primarily for optical films, such as light diffusers, but the potential to apply it to produce new products is driving innovation with this familiar production method.

Emerging product segments like flexible electronics are pushing technological boundaries as companies attempt to produce multilayered products with sophisticated attributes and small feature sizes using a process that keeps bendable substrates moving at a high rate of speed. Further development and widespread adoption of this manufacturing technology will require resolving key technical challenges in standards, metrology, and manufacturing technology platforms.

This report, commissioned by the National Institute of Standards and Technology (NIST), explores stakeholder perspectives on needs for technology infrastructure supporting R2R manufacturing and the potential economic impact of meeting these needs. The research supporting this report was informed by in-depth interviews with individuals representing manufacturers, university-based research centers, and manufacturing engineering consultancies.

R2R manufacturing has its roots in low-resolution/high-throughput newspaper and textile products, with methods that include offset, gravure, and ink jet printing. U.S.-based companies Kodak and Polaroid pioneered the use of R2R processes for advanced, multilayer coated film products, creating a new, more sophisticated manufacturing sector that leveraged the economies of scale. In parallel, advancements in the microelectronics sector enabled the generation of increasingly high-fidelity, complex two-dimensional (2D) and 3D patterns.

Manufacturing methods that merge the precision and uniformity of the microelectronics industries with the scale and cost structure of the films industries represent the R2R additive manufacturing of the present and future.

Early adopters focused on large patterned, single-level products—primarily optical film products, including microlenses, diffusers, and holograms. More recently, applications in printed electronics have emerged, requiring lower tolerances and offering lower costs than products produced with traditional batch semiconductor processes. The printed electronics industry has expanded into a broad range of market applications, including flexible electronics, diagnostics, displays, photovoltaics (PV), sensors, and energy storage. This means new sectors are contributing to innovation and development with R2R, including wearables, medical devices, pharmaceuticals, environmental technologies, and solar energy technologies.

This report explores how an improved technology infrastructure can accelerate the introduction and adoption of manufacturing technologies that would deliver new products and create more market opportunities for American companies.

1.1 DEFINITION OF TECHNOLOGY INFRASTRUCTURE

Technology infrastructure is the broad base of public and quasi-public technologies[2] and technical knowledge that support the research and development (R&D) and production efforts of firms, universities, and laboratories, as well as the development and adoption of improved and entirely new products, processes, and services (e.g., higher quality, more efficient, more productive).

Technology infrastructure supports and accelerates enhancements in advanced manufacturing capabilities. For R2R manufacturing, enhanced technology infrastructure has the potential to decrease cost and increase quality through infratechnologies, such as standards or reference information,

[2] Technologies with varying degrees of public good content.

and technology platforms, which are precompetitive technology concepts that can be adapted to meet specific applications (see Table 1-1).[3] It is often the case that the public sector supports the majority of technology infrastructure research because of its public-good content (Tassey, 2008).

Infratechnologies are a varied set of "technical tools" that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for physical and functional interfaces between components of systems technologies such as robotics and automation technologies. Historically, NIST has focused resources on this aspect of technology infrastructure. As written in Tassey (2008), "[c]ollectively they constitute a diverse technical infrastructure, various types of which are applied at each stage of economic activity." New infratechnologies often replace less efficient forms of infratechnology that support current standards (Tassey, 2008).

1.1.1 Infratechnologies

Infratechnologies provide the technical basis for standards that are set using consensus standard-setting processes that are usually led by industry organizations and/or government. Their benefits include full disclosure of information, reduced uncertainty regarding product attributes, and an overall improved level of trust that helps reduce market transaction costs.

The provision of infratechnologies requires a combination of industry and government investment because infratechnologies have substantial public good content (Antonelli and Link, 2015). Some industries depend on hundreds of distinct infratechnologies and associated standards. Furthermore, a

[3] Proprietary technologies are commercialized products, processes, and services that may be derivatives of technology platforms and have been influenced by infratechnologies. Generally, firm investments in proprietary technology fall under the category of R&D spending. Proprietary technologies that are relatively ubiquitous may have quasi–public good characteristics even though they are almost exclusively funded and developed by private-sector firms. These technologies are in-scope to the extent that the technology infrastructure on which we focus enables their development and adoption.

particular infratechnology may have spillover benefits for many industries.

Infratechnologies influence the development of technology platforms and proprietary technologies. They also support efficient R&D, production, and market transactions such as complying with customer requirements and regulations.

Table 1-1. Definitions of Key Concepts

Term	Definition	Examples
Technology infrastructure	The broad base of quasi-public technologies and technical knowledge that support the R&D and production efforts of firms, universities, and laboratories, as well as the development and adoption of improved products, processes, and services.	• Infratechnologies • Technology platforms
Infratechnologies	A varied set of "technical tools" that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for physical and functional interfaces between components of systems technologies such as factory automation and communications.	• Standard reference materials • Process models • Techniques for process and quality control • Calibration services • Traceability of measurements and test methods • Benchmarks and testbeds for characterizing a new technology's expected performance under realistic conditions • Objective characterization of performance attributes of component technologies • Reference datasets of materials properties
Technology platforms	Precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. A characteristic of a technology platform is that it will often be foundational to multiple products and processes, generally from multiple firms.	• Novel metal ink formulations and substrates • Technology for producing seamless patterned tooling • Technology for alignment and registration on a moving web

Note: A fourth classification—proprietary technologies—are commercialized products, processes, and services that are funded and developed almost exclusively by private-sector firms. These technologies are in-scope only to the extent that the technology infrastructure on which we focus enables their development and adoption.

1.1.2 Technology Platforms

Technology platforms are precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. These fundamental technical concepts originate from basic science research and can even be enabled by measurement infratechnologies (Link and Scott, 2010).

A characteristic of a technology platform is that it will often be foundational to multiple products and processes, the scope of which is typically broader than the business model of any one firm. Therefore, no firm is able to fully appropriate the benefits of investing in the development of a technology platform, so achieving the socially optimal level of investment will generally require additional public investment.

1.2 ANALYSIS SCOPE

This report identifies gaps in technology infrastructure inhibiting the development and adoption of advanced R2R production techniques in the U.S. manufacturing sector, and it quantifies the prospective economic benefits associated with addressing those gaps. The report also outlines specific potential opportunities for NIST to accelerate the development and adoption of critical technology infrastructure.

The research supporting this report was informed by primary data collection that consisted of interviews with experts in the R2R manufacturing community. It also was informed through a secondary collection of industry information.

Interviewed experts represented various stakeholder groups from across the R2R value chain.[4] We interviewed 45 experts from industry associations, universities, and research centers; developers of R2R manufacturing technologies; system integrators and consultants; and end users within the manufacturing sector. Because firms' tooling is a primary source of competitive advantage, many R2R end users develop their own manufacturing technologies. We specifically focused on end users in optical films, flexible electronics, biomedical

[4] The value chain concept is a broader concept than the supply chain. Value chains include any stakeholders that add value to the end product or process, whether through providing goods, services, knowledge, or coordination, for example.

applications, energy technologies, and environmental technologies.

1.3 BARRIERS TO THE DEVELOPMENT AND ADOPTION OF TECHNOLOGY INFRASTRUCTURE

A motivating factor for this study is that private investments in innovation and diffusion of new technologies typically generate social value in excess of their private returns. As a result, some socially productive technology investments are not undertaken because private firms do not perceive the research as profitable.[5]

The rate and extent of development of R2R production technologies and the rate and extent of their adoption in advanced manufacturing applications will depend on the parallel development and diffusion of technology infrastructure that is generally underprovided by the market. This resulting market failure—the failure of the market to allocate a socially optimal level of infrastructure investment—provides an opportunity to improve the efficiency of economic outcomes through public investments in technology infrastructure.

Table 1-2 lists eight barriers to investment identified in the literature.[6] These barriers that bring about market failure are present for R2R production systems and can be expected to result in a reduction of overall economic welfare unless they are addressed through public support or other means. Each barrier describes general R&D market failures, and some barriers are specific to technology infrastructure. Throughout this report we identify barriers that bring about market failure and discuss potential roles for NIST that may mitigate or eliminate these barriers.[7]

[5] The private rate of return is less than what is required (the private hurdle rate), even though the social rate of return exceeds that required by society (the social hurdle rate).

[6] The taxonomy of barriers presented here draws insight from Link and Scott (2010) and Jaffe (2005).

[7] Tassey (2010) provides an excellent discussion of the roles of infratechnologies and technology platforms in innovation.

Table 1-2. Barriers to Developing and Adopting New Technology That Bring about Market Failure

Barrier	General R&D Market Failures	Market Failures with Regard to Technology Infrastructure
Inability to appropriate all social benefits, such as positive network externalities	●	●
Scope of commercial applications is broader than the market strategy of any one firm	●	●
Risk that R&D outcomes will be technically insufficient (technical risk)	●	
Risk that R&D outcomes, although technically sufficient, will not be received well by the market, thereby providing an unacceptable return on investment (commercial or market risk)	●	
Long and uncertain lag between R&D investments and returns	●	
Asymmetric information between developers and adopters of new technology	●	●
Difficulties in bringing together component technologies from different industry segments	●	●
Industry structure, such as network externalities, presenting market-entry barriers to new technology	●	

1.4 NEEDED TECHNOLOGY INFRASTRUCTURE TO SUPPORT R2R MANUFACTURING

The needed technology infrastructures reviewed in this report are (Table 1-3):

- standards and measurement methods for input materials,
- new materials and substrates,
- patterned tools,
- metrology for tooling and real-time feedback,
- alignment and registration on a moving substrate,
- process modeling and controls, and
- consistent terminology.

Table 1-3. Technology Infrastructure Needs for R2R Manufacturing

Infrastructure Need	Technologies
Standards and measurement technology for input materials	Reference materials and quality standards Standard protocols and best practices to improve repeatability and materials quality validation
Metrology for tooling and real-time feedback	Advanced analytical tools and sensors for probing a moving surface and metrology that extends beyond optical resolution Large-area metrology Metrology for obtaining measurement on a moving, reflective, and/or optically transparent web In-line flexible-substrate metrology for mechanical reliability, thermal effects, positional accuracy and reliability across a wide surface, processing on a fast-moving web
Technology for alignment and registration on a moving substrate	Technology to enable high throughput alignment
Process modeling and controls	Process control (move to closed loop, develop and integrate sensors) Automated design flows Process simulation tools
Terminology	Consistent international standards for nomenclature
Tooling for seam-free fabrication, including cylindrical masters that are seamless and have nanoscale fidelity	Removing the barriers that impede product size or length, thereby expanding product portfolios Removing the need to create molds from masters, which would greatly lower turnaround times, decrease wastage, and greatly decrease cost of goods
New materials and substrates	New materials formulations, especially for high-conductivity applications

1.5 REPORT ORGANIZATION

This report is organized as follows:

- **Section 2** describes our data collection and analysis methods.
- **Section 3** describes industry trends and technology infrastructure needs described by study participants.
- **Section 4** presents quantitative impact estimates of the economic benefits of meeting industry needs.
- **Section 5** explores technology infrastructure needs, the associated technical hurdles, barriers that result in market failure, and how meeting these needs would have an impact.
- **Section 6** provides concluding remarks.

2 Analysis Methods and Data Collection

RTI conducted 45 interviews with industry executives, university faculty members, and independent researchers and consultants representing a cross section of the R2R research and manufacturing community. Many more informal conversations were held with individuals at conferences and industry events. These stakeholder engagement and interview activities were complemented with an extensive review of the relevant literature, issue briefs, and industry reports. The combined results of these activities built our knowledge base of R2R technology, key industries and application areas, and the barriers and pitfalls in R2R manufacturing that are preventing it from being fully optimized.

Interviews were particularly important for this study because there was little preexisting structured data about technology infrastructure needs in R2R manufacturing and the associated economic impact of meeting those needs. Several technology assessments, roadmaps, and opinion pieces allude to the need for and importance of technology infrastructure for R2R manufacturing, but no economic analysis exists that addresses what is admittedly a nuanced yet critically important issue in manufacturing technology development.

Our interviews investigated technology infrastructure needs, current research trends, barriers to technology adoption, benefits that could be achieved from an improved technical infrastructure, and potential roles for NIST. Quantitative information was collected on the potential benefits in terms of increased productivity, R&D efficiency, decreased production cost, and improved product quality. These quantitative impacts were used to calculate national economic impacts associated with an improved technical infrastructure to support R2R manufacturing.

This section presents our analytical approach to collecting and analyzing industry data and interview responses. These data were analyzed quantitatively using economic models that estimate the economic impact that enhanced technology infrastructure would have on the U.S. manufacturing sector.

2.1 INTERVIEW-BASED DATA COLLECTION

Interviews were selected as the principal mode of primary data collection (rather than a closed-form survey) because of the complexity of the subject matter and the need to be flexible with respect to the respondents' areas of expertise. This approach to data collection provided a richness of information that could not be obtained using close-ended survey methods. Our interview guide is included as Appendix A.

2.1.1 Industry Selection

We selected relevant sectors based on the manufacturing sectors where R2R technology is used or is expected to be used more broadly as the result of improved capabilities and enhanced infratechnology. Various industry reports, the membership of industry associations, and the composition of working groups, combined with the assessment of consulting industry experts, helped us determine the following sectors of primary interest:

- optical films
- electronics
- biomedical devices and drug delivery systems
- energy
- environmental technologies

These sectors are explored in detail in Section 3.

2.1.2 Interviewee Selection

RTI conducted 45 interviews that contributed to the analysis results presented in this report.[8] This total excludes informal

[8] More than 106 interviews were attempted, but most were unable to be completed because of the nuanced topic of technology infrastructure, because the targeted interviewee determined that he or she did not have enough information to provide responses with

conversations that were not facilitated by an interview guide and that occurred at conferences, industry events, or consultations with NIST or other technical experts working in government. Table 2-1 summarizes the industries (by detailed NAICS) represented by the actual respondents. Respondents represented a broad set of industries across all four types of advanced manufacturing.

Titles for interviewees included the following:

- Chief Technology Officer or Chief Operating Officer
- Chief Scientist
- President or Vice President
- Founder or Co-Founder
- Director of Manufacturing
- Senior Engineer
- Professor or Department Head
- Principal or Senior Consultant

The majority of interview participants were from goods-producing firms that either use R2R currently or have explored the potential for R2R's implementation. The remaining

Table 2-1. NAICS Codes for Industry Participants

NAICS	Title
33591	Battery manufacturing
325414	Biological product (except diagnostic) manufacturing
325992	Photographic film, paper, plate, and chemical manufacturing
326113	Unlaminated plastics film and sheet (except packaging) manufacturing
333314	Optical instrument and lens manufacturing
334413	Semiconductor and Related Device Manufacturing
334418	Printed circuit assembly (electronic assembly) manufacturing
334419	Other electronic component manufacturing
335931	Current-carrying wiring device manufacturing
541712	Research and Development in the Physical, Engineering, and Life Sciences (except Biotechnology)

confidence, or because he or she was concerned about discussing R2R technology development with a third party.

participants included researchers from universities and national laboratories and technology consultants with manufacturing and scale-up experience.

2.1.3 Interview Topics

Interview guides were developed and shared with respondents before the interviews. Interview questions included their expectations of impacts that new R2R technology infrastructure, access to knowledge, and other capabilities would have on their firm's capital, labor, energy, and materials expenses, as well as ancillary measures such as time required for quality assurance and control, scrap rate, and yield. We asked respondents to provide their quantitative answers in terms of percentage changes from today's baseline R2R processes to the counterfactual assumption that new technology capabilities would be available in 5 years. We also collected rich qualitative feedback and anecdotes on the specific tools and infrastructure technologies that NIST could help develop, as well as future products of interest and market opportunities, from both firms using R2R and organizations exploring its applied research.

Respondents' backgrounds: Respondents were asked to describe their background as it relates to R2R manufacturing and what share of their company's or industry's activities/ sales/research was associated with R2R manufacturing. Respondents were also asked if they were familiar with NIST's activities and/or if they participated in research organizations (standards, calibration and measurement, scientific or data exchange/analysis relevant to smart manufacturing).

Current and planned use of R2R manufacturing: Respondents were asked to provide a brief description of their company's current use of R2R manufacturing technologies and what additional areas of R2R manufacturing their company has considered, investigated, or researched for potential future adoption. For example, has the company conducted feasibility studies or developed preliminary cost/benefit models?

Barriers to adoption: Respondents were asked why they decided not to move forward (or are not moving as fast as they would like) with certain investments in R2R manufacturing.

A better state of the world: Respondents were asked what capabilities/technologies are needed to promote greater adoption of R2R manufacturing and how these enhanced capabilities/technologies would affect their manufacturing activities. Then respondents were asked to rank the importance of these capabilities along with the level of additional development needed.

Economic valuation: Given the enhanced capabilities/ technologies cited, respondents were asked about the impact of these technologies on their manufacturing processes, products, and services. They were asked to quantify these impacts in terms of percentage reduction in costs and improvements in productivity.

Importance: Respondents were asked to rate the importance of different R2R manufacturing capabilities and technologies.

Technology infrastructure needs: Respondents were asked about which areas needed the most research in terms of technology infrastructure and to identify specific research activities that should be pursued to further enhance R2R manufacturing capabilities and functionality.

NIST's potential role: Throughout the interviews, respondents were asked to consider the role NIST might play in supporting the development of an enhanced technology infrastructure. At the end of the interviews, respondents were asked to summarize their thoughts on NIST's role and what activities NIST should prioritize.

2.2 ECONOMIC ANALYSIS METHODOLOGY

Respondents provided percentage changes to capital, labor, energy, and materials (KLEM) costs for the proportion of their production that was relevant for R2R. They also provided data for other production variables, such as production yield and scrap rate. We limited the industries included in the quantitative analysis to only those sectors for which there is appreciable R2R manufacturing activity at present (Table 2-2).

Table 2-2. NAICS Codes Included in Economic Impact Model

NAICS		Applications
33591	Battery manufacturing	Energy, Sensors, and Other
325992	Photographic film, paper, plate, and chemical manufacturing	Optoelectronics
326113	Unlaminated plastics film and sheet (except packaging) manufacturing	Optoelectronics
333314	Optical instrument and lens manufacturing	Optoelectronics
334418	Printed circuit assembly (electronic assembly) manufacturing	Electronics
334419	Other electronic component manufacturing	Optoelectronics
325414	Biological product (except diagnostic) manufacturing	Energy, Sensors, and Other

Relevant sales data were collected during interviews or were pulled from annual reports, public filings, and the Hoover's database of company profiles. For larger firms with multiple lines of business where it was clear that the impact estimates only applied to a certain division, division-level sales were estimated using information from annual reports. Potential cost reductions were estimated to be a percentage of current sales.

To estimate costs-to-sales ratios for in-scope industries, we used the 2013 Annual Survey of Manufactures (ASM). Capital costs include capital expenditures on machinery and equipment (CEXMCH, RPMCH), computer and peripheral equipment (CEXMCHC, PCHCMPQ), and other machinery and equipment (CEXMCHO, RPMCH). Labor costs include production workers' annual wages (PAYANPW) grossed up to include nonwage benefits such as health insurance (BENHEA), retirement (BENPEC, BENPEB), and other fringe benefits (BENOTH). Energy costs include purchased fuels (CSTFU) and purchased electricity (CSTELEC). Material costs include materials, parts, containers, packaging, etc. (CSTMPRT).[9]

[9] We considered using industry data from the national accounts provided by the Bureau of Labor Statistics (BLS); however, the BLS data do not accurately identify "shop floor" activities for capital and labor because they have broader definitions of capital and labor. Although BLS did have appropriate definitions for energy and materials, the BLS data are only available at the 4-digit NAICS level. The R2R economic models are based on 5- and 6-digit NAICS codes because R2R remains a niche production technology. Thus, the ASM data that had the same level of industry detail were more appropriate.

Firm-level KLEM cost estimates then equal the estimate of firm or division sales times the relevant industry's cost-to-sales ratio based on the BLS (energy and materials) or ASM (labor and capital) data.

The proportion of in-scope industries for which R2R is applicable was estimated using market data compiled by BCC Research and published in the report *Global Markets for Roll-to-Roll Technologies for Flexible Devices.* According to BCC Research, the U.S. market for R2R technologies was estimated to be $4.7 billion in 2015. As Table 2-3 shows, 94%, or $4.4 billion, was associated with electronics manufacturing. Flexible printed circuits was the primary product line that the electronics category encompassed in 2015. Optoelectronics, which includes advanced displays and solid-state lighting, accounted for 5% of the R2R market, or $217 million, in 2015. The balance is primarily related to energy, including PV, flexible batteries, and supercapacitors.

In short, the combination of firm-level impact data, sales revenue and detailed cost data for selected industries, and estimates on the proportion of sales for those industries associated with R2R manufacturing permitted the estimation of national impacts.

2.3 CONSERVATISM OF ANALYSIS APPROACH

The quantitative economic impact estimates calculated in this study are considered to be conservative in that they do not capture all the benefits that would result from an improved technology infrastructure. As discussed below, our analysis focused on reductions in manufacturers' production cost

Table 2-3. Estimated Size of U.S. Market for Products Produced Using R2R

Industry/Application	2015 Sales Revenue ($ million)	% of Total
Electronics	4,406	93.6%
Optoelectronics	217	4.6%
Energy	80	1.7%
Sensors	5	0.1%
Total	4,707	100.0%

Source: BCC Research.

that would result from meeting the identified technology infrastructure needs. However, this does not capture all of the potential economic benefits associated with an enhanced technology infrastructure.

For example, tooling for seam-free fabrication (such as seamless cylindrical masters with nanoscale fidelity) could, by overcoming existing limitations to product size, enable the application of R2R technology in new product markets. These new products would have increased economic value stemming from enhanced attributes, such as greater functionality, lower maintenance costs, and increased life expectancy. However, valuing new (yet to be defined) products or product attributes is difficult, has great uncertainty, and is beyond the scope of this study.

An improved technology infrastructure will also lead to reduced R&D costs. However, interviewees were not able to quantify R&D savings, saying that the benefits would be a mixture of improved/accelerated R&D and enhanced product quality. Hence, these categories of benefits are discussed qualitatively but are not included in the quantitative economic impact estimates.

In general, focusing on manufacturing cost savings implies that the analysis captures primarily gains in producer surplus and does not capture gains in consumer surplus associated with improved product quality. In addition, the analysis does not capture increases in social welfare from increased output (sales), which result from lower cost and higher demand. The analysis also does not capture increased exports that would result from the enhanced competitive position of U.S. manufacturers.

For these reasons, the economic impacts presented are considered to be conservative, lower-bound estimates. These estimates should also be interpreted as benefits per year. Benefits were quantified for a single year using recent industry data at NIST’s request; enhanced technology infrastructure would last significantly longer than just 1 year.

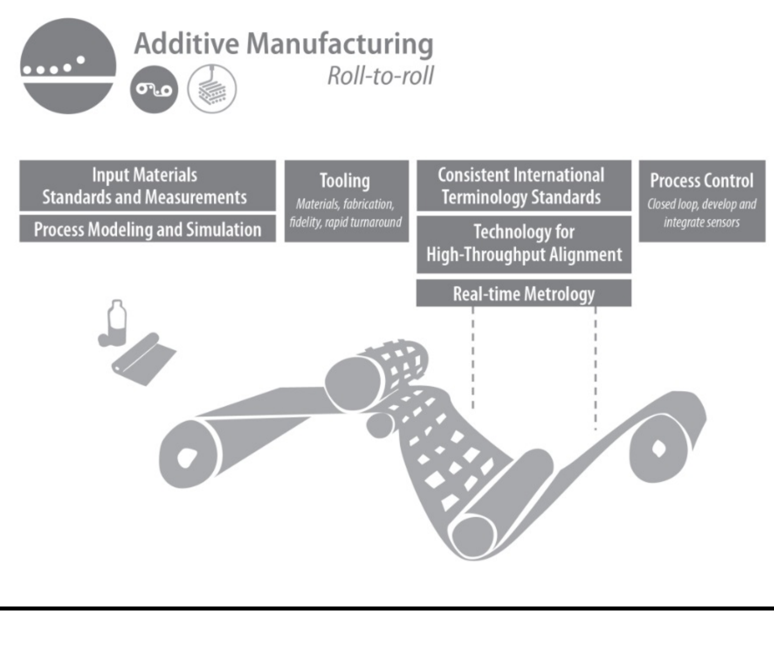
3 Industry Trends and Technology Needs

This section provides a high-level overview of R2R manufacturing methods, industry sectors and products for which it is relevant, and the technology infrastructure needs emphasized by the manufacturing and research communities as being of critical importance.

3.1 R2R MANUFACTURING METHODS

The R2R manufacturing platform can be broadly defined as a collection of processes whereby a flexible substrate (web) moves between two or more rolls, and materials are added (or less commonly, subtracted) from the web surface. In this manner, high volumes of solution-printed products can be manufactured. See Figure 3-1.

Figure 3-1. Technology Infrastructure Needs for R2R Additive Manufacturing



As described in the introduction, R2R manufacturing has its roots in low-resolution/high-throughput newspaper and textile products, with methods that include offset, gravure, and ink jet printing. U.S.-based companies Kodak and Polaroid pioneered the use of R2R processes for advanced, multilayer coated film products, creating a new, more sophisticated manufacturing sector that leveraged the economies of scale that are the inherent advantage of R2R processing.

In parallel, advancements in the microelectronics sector have enabled the generation of increasingly high-fidelity, complex 2D and 3D patterns. Process innovations have pushed this inherently high-resolution/low-throughput industry to larger areas and at a more rapid production rate, through molding, imprinting, embossing, and other replication techniques.

Manufacturing methods that merge the precision and uniformity of the microelectronics (semiconductor) industries with the scale and cost structure of the films industries represent the R2R additive manufacturing of the present and future. R2R manufacturing methods range in scale and throughput, from those that produce disposable printed radio-frequency identification (RFID) tags in large volumes to those that produce large-area, high-value devices in small volumes, such as PV films, and across markets, from medical devices to alternative energy. Opportunities and challenges exist across these seemingly diverse platforms.

New, emerging industries are taking advantage of the ability to generate high-fidelity patterned structures in a continuous, R2R additive process. The early adopters focused on large patterned, single-level products—primarily optical film products, including microlenses, diffusers, and holograms. More recently, applications in printed electronics have emerged, requiring lower tolerances and offering lower costs than products produced with traditional batch semiconductor processes. The printed electronics industry has expanded into a broad range of market applications, including flexible electronics, diagnostics, displays, PV, sensors, and energy storage.

Thus, the attractiveness of the R2R manufacturing process is the possibility of highly automated mass production of novel products at potentially very low per-unit cost. A variety of technologies allow high-speed printing, but resolution and the subsequent product categories vary widely depending on the method. Table 3-1 lists general R2R methods, an approximation of their minimum feature size, and a brief description.

R2R processes can be married to thin film coating processes, which entail depositing smooth and flat or conformal layers. Polymers and inks can be deposited and metered through rod, blade, and air-knife techniques. Metals can be added via vacuum deposition, electroplating, or electroless plating technique. Thin film processes cannot generate patterned surfaces inherently; they must be married with additive patterning techniques listed in Table 3-1.

Table 3-1. R2R Manufacturing Methods

Methods	Minimum Feature Size	Description
Offset printing	10–50 µm	An image is inked onto a plate and transferred (offset) onto a polymer/rubber film and then to the printed surface (newspaper printing).
Rotogravure	5–25 µm	An intaglio printing process in which a metal image carrier (patterned roll or tool) has an image cut or etched below the surface. As the roll rotates, ink fills the cells and is subsequently drawn out of the cells onto the substrate by capillary action (and often assisted by an electric field).
Flexogravure (or flexography)	20–50 µm	Similar to gravure, but with a patterned polymer roller. This technique forms the basis for most R2R imprint lithography techniques.
Inkjet printing	1–20 µm	Traditional inkjets work by pushing ink out of a nozzle to form droplets, either by heating the ink or applying physical pressure to force it out. To reduce droplet size, advancements have been made in inks as well as techniques such as electrohydrodynamic inkjet (e-jet) and piezoelectic printing.
Hot embossing	0.5–10 µm	Hot embossing is essentially the stamping of a pattern into a polymer softened by raising the temperature of the polymer just above its glass transition temperature.
Nanoimprint lithography (NIL)	0.01–1 µm	The extension of embossing processes to nanoscale features, where a photolithographically defined “master” is brought into contact with a fluid that is hardened through a phase change or photochemical reaction to yield a surface with nanopatterned relief. In R2R NIL, the “master” is a precisely patterned cylindrical tool.
Direct-write (or tip-based) manufacturing	0.005–1 µm	The use of massively parallel arrays of ion or electron beam columns or scanning probe lithography tips to directly generate a high-fidelity pattern.

3.2 R2R MANUFACTURING INDUSTRY SECTORS AND PRODUCTS

Because of their potential for low cost and high throughput, continuous additive processes like R2R are attractive methods for many product categories (Dumond and Low, 2011). Historically, R2R manufacturing was used to produce high volumes of disposable goods and other paper and plastic products. In recent years, however, R2R processes have been adapted to manufacture a range of products for various technology and mechanical applications. In some market segments it is not uncommon for firms using R2R to compete with firms who do not use it. R2R is therefore not just a production method but also a central element of a business strategy.

Table 3-2. Current and Future Industries and Product Categories for R2R Manufacturing

Industry Sectors	Example Product Categories	Materials Classes
Optical films	Microlenses Grating Transparent conductors IR reflectors Light guides Holograms	Polymers Ultrathin metal
Electronics	Flexible electronics, including printed circuit boards, displays, wearables, and disposables Sensors Storage and memory devices Thermoelectric devices RFID technologies	Polymers Metal inks Dielectrics Semiconductors
Biomedical devices and drug delivery systems	Microneedles Particles for drug delivery Diagnostics Antibacterial films	Polymers Ceramics
Energy	Thin film solar cells Battery electrodes	Metal inks and thin films Semiconductors
Environmental	Water purification Super hydrophobic coatings Anti-icing coatings Antifouling coatings	Polymers

Table 3-2 presents the industries and products offered by interviewees for this study with current or future applications and products for R2R methods. In many cases, the products produced in R2R processes are considered “intermediate products” that are later incorporated into a final product (e.g., an R2R-patterned touchscreen film that is incorporated with electronics and packaging to create an electronics device).

R2R processes are being developed for several sectors, including the electronics, optics, biomedical, energy, and environmental industries. Firms are seeking new innovative R2R processes for printing structures with increasing complexities (multilayered, multimaterial) and at high resolution (nanoscale) (Morse, 2011). Flexible electronics, for one, is a broad product category encompassing printed circuit boards, touchscreen displays, and PV cells, to name a few. The biomedical industry is also interested in R2R, as is the health industry in the form of monitors and smart packaging labels for food and pharmaceuticals.

Although there is consensus on the product categories and industrial sectors where R2R may establish a foothold, there is less consensus on what the size of the market may be within the next 5 to 10 years and what applications are likely to account for the greatest proportion of sales most significant for the industry.[10] MarketsandMarkets estimates $13 billion by 2020 for flexible devices. IDTechEx estimates $69 billion for printed, flexible, and organic electronics by 2026. Although the estimates and included product segments vary across these estimates, they all suggest growth in the application of R2R manufacturing methods. Using BCC data, we estimate the U.S. R2R industry to be $4.7 billion at present.

This analysis focuses on the following sectors:

- optical films
- electronics

[10] Several firms have developed market forecasts for specific applications, including BCC Research (R2R for flexible devices), IDTechEx (printed, flexible, and organic electronics), and MarketsandMarkets (flexible displays, batteries, sensors, memory, and PVs). BCC Research analyzed the market for applications specifically produced using R2R processes. Although the other market reports pertain to flexible devices in some way, the applications vary and are not necessarily specific to R2R.

- biomedical devices and drug delivery systems
- energy
- environmental technologies

3.2.1 Optical Films

Optical films have long been manufactured via R2R processes, ranging from simple light diffusers to products that incorporate complex holograms. It is now trending toward nanoscale features smaller than the wavelength of light.

Patterns include prisms, microlens, and other shapes at the micron to submicron scale to diffuse, redirect, or reflect light. Because both the lighting and electronics industries are constantly evolving, optical films will continue to advance to support new product development, including 3D and heads-up displays, and “smart” building technologies.

Some of the general applications where optical films are employed as an intermediate product include

- displays and screens;
- PV, or solar cells;
- light-emitting diode (LED) and organic light-emitting diode (OLED) lights; and
- windows.

3.2.2 Flexible Electronics

Although the majority of optical films are made from polymers, the technology has begun to crosscut with electronics through the use of advanced materials. Flexible electronics are a broad product category that encompass things such as printed circuit boards, touchscreen displays, and PV cells.

For example, metal inks, nanowires, or other conductive materials are being deposited onto thin films to produce functional touchscreens and displays for consumer electronics. When pairing these conductive optical films with printed circuitry, a new platform—flexible electronics—emerges. Inherently, R2R processes require flexible substrates such as plastic; polymer; or, more recently, flexible glass. Printing electronics on a moving web implies that the materials and structures be somewhat flexible; thus, the term “flexible electronics” is often used when referring to materials produced using R2R processes.

Flexible electronics is driving the development of new applications, materials, and manufacturing processes. Circuit boards, wearables, disposables, sensors, semiconductors, and storage and memory devices are all components that are in laboratory development, early stage development, or pilot manufacturing.

Advanced manufacturing in the R2R process field will be largely focused on flexible electronics, a market that is expected to grow significantly over the medium and long terms. According to a survey conducted by FlexTech Alliance, 56% of electronics retailers, medical and health care providers, and sporting goods manufacturers intend to purchase implantable sensors, wearable electronics, and other technologies in demand within the next 3 years (FlexTech Alliance, 2014).

Though in the early stages of development, organic electronics may become a player in the longer-term outlook for flexible electronics (more than 3 years) (Lupo et al., 2013). Some electronics that feature organic (nonmetallic) molecules have already reached the market, most notably OLED televisions. Other electronics—organic or otherwise—that are under development or furthering development for the electronics and energy industries, broadly, include

- PV, or solar cells;
- LED-based lighting and smart textiles (wearables);
- RFID cards and tags;
- flexible batteries; and
- memories and sensors.

Additionally, flexible electronics will not only drive new product lines into the market, but also the packaging and delivery systems that control the distribution and retail of goods. Because of this, industries that are neither producers nor consumers of flexible electronics may use the technology to support their own products and services.

3.2.3 Biomedical

The biomedical industry is currently developing R2R processes to mass produce particles for drug delivery, microneedles, antibacterial films, and other products specific to industry needs. In the particle-based therapeutic field, R2R technology has merged with microelectronics precision to produce particles of different shapes and sizes. The manufacturing platform enables novel size and shape characteristics that play a large part in determining the effectiveness of drug delivery, and improvements and continual iterations to the manufacturing process will likely extend well into the long term.

Microneedles are another form of drug delivery by permeating the skin to allow a drug to dissolve in the body. Patches are one of the mechanisms whereby microneedles can be administered and have been manufactured through R2R methods to a limited extent. Patches have been used for a number of years to deliver therapeutic compounds into the body, and recently they have been explored for vaccines (Kim, Park, and Prausnitz, 2013). In a collaborative effort by researchers at Georgia Tech, Emory University, and the Centers for Disease Control and Prevention, a new patch containing 50 microneedles has been tested for delivering the flu vaccine (Med Gadget, 2014). Although the patch was only tested for skin permeability and did not deliver the flu vaccine, delivery by means of microneedles will likely be explored in the short term to promote vaccinations and other therapeutics, avoiding needle-phobia, inconvenience, or other factors preventing higher rates of vaccination (Giudice and Campbell, 2006). The longer-term potential for microneedles in the biomedical field could be the permeation of smaller, more sensitive surface areas, such as the eye or individual cells (Jiang et al., 2009).

A growing concern for hospitals and health care facilities is maintaining a sterile environment and eliminating costly hospital-acquired infections (Page et al., 2009). Antimicrobial films produced by R2R processes that contain metals (e.g., copper, silver) or patterned surfaces act to kill or limit the growth of microorganisms (Michels et al., 2005). Aside from the biomedical industry, these films have utility for consumer applications on a multitude of industrial and household surfaces to prevent the spread of microorganisms and infections.

Lastly, there is an increasing interest in leveraging flexible electronics in wearable electronic devices, such as smart watches, for human performance monitoring (Thompson, 2014). Current state-of-the-art technology is able to measure, record, and report biometrics such as heart rate, blood pressure, and skin temperature. For example, members of the Nano-Bio Manufacturing Consortium, with support from the Air

Force Research Laboratory, are investing in research for real-time biomarker analysis in flexible, wearable electronic devices. This real-time analysis would theoretically be able to read and report biomarkers for cognitive effectiveness, fatigue, stress, and the wearer's exposure to chemical and/or biological agents.

3.2.4 Energy

The Department of Energy (DOE) has identified many beneficial applications of the R2R process within the energy arena, which include the creation of membranes for hydrogen gas separation, airflow panel membranes, proton exchange membrane fuel cells, polymeric and ceramic/metallic membranes for CO_2 separation, and battery/super capacitor/superconducting cable/sensor technologies (Johnson, 2015). In addition, more efficient solar cells, coupled with less costly manufacturing inputs, will lower the fixed costs associated with installing solar energy-capturing infrastructure while increasing energy output.

To retain competitiveness in the global market, existing PV firms have focused on increasing module efficiency, reducing operating costs, and increasing capacity utilization at factories. Even though reports of record-setting efficiencies in the different PV technologies are a regular occurrence, their cost/efficiency ratios have yet to reach the levels required to compete with grid electricity. Components and modules made via R2R processes offer a compelling opportunity to add critical efficiencies within a practical manufacturing process and a reasonable cost structure to increase the competitive potential of solar product lines. Aftermarket products, including patterned optical film that acts to reduce reflectance losses on the top surface of the solar cell and antidust coatings, have gained global interest and attention.

Additionally, many products described in the above optical films category have a significant role as energy-efficient technologies. Window films that reflect infrared light significantly reduce cooling costs, while light-redirecting films increase natural lighting and reduce luminaire needs. Diffusers and reflector films with high efficiencies lower the cost of lighting by extracting more light from each fixture.

3.2.5 Environmental

Surface protection is also important to maintain longevity and efficiency in applications that experience punishing environmental conditions. In maritime applications, R2R processes are being investigated to manufacture superhydrophobic coatings designed to repel water or slow the growth of organisms on a ship's hull using antifouling. Similar materials and manufacturing processes are used to produce anti-icing coatings for removing or preventing frozen moisture (Cao et al., 2009).

Much like particles for drug delivery, R2R processes can manufacture particles that are suspended in a solution or membrane until they are put to use. Water purification is an example of this sort of nonmedical application, whereby particles made of a combination of materials purify water through various filtration methods (Crittenden et al., 2012).

3.2.6 Other Application Areas

Myriad other applications are possible, often in the area of hybridizing flexible electronics with other products, such as clothing or packaging.

Integrating digital sensors and interactivity into packaging products is largely in the early-stage R&D phase, primarily supported by research grants and industry–university collaboration. In the nearer term for smart packaging, there is interest in monitoring the quality and safety of food and pharmaceuticals. One interviewee at a university noted that it is only a matter of time before smart labels are mandatory for health and food products. Detecting freshness, spoilage, pathogens, or tainted or counterfeit compounds is a likely application of this technology. However, until smart sensors can be cost-effectively produced, it is unlikely that other markets, such as those for consumer products, will adopt them.

R2R has the potential to yield components that can be integrated into different products, enabling new functionalities, product features, and characteristics.

3.3 PUBLIC–PRIVATE INITIATIVES ADDRESSING TECHNOLOGY NEEDS IN R2R MANUFACTURING

R2R manufacturing technologies are complex, fast-moving systems that require precision to successfully manufacture products. Industry groups and government initiatives have formed to address common challenges, and their efforts complement those for which there is a strong case for NIST applying its technical and standards coordination expertise, as reviewed in-depth in later sections of this report.

Among those industry groups with a significant proportion of members using or developing advanced R2R systems are FlexTech Alliance, Nano Bio Manufacturing Consortium, and Organic Electronics Association (Table 3-3). These associations facilitate working groups on issues related to technology infrastructure, including standards development and precompetitive research. Often NIST staff members are integrated into activities, although NIST is not formally a sponsor.

Government support for R2R as a method for manufacturing products in the public interest has emerged. Since President Obama’s 2009 call to grow and progress a national advanced manufacturing initiative, the White House and Congress have encouraged and orchestrated the formation of multiple “innovation hubs” around the United States whose mission is to

Table 3-3. Industry Associations Active in R2R Manufacturing

Association	Example Activity
FlexTech Alliance	The largest member-based industry organization in the R2R space, FlexTech has awarded numerous research projects to industry and academic partners, covering such topics as flexible tablet devices, flexible ceramics, R2R printing of large-area energy-harvesting devices, and digital fabrication of large-area hybrid sensing systems.
Nano Bio Manufacturing Consortium (NBMC)	Established by the FlexTech Alliance and other partners for the Air Force Research Laboratory, the NBMC focuses specifically on biological and nanoparticle materials in R2R manufacturing.
Organic Electronics Association (OE-A)	OE-A focuses on organic and printed electronics and has established working groups centered on specific thrust areas in the flexible electronics industry. Among the areas of focus is a group for standardization, quality control, and measurement.

pursue the missing middle of the U.S. advanced manufacturing sector—the link between government agencies and their university counterparts, and the private sector. As a result of the call to form such organizations, agencies such as the Department of Defense (DoD), DOE, NIST, and the National Aeronautics and Space Administration (NASA) have launched initiatives that focus on major processes that can rapidly accelerate the U.S. advanced manufacturing industry.

Under the National Network for Manufacturing Innovation, NextFlex—the Flexible Hybrid Electronics Manufacturing Innovation Institute—convenes government agencies, academic departments, and industry to address common challenges associated with manufacturing flexible hybrid systems (e.g., device scale-up and process optimization, reproducibility, substrate selection and formation, adaptation of validated tools and models). NextFlex coordinates working groups and provides funding and support mechanisms for the development of technologies to improve R2R manufacturing of flexible electronics.

Application areas for government agencies include

- wearable technologies for use as soldier information devices, sensors, and performance monitors (DoD);
- sensors for data collection during space missions (NASA); and
- creating efficient, low-cost, and durable materials and technologies for solar PV cells, carbon fibers, light emitting diodes (LEDs), and electric vehicle batteries (DOE).

NextFlex is the largest public–private partnership for R2R in the United States and is operated under a cooperative agreement awarded by DoD to the FlexTech Alliance. The $75 million award from DoD was matched with $96 million in cost sharing from a mix of public and private sources (see Table 3-4).

Table 3-4. NextFlex Membership

Membership Category	Members
Corporate	The Boeing Company; Brewer Science, Inc.; Eastman Chemical Company; General Electric Company; United Technologies Research Center; Acellent Technologies Inc.; American Semiconductor, Inc.; Custom Electronics, Inc.; E Ink Corporation; Jabil; Molex, LLC; On Semiconductor; Raytheon; SI2 Technologies, Inc.; SRI International; STI Electronics; Uniqarta, Inc.; Harris Corporation; i3 Electronics, Inc.; Integra Lifesciences; Optomec; PARC, a Xerox Company
Academic/nonprofit	Auburn University; Binghamton University; Georgia Tech Research Corporation; University of Massachusetts Lowell; University of Texas at Austin; Purdue University; University of Arizona; University of Connecticut; University of Washington; Washington State University; Western Michigan University; University of Arkansas; California Polytechnic State University; Clemson University; Rochester Institute of Technology; UC San Diego; University of Massachusetts Amherst
Federal government	U.S. DoD; Department of Defense Manufacturing Technology Program; U.S. Department of the Army; U.S. Department of the Air Force; U.S. Department of the Navy; Defense Threat Reduction Agency; DoD Laboratories; Defense MicroElectronics Activity; Defense Advanced Research Projects Agency; U.S.DOE; NASA; NIST; U.S. Forest Service; National Science Foundation; U.S. Department of Education; Food and Drug Administration; National Institutes of Health
Local government	City of San Jose, California

Source: NextFlex.

Other publicly funded efforts in advancing R2R technologies exist. For example, there is the Center for Hierarchical Manufacturing, which is led by the University of Massachusetts Amherst, and the Center for High-Rate Nanomanufacturing at Northeastern University. Both are funded by the National Science Foundation.

3.4 TECHNOLOGY INFRASTRUCTURE GAPS IN R2R MANUFACTURING

This section discusses interviewees' assessments of key gaps in the technology infrastructure supporting R2R manufacturing. It also considers the urgency and priority for increased investment to mitigate them (see Table 3-5 and Figure 3-1). The key gaps are

- standards and measurement methods for input materials,

Table 3-5. Infrastructure Needs and Potential Impacts: R2R Manufacturing

Infrastructure Need	Potential Impacts
Standards and measurement technology for input materials	
Reference materials and quality standards Standard protocols and best practices to improve repeatability and materials quality validation	Improve reliability and increase reproducibility Improve robustness of results and increase yields Simplify design by reducing or removing defect-tolerant design criteria Lower R&D costs, shorter and fewer R&D cycles
Metrology for tooling and real-time feedback	
Advanced analytical tools and sensors for probing a moving surface and metrology that extends beyond optical resolution Large-area metrology Metrology for obtaining measurement on a moving, reflective, and/or optically transparent web In-line flexible-substrate metrology for mechanical reliability, thermal effects, positional accuracy and reliability across a wide surface, processing on a fast-moving web	Point defect detection to eliminate additional processing for defective parts, lowering scrap rates and costs Catastrophic defect detection to eliminate portions of costly batch-level destructive testing at end of production run Quickly identify unit operation and quality issues during production runs Increase production speed
Technology for alignment and registration on a moving substrate	
Technology to enable high throughput alignment	New products and decreased costs of existing products
Process modeling and controls	
Process control (move to closed loop, develop and integrate sensors) Automated design flows Process simulation tools	Integration of smart manufacturing processes to support predictive understanding of frequency and source of errors, reducing both production scale-up time and machine downtime As scale increases, design for manufacturing becomes more important as do integrated sensors to support metrology
Terminology	
Consistent international standards for nomenclature	Reduce uncertainty, lower transactions costs
Patterned tools	
Tooling for seam-free fabrication, including cylindrical masters that are seamless and have nanoscale fidelity	Removing the barriers that impede product size or length, thereby expanding product portfolios Removing the need to create molds from masters, which would greatly lower turnaround times, decrease wastage, and greatly decrease cost of goods
New materials and substrates	
New materials formulations, especially for high-conductivity applications	New formulations for metal inks will enable mass-produced flexible electronics. Reduced substrate defects would greatly lower costs and support product innovation

- new materials and substrates,
- patterned tools,
- metrology for tooling and real-time feedback,
- alignment and registration on a moving substrate,
- process modeling and controls, and
- consistent terminology.

Several respondents mentioned that their own R&D activities target select gaps—albeit to varying degrees of success—with one interviewee going so far as to state that the ability to address challenges can be viewed as a competitive advantage. Firms that can develop seamless patterned tools, for example, that reproduce features at high fidelity have a stronger market position and potentially broader product portfolio than those that cannot. He went on to note that his firm's process-related R&D in the face of technology infrastructure gaps consumes resources that would otherwise be directed toward product development. Thus, R&D efficiency would be greatly improved if problems common to all manufacturers were addressed.

Our interviews revealed that firms are spending money duplicating one another's efforts to address strikingly similar challenges: validating the quality of input materials, building reference databases, sorting out alignment and registration on moving substrates, and developing real-time metrology and process modeling software and tools. This is particularly inefficient given that many manufacturers using R2R processes are small- to medium-sized companies or start-ups aspiring to introduce disruptive products to the market.

In describing technology infrastructure gaps, small firms in particular noted how many related to the significant hurdles of scaling-up pilot R2R processes. Increasing the width of the web, line speed, and tooling capacity greatly increases the rate of error during production. Measuring a scaled-up R2R system is also more difficult because of the additional material, greater surface area, and increased speed. Thus, tools and techniques for scaling up production processes would be helpful to achieve increased yields without sacrificing quality.

4 Economic Impact of Meeting Technology Infrastructure Needs

We estimate that the economic benefit of an improved technology infrastructure supporting R2R manufacturing would be at least $353 million per year. This benefit, which is based on interview data and current costs of manufacturing for those industry sectors in which R2R is most used today, equates to approximately 15% of the total cost of goods sold (COGS) for R2R manufacturers in 2015.[11]

Note that this $353 million estimate is conservative because it is based on the size of the market today and does not take into consideration the impacts associated with market transformation, earlier introduction of novel products and services, benefits to consumers, or other types of benefits. The estimate is simply the potential impact using known information. It was apparent from our interviews that addressing these critical needs has the potential to help the industry be more competitive in the marketplace, be more cost competitive, improve quality, and hasten the introduction of new products with novel functionality.

4.1 SUMMARY IMPACT

Meeting critical technology infrastructure needs would de-risk the application of R2R manufacturing technologies and encourage, or "crowd in," further investment by the private

[11] Total COGS for R2R manufacturing companies is estimated to be 51% of $4.7 billion in U.S. sales, or about $2.4 billion. Reducing the COGS by $353 million results in 14% savings.

sector. Other key impacts noted by interviewees include improved quality, reduced timelines for product development, lower scrap rates, and increased system utilization and production yields.

The composition of our $353 million impact estimate is presented in Table 4-1. Holding production quantities constant, study participants believe that if needs were met today, the economic benefit would be equivalent to a 25% reduction in production-related labor expenditure, 12% in materials costs, 8% in capital expenditure, and 7% in energy expenditure.

A potential overall production cost savings of 15% is significant, and it is clear that solving critical technology infrastructure barriers facing R2R manufacturers holds the prospect of greatly enhancing firms' viability and competitiveness. Ultimately, R2R manufacturers' competitiveness is closely related to their tooling and production process; increasing the accuracy, reliability, quality, and utilization of production lines would free resources for R&D, product development, and other activities.

When providing their impact estimates, study participants also shared their perspectives on such topics as changes in production yields, scrap rates, and system utilization. This section reviews those impacts that relate to the combined economic impact of meeting technology infrastructure needs. Analysis of the potential impacts meeting specific needs are presented in Section 5.

Table 4-1. Economic Impact of Meeting Technology Infrastructure Needs in R2R Manufacturing

Cost Category	Estimated 2015 Expenditure: $ Million	Estimated 2015 Expenditure: % of Total	Impact of Improved Technology Infrastructure[a]	Potential Cost Savings (Benefit)
Capital	153	6%	−8%	$12 million
Labor	574	24%	−25%	$144 million
Energy	44	2%	−7%	$3 million
Materials	1,621	68%	−12%	$194 million
Total	2,391	100%		$353 million

[a] Represents the mean estimated percentage change in the costs of production of meeting all technology infrastructure needs described by interviewees (see Section 4), holding production quantity constant. As described elsewhere in this report, meeting technology infrastructure needs is expected to de-risk advanced R2R manufacturing methods and thereby crowd in capital investment and expand R2R manufacturing activity, all else held equal.

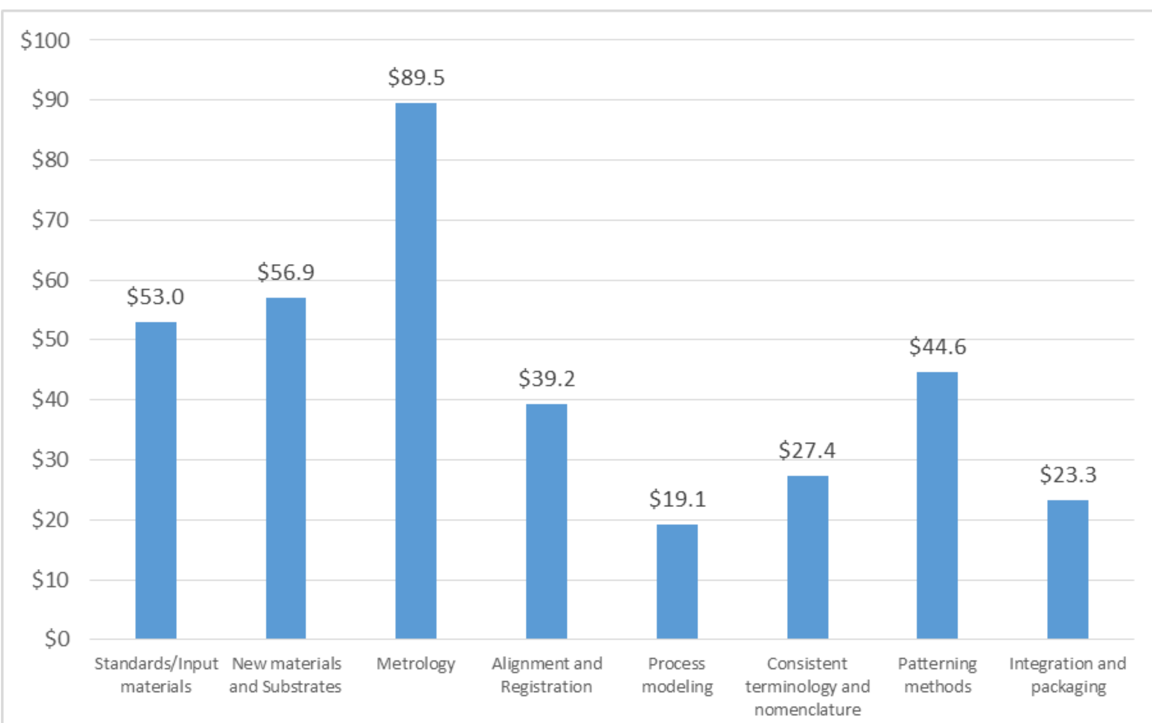
Figure 4-1 presents impact results by technology infrastructure need. An exploration of participants' perspectives on needs is in Section 5, but comparing their assessments with our economic impact data suggests that meeting needs in metrology, standards and measurement protocols for input materials, and new materials and substrates would have the greatest impacts.

4.2 CAPITAL EXPENDITURES

On average, we estimate an 8% reduction in capital expenditures for a potential benefit of $12 million, all else held equal. Underlying this result, however, are three narratives provided by study participants that explain the impact and that have the effect of dampening the potential cost savings:

- no change in capital expenditures
- an increase in capital expenditures to incorporate new capabilities as a result of an improved technology infrastructure
- a reduction in capital expenditures

Figure 4-1. Economic Impact by Technology Infrastructure Need Area



One-third of private companies and research groups saw no net change in their capital expenditures for production activities, exclusive of any investment that would bring new production capacity online. Respondents in this group believed that any capital savings would essentially be offset by the cost of new sensors or other technologies. They emphasized that the majority of their savings would be in terms of reductions in labor and materials costs.

A second third expected that the new capabilities enabled by an improved technology infrastructure would increase their capital expenditures. This group of respondents, which are predominantly companies operating in the flexible electronics and optical films market segments, predicted, on average, a 10.5% increase in capital expenditures (range of 5% to 15%). Improved standards, metrology, and technology platforms would reduce technical and business risks and thereby increase the willingness of corporate boards and investors to invest.

The final third predicted significant reductions in capital expenditures on the order of 20 to 30%. These respondents predicted that an improved technology infrastructure would, in particular, avoid expenditures on instrumentation and equipment for the development of masters, as well as lower the overall cost of tooling development.

Section 5 explores the relationship between specific technology infrastructure needs and the optimization of capital expenditures in depth.

4.3 LABOR EXPENDITURES

Despite its promise of highly automated production, at present R2R manufacturing often requires a significant amount of manual intervention at multiple stages of production. Respondents uniformly predict significant reductions in production labor costs: $144 million. This is equivalent to 25% of the current cost of manufacturing labor.

Manufacturers report what they view as an excessive amount of inspection of incoming materials. For example, the quality of polyethylene terephthalate (PET)—a commonly used substrate material—must be closely inspected to ensure that surface roughness and energy are within acceptable parameters. Likewise, there is significant batch-to-batch variability for inks and little by way of robust standards to facilitate market transactions. Most manufacturers conduct comprehensive testing and characterization of inks to ensure they will produce the desired product attributes.

Tooling is closely monitored during production runs. It must also be frequently inspected to ensure that alignment and registration are acceptable. For many production lines, patterned drums (tools) must be regularly replaced, which equates to teardown time and increased risk of damaging the products and tooling via handling. Improved or replacements to patterned drum technologies could reduce these costs.

Furthermore, improved metrology and process control could reduce the amount of labor expended on quality control and final product inspection. Some manufacturers reported hand picking and sorting of final product in addition to extensive testing of a substantial proportion of product.

4.4 MATERIALS EXPENDITURES

Interviewees described a significant amount of waste resulting from inadequate process control and the inability to measure, identify, and address defects during production runs. Improving defect management would have a significant beneficial impact on scrap rates and costs of goods sold. Failed production runs due to defects are scrapped. Defect management related inadequate process control is one of the main inhibitors to R2R production of some products, such as transistors.

Addressing technology infrastructure needs would provide a 12% reduction in materials expenditures (holding production quantities constant), which amounts to $194 million given current industry data.

The potential for standards and metrology to unlock value in materials expenditures is the single most important benefit described by interviewees. Raw materials markets are generally viewed as being competitive, with little room for any appreciable reduction in unit prices. But there are periodic shortages of some materials, which can cause costly downstream disruption and delay, and some raw materials are simply very expensive, costing hundreds of thousands of dollars per gram. Reducing scrap rates through better process control and metrology is therefore a priority, but the necessary science, engineering, and technology development is expensive and beyond most manufacturers' capabilities, manufacturing R&D budgets, or both.

4.5 IMPACT ON COMMON PERFORMANCE INDICATORS

Table 4-2 presents an assessment of how an improved technology infrastructure would affect common performance indicators used by manufacturers:

- 17% reduction in product development time
- 25% reduction in quality control and inspection time
- 22% increase in overall system utilization
- 23% reduction in scrap rate
- 25% increase in sales volume over current projection in the near term

4.5.1 R&D Cycle Times

Meeting technology needs would have a significant impact on R&D-related spending and product development cycle times, perhaps reducing such cycle times by about 17%. A significant amount of resources is consumed by overcoming inadequacies with the existing technology infrastructure, especially for start-ups and small- to medium-sized manufacturers.

Most firms would redirect cost savings resulting from improved metrology, improved mastering and seam-free tooling, or better materials formulations toward product development. There is potential to improve existing products as well as launch entirely new ones that would be possible only because the process control, materials, and manufacturing capabilities are available.

Table 4-2. Impact on Common Performance Indicators

Indicator	Potential Impact
Product development and R&D cycle time	−17%
Quality control and inspection time	−25%
System utilization	+22%
Scrap rate	−23%
Sales revenue	+25%

At present, replicating the same quality at production scale as in the laboratory environment is a key roadblock inhibiting further development of the industry. An improved technology infrastructure would greatly facilitate scaling product concepts from the laboratory to a production setting.

4.5.2 Time Requirements for Quality Assurance and Control

The impact on time requirements for quality assurance (preproduction activities) and control (postproduction activities) is estimated to be a 25% reduction, all else held equal. As described earlier in this section, there is significantly more materials inspection and quality control that is required and that would be unnecessary with more robust standards and measurement technologies.

4.5.3 Scrap Rate

The reduction in materials expenditures per unit of output described in Section 4.4 results from lower scrap rates. Study participants think they would be able to reduce this rate by about 23%, on average, by adopting and incorporating the new capabilities enabled by improved metrology. Scrap rates today are higher than they should be because of inadequate defect management, process control, or materials characterization because that metrology is not available.

4.5.4 Sales Revenue

Increases in quality, reliability, and yield paired with new production capabilities would lead to lower prices and expanded markets, with market expansion dominating so that the combined effect is to increase sales revenue. The increase in sales revenue was estimated to be about 25%.

All respondents saw opportunities to expand the market for existing products or product lines and branch into entirely new ones. As one interviewee noted, "[m]any product types suitable for R2R manufacturing can already be produced using other methods. … [The goal] is to somehow go from established processing procedures that have been developed for silicone or glass to flexible substrates where you have less subtractive processes and more additive, producing large volumes inexpensively." Respondents highlighted opportunities in lighting, environmental and energy applications; RFIDs; and flexible electronics as within reach given an improved technology infrastructure. Finally, the impact estimate for R2R is smaller than RTI's estimates for companion studies in advanced robotics and automation, smart manufacturing, and additive manufacturing. This is because the overall market today is comparatively small, the use of R2R manufacturing technology is still emerging, and uncertainties remain in several potential applications about the financial viability of R2R production systems. Those uncertainties themselves related back to the technology infrastructure needs. There is a direct link between the development of a robust technology infrastructure supporting R2R manufacturing and the economic viability of this approach to manufacturing (and the resultant products).

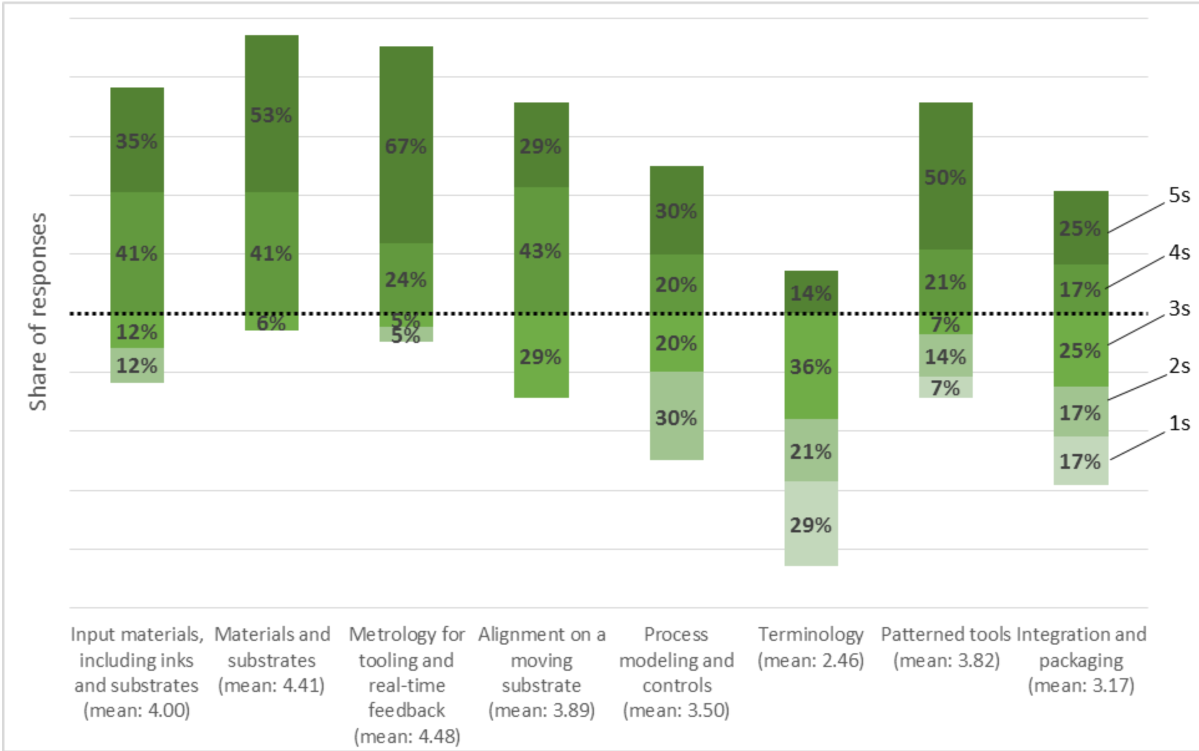
5 Stakeholder Perspectives on Technology Infrastructure Needs

This section explores stakeholder perspectives on the technology infrastructure needs whose impacts were explored quantitatively in the preceding section. For each of the following needs, we explore expected impact, the underlying market failures that have prevented progress, and potential roles for NIST:

- standards and measurement technology for input materials
- new materials and substrates
- patterned tools
- metrology for tooling and real-time feedback
- technology for alignment and registration on a moving web
- process modeling and controls
- consistent international terminology

Using a Likert scale, interviewees rated the importance of addressing the needs from “very important” to “not at all important” (Figure 5-1). Metrology for tooling and feedback was identified to be the most important technology infrastructure need, followed by the development of new materials and substrates and measurement and standards for those materials.

Figure 5-1. Interviewees' Rating of Importance of Technology Infrastructure Needs



Note: Respondents rated each need on a scale of 1 (not at all important) to 5 (very important). Shares of responses of 5 or 4 are indicated above the dotted line; shares of responses of 3, 2, or 1 are indicated below the dotted line.

5.1 STANDARDS AND MEASUREMENT TECHNOLOGY FOR INPUT MATERIALS

Input materials for R2R processing fall into two general categories: fluids, in the form of polymer solutions and metal inks, and substrates, primarily plastic film.

Fluid deposition is the primary means for adding materials to a surface in an R2R process; these materials are often subsequently patterned to yield functional surface relief (e.g., light guiding, hydrophobicity). For fluids applied in R2R processes, the desired properties, depending on application, can include viscosity, surface tension, refractive index, color, electrical conductivity, toughness, surface energy, and many more.

The R2R substrate, also referred to as a "web," generally acts as a carrier for the deposited fluid but can also provide functionality by adding optical, mechanical, or thermal benefits.

The substrate choices are generally more limited to drawn polymer films, and polyesters such as PET are the most commonly used.

Interviewees regarded standards and measurement methods for input materials as one of the most important needs to address. Challenges in reliability and reproducibility are the primary reasons why companies incur excessive costs in validating the quality of their input materials and substrates. Despite the presence of industry associations, a robust standards infrastructure has not emerged because the proper combination of objectivity, funding, timelines, and knowledge has not been present to focus and sustain the effort.

5.1.1 Standards and Measurement Methods for Fluids and Metal Inks

R2R is limited by the performance and quality of existing materials, particularly metal inks but also other fluid inputs. Ink quality is reported to be highly variable vendor to vendor, as well as batch to batch from the same vendor. Without well-established materials standards, the supply chain for conductive inks is somewhat unreliable.

Reliability and reproducibility were the primary concerns described by industry, stemming from the lack of robust standards and measurement methods that allow producers to control their product quality and specifications and that allow end users to have confidence in their vendors. One university professor stated in an interview that “the biggest challenge is to control the consistency in materials in inks to reduce batch to batch variation.”

Equally important to standards for the industry are standard measurement protocols for quality control and assurance. Standard test methods and reference data would significantly increase confidence. Without quality materials “everything else will suffer down the line.” Just as materials standards offer confidence at the front end of a production run, standard test methods and reference data would improve quality control. They would also allow for more complete process optimization studies because the variability in raw materials is constrained. Fluids that contain metallic particles can suffer from dispersion issues, and some require expensive, high-temperature sintering post-processes to provide the conductivity needed for active circuitry.

5.1.2 Standards and Measurement Methods for Substrates

Thermal and mechanical stability, surface energy, transparency, and chemical resistance are important factors to consider in substrate selection. For biomedical applications, substrates must be highly pure, with minimal leachables and extractables. In all cases, commercial availability and cost must be balanced with the product requirements.

Per an interviewee, "[o]ne of the most critical issues facing printed electronics is the interaction of ink and flexible substrates." Performance challenges arise when ink technology does not adequately flow, adhere to, or wet the substrate surface. Batch-to-batch variability, as noted in the previous section, is a challenge when considering compatibility and performance with respect to the substrate material. Materials and substrates are interconnected in an R2R process, so quality raw materials are still wasted if deposited on a defective substrate and vice versa.

Issues surrounding substrate quality and selection were themes in a majority of the discussions with manufacturers. Stakeholders noted that surface roughness and defects remain a large concern, with catastrophic impacts on yield.

In one specific product example, a company was printing 5 µm conductive lines across a 1 meter web. Lines that intersected with a particle or scratch defects in the substrate films were frequently broken, leading to extremely low yields. Guaranteeing reduced defects adds substantially to substrate cost, but surface finish requirements for printed electronics are particularly strict by necessity. Large-area metrology enabling companies to detect and measure defects on the substrate before printing to it will be critical to address such issues—by supporting companies in their efforts to establish and ensure compliance with quality standards in their supply chains.

Large manufacturing companies interviewed used a 6-month to 3-year qualification process for substrate vendors, with stringent certificate of analysis requirements. The quality metrics, however, are highly dependent on the resolution of the printed objects and have been difficult to standardize.

Standards for the environment of use is another need that many interview respondents stressed as being important to producing durable advanced flexible devices. Necessary to this need is proper handling of materials and substrates, precision coating methods, and guidelines for application-specific tools and processes.

The challenges related to standards and measurement technology for materials are emblematic of many fundamental barriers that bring about the failure of markets to provide essential technology. Standards and measurement technologies are not only challenging to develop but they also require buy-in from entire communities in order for them to have the desired effect. Although there is an incentive for firms to participate in standards development, standards must be developed by neutral, independent, and objective third parties or associations. Thus, all study participants saw a clear and obvious role for NIST in the provision of standards and measurement technology for input materials and substrates.

5.2 NEW MATERIALS AND SUBSTRATES

Several manufacturers noted that a primary barrier to flexible electronics is the lack of materials that can hold up to the thermal and mechanical stresses of the production process. Another barrier is that many metal-based inks oxidize very quickly, so separating the raw materials from humidity and environmental impurities is essential to maintaining the structural integrity of a product. New materials formulations, especially for metal inks, that can withstand processing conditions and support desired product characteristics are a critical gap. Likewise, substrate materials that are alternatives to PET, which suffers from variabilities, were mentioned as a critical need.

The need to develop new input materials and substrates was ranked by interviewees as the second most significant gap. The material science for identifying new formulations for different applications is very challenging and beyond the capabilities of most firms. Development of precompetitive formulations and concepts for metal inks and substrates was a priority and an area in which interviewees felt that NIST could make a significant contribution to the development of the industry. NIST is positioned to advance the science of printing, especially via building the knowledge base of how to make ink formulations and substrates compatible. The private sector is not generating and publishing this fundamental knowledge because they are unlikely to be able to capture any profits from their efforts, which in turn inhibits the technology's advancement.

5.3 PATTERNED TOOLS

Cylindrical rolls are widely used in a range of R2R industrial manufacturing processes, from the production of paper and plastic, to graphic arts printing, to hot stamp foil and hologram formation. The technical and patent literature is replete with methods and concepts for making rolls for low-resolution applications; however, this body of work does not address the unique requirements of the formation of a continuous, high-fidelity patterned film demanded by industry.

In particular, feedback across the range of manufacturers and R&D professionals pointed to the desire for cylindrical tooling with the following qualities, few of which are available today:

- submicron fidelity
- seamless
- long life (preferring metal tools over polymer)
- reduced cycle times
- tooling-specific metrology

High-fidelity structures are typically produced in a small area, on a flat substrate, using costly photolithography or beam patterning techniques. These small area "masters" can be replicated and the individual elements pieced together to create a cylindrical roll using welding or mechanical/chemical bonding. These processes result in "production seams" in the patterning roll whereby several substrates containing a pattern to be replicated are joined. Such seams cause defects in the micro- and nanopatterned products that range in size from hundreds of nanometers to hundreds of microns. Tooling capable of seam-free products would vastly expand available products.

In addition to continuous, seam-free tooling, one optical film patterning company suggested that smaller microstructures alone could result in a vastly broader product offering, with the "potential for 50% improvement to [their] product portfolio." In fact, nanoscale fidelity was consistency deemed to be the most important need related to patterned tools, more so than eliminating the seam in the roll.

Developing a high-fidelity, small area master structure is expensive, on the order of $10,000 to $100,000, with cycle times ranging from 1 to 2 months. Two companies reported that the tooling expense is a significant contributor to the cost of the final product, even with large-volume R2R processes. Very few vendors are capable of generating high-fidelity structures in the relatively low volumes needed by the industry (particularly when compared with the competing production of active circuits on the same toolset). Academic institutes and some private companies offer small-scale patterning, but producing masters on the order of meters needed for typical R2R production lines is a significant gap. One company reported that "manufacturing the master became the bottleneck in terms of cost and time." Another company noted that it lost business because its suppliers were unable to provide step patterned images.

Tooling was a topic mentioned in every conversation, yet—because R2R technology is often intellectual property—companies were reluctant to disclose the specific methods used to generate their tooling. Electroforming approaches, direct write processes, subtractive processes such as diamond turning, and disposable polymer tools have been named; most companies are fabricating tools in house with proprietary processes, yet all admitted a need for improvement in availability, cost, and fidelity. Improvements in processes for tool changeovers are also needed. An interviewee added that metal molds would be the "Holy Grail" for their optical films company.

Our interviewees revealed that improvement in these areas would be significant for companies operating in thin-film manufacturing, as well as those with advanced electrical circuitry requirements. Like with standards and measurement technologies, the fundamental knowledge for the production of seam-free masters requires sustained, long-term focus and investment coupled with the scientific and technical knowledge that is beyond the near-term investment horizon of the young firms that constitute the industry. NIST has the laboratories and technical expertise to integrate materials science disciplines and different component technologies to develop and demonstrate how new patterned tools or seam-free tools could be developed.

5.4 METROLOGY FOR TOOLING AND REAL-TIME FEEDBACK

Metrology, in general, was determined to be the most important area of need across all industries and research organizations. Manufacturers emphasized the need for metrology to detect defects before or during manufacturing for quality control, monitor the deposition of functional materials, and ensure correct alignment and registration, which is discussed further below. Real-time metrology tools would also help advance the R2R process and applications by analyzing data across numerous production runs.

Metrology methodologies from traditional semiconductor industries are being applied, but adequate solutions do not yet exist. The desired in-line metrology systems would have one or more of the following characteristics:

- rapid and nondestructive
- high resolution (with requests ranging from 10 nm to 5 µm)
- measure film thickness
- measure height, width, and 3D shape of a structure
- particle/defect measurements
- simple and inexpensive
- low data requirements, rapid data assessment and response parameters

Advanced analytical tools for probing a moving surface and metrology that extends beyond optical resolution pose a significant challenge to R2R manufacturing processes. Advancements in high-volume, cost-effective production depend on developing next-generation instrumentation for accurate and rapid characterization of film-based products. Metrology needs exist for (1) the raw substrate material; (2) the patterned tooling; (3) the patterned substrate, after patterning and additional processes; and (4) the final product.

Specific challenges of obtaining measurements on a flexible substrate, such as plastic or flexible glass, compared with a rigid substrate include mechanical reliability; thermal effects such as expansion and contraction; positional accuracy and reliability across a wide, flexible surface; and processing on a fast-moving web as opposed to plate to plate or wafer to wafer.

Additional challenges being addressed include taking measurements on high-resolution patterns with reflective and often optically transparent material.

One specification with R2R processes involves maintaining uniform coating thickness with high precision over large areas. A typical coating layer has a uniformity of approximately 100 to 1,000 nm, requiring equipment controls to be pushed to their current design limits. R2R equipment naturally involves the mating of macro components, such as rollers, coaters, drive mechanisms, and nip points, to surfaces and materials that will have nano and micro features. Very slight nonuniformities in these macro components can have detrimental effects on the high-precision advanced products produced. For applications such as circuits and displays, an ultra-barrier, or protective coating, is required to separate materials from environmental elements. The ultra-barrier must be very smooth before it is coating. According to a company producing thin films, however, it can take 2 weeks or more to measure the properties in that coating film at the nanoscale before layering.

Although in-line metrology is required for efficient, quality product development, the suite of suitable techniques has yet to be defined. As such, a multitude of monitoring and inspection technologies is presently being developed. Optical methods currently used in metrology can be accurate, fast, and integrated in-line for process control, but many have reached their detection and resolution limits for probing structures and have challenges with transparent and reflective surfaces. Super resolution imaging, reflective optics, laser light microscopy, scatterometry, interference, contact profilometers, and parallel arrays of probe microscopy techniques are being investigated by the manufacturers and researchers that we interviewed, although none felt that a complete solution set has been identified.

Metrology is an area that many industry representatives classified as “underinvested.” Although these groups each pointed out that technology has been developed and can be leveraged from semiconductor fabrication, migration to a new R2R process and associated product has been a more difficult transition than anticipated because of the inherent difficulties in measuring microstructures at high speeds across a relatively wide, transparent surface area. One interviewee noted that it is simply not practical to measure microstructures during a production run and that the focus should be "finding ways to control morphology and protocols."

Despite challenges, the economic benefits of realizing such a metrology portfolio are expansive and include the following:

- midstream defect detection to eliminate additional processes for defective parts
- point defect determination to lower scrap rate
- characterization of the substrate's quality before using it
- real-time feedback of tooling and other additive printing processes to quickly identify unit operation issues during manufacture
- smaller data sets to increase process speed
- catastrophic defect detection for active devices to eliminate costly quality assurance/quality control testing of the end product
- elimination of destructive, batch-level quality control processes, such as cross-sectioning

As with metrology for input materials, metrology for tooling and real-time feedback were viewed by respondents as a classic role for NIST and areas in which market failure persists.

5.5 TECHNOLOGY FOR ALIGNMENT AND REGISTRATION ON A MOVING WEB

The production of more complex devices, such as PV, displays, sensors, and other components with active circuitry, requires an even greater level of metrology and control. It is difficult to achieve precise overlay and long-range placement accuracy in R2R because of the tendency of the flexible substrate to deform during processing; therefore, many potential high-value applications that require the precise and accurate placement of multiple levels of materials await improvements in metrology and control technologies.

Single-level structures, used in applications such as optical films and controlled-energy surfaces, do not require such precision and were thus the first products developed. HP's SAIL process, self-aligned imprint lithography, used a multilevel template that effectively produces pre-aligned structures, avoiding the level-to-level registration problem. This well-known process has been used to generate large-area, low-cost electronics such as display backplanes with minimum feature sizes of 1 µm at web speeds of up to 5 m/min. Current alternative solutions work by attaching plastic films to glass plates to generate a temporary rigid substrate. This technique can leverage equipment and processes designed for liquid-crystal display manufacture at large volumes, but it is exceedingly expensive.

Alignment and registration greatly affect the quality and yield of a product. The inability to properly align the web led to one advanced display company to drop a particular product they were trying to manufacture. Alignment is not a problem with the product that the company uses now, however. Interestingly, the discussion surrounding this technology need received the most criticism related to using R2R manufacturing in place of other, well-established processes. One well-respected interviewee with a semiconductor background noted that “precision and speed are never going to go together until huge revolutions are made.” Another interviewee indicated uncertainty in using R2R for flexible electronics as a consequence.

The extent to which NIST could bring together sensing technologies and measurement systems to demonstrate manufacturing strategies for alignment and registration on a moving web would be valuable for flexible electronics manufacturers. Addressing this need requires a unique combination of multidisciplinary expertise and specialized facilities to solve a problem for an industry that does not have the requisite breadth of expertise and lab facilities in house.

5.6 PROCESS MODELING AND CONTROLS

In close combination with metrology, real-time diagnostics complements the development of process modeling and control methods. Many interviewees had never considered process modeling to test and predict production runs. Those that had generally fell into two groups: the first group included interviewees who see great value in simulating the processes, materials properties, and thermal and physical stresses and the second group included the skeptics who believe that process modeling is more of a “science project,” as one interviewee called it.

The average rating of importance for this technology need was 3.5, which corresponds to a moderate level of importance. Companies involved in printed and flexible electronics were less interested in process modeling. University researchers, however, were the keenest on this potential technology.

R2R process models enable an improved, predictive understanding of frequency and source of errors in the manufacturing process. If reliable, modeling offers high return at low labor and materials costs. These features make it attractive for screening a number of error sources and frequency, allowing process engineers to prioritize and troubleshoot unit operations during development. Error sources include tooling and the associated patterned product, including bending, thermal stress, and shrinkage, as well as the substrate, including surface roughness, distortion, and planarity. Although this modeling will not replace metrology and quality processes, it can improve the quality of the manufacturing process and reduce downtime and failure rates to reduce overall costs.

Modeling also is the first step in scaling from a bench-scale or pilot system to a large production factory. Challenges in large-scale substrate handling, alignments, slack in the web, tooling changeovers, and fluid deposition can all be considered simultaneously. As scale increases, manufacturers report that “design for manufacture” principles are more stringent; therefore, there is increased incorporation of defect-tolerant designs. One interviewee with a semiconductor background exclaimed that R2R is currently “disposable manufacturing” and that digital design to manufacturing is “as important for flexible electronics as they are for wafers.”

The use of process controls, including robotics and sensors for “smart manufacturing,” becomes necessary as components become too large and tolerances too small for the human interface. Several large manufacturers reported that products that are straightforward to manufacture at pilot scale are often difficult to transition to wider web, faster processes; improved modeling tools may help reduce the cycle time.

5.7 CONSISTENT INTERNATIONAL TERMINOLOGY

R2R methods address a very diverse set of markets and products and include a multitude of unit operations. Defining these operations in terms that are well understood and characterized by industry, with industry-wide consensus, is crucial to support further development in the field.

Currently, inconsistent process definitions, classifications, and taxonomies are applied across R2R platforms. These inconsistencies make it challenging to analyze the industry as a whole, as well as provide roadmaps and consensus.

As a noninclusive, exemplary list, the following terms all represent the additive production of a pattern on a substrate: NIL, embossing, particle replication in nonwetting templates, soft lithography, J-FIL, SAIL, transfer printing, microcontact printing, imprint lithography, micromolding in capillaries, microtransfer molding, and replica molding.

Standard terminology was rated the least important technology with an average rating of 2.46. Although some interviewees noted that consistent nomenclature and other like standards can be helpful for the industry, they are not a barrier. Several respondents during interviews characterized consistent terminology need as “nice to have” but not critically important. The extent to which NIST can support efforts that drive toward consistent terminology would be advantageous to manufacturers, but they would prefer that NIST allocate a marginal dollar to critical issues in standards and measurement technology.

6 Concluding Remarks

This study conservatively estimates that the economic benefit of an improved technology infrastructure supporting R2R manufacturing would be at least $353 million per year,[12] or about 15% of COGS for R2R manufacturers in 2015, all else held equal.

An improved infrastructure would unlock significant economic value by lowering scrap rates, improving yields, and improving R&D and manufacturing efficiency. Increased quality and reliability combined with improved processes would expand existing product lines and allow the industry to move into new markets where automated, high-speed R2R production methods would be attractive. Although the market is relatively small today, there is great promise for wearable technologies, flexible electronics, and environmental technologies, among others.

As in other studies prepared for NIST, this work explored and documented barriers and challenges that have resulted in the failure of the marketplace to provide essential public-good technology. NIST can accelerate the realization of the economic benefits of R2R manufacturing technology. As described in Section 5, industry experts highlight a number of opportunities for NIST to support and guide technology infrastructure development, particularly in the following areas:

- standards and measurement technology for input materials
- new materials and substrates
- patterned tools

[12] The estimate is conservative because it is based on the size of the market today and does not take into consideration the impacts associated with market transformation, earlier introduction of novel products and services, benefits to consumers, or other types of benefits.

- metrology for tooling and real-time feedback
- technology for alignment and registration on a moving web
- process modeling and controls

Manufacturing industries' needs in these areas align closely with NIST's unique mission in the U.S. innovation landscape.

We interviewed a large number of experts, both formally and informally, in conducting this analysis. When commenting on the potential impact addressing critical needs in technology infrastructure would have, many offered their perspectives on broader issues by way of describing either why a technology need may exist or what the opportunity would be if a need were to be addressed. They emphasized the importance of an industry roadmapping exercise for R2R similar to what was done for the semiconductor industry via SEMATECH.

Another perceived challenge is the availability of physical research and manufacturing infrastructure to support U.S. entities. When commenting on technology infrastructure issues, many experts highlighted the strength of Asian firms in the emerging hybrid flexible electronics marketplace. Beyond having large multinational corporations active in markets for which R2R is considered an attractive production method, there is substantial physical research and manufacturing infrastructure in Asia that does not exist in the United States. There is a need for foundries in the United States with the capability to produce multilayered products. Presently, it is estimated that two foundries in the United States provide production-related services. However, these are not understood to have the capability to produce multilayered products like flexible electronics. Such capabilities may be present or emerge first in Korea, Japan, and Taiwan, which currently have advanced assembly and lamination operations.

Furthermore, the United States has few process engineers with expertise in R2R. Small- to medium-sized enterprises, in particular, often do not have the process engineering expertise needed to scale up their operations and cannot afford to bring this expertise in house on a full-time basis. Programs that can make experienced process engineers available on a contract basis would be useful.

Experts also echoed findings from other studies about developing a sophisticated advanced manufacturing workforce. The operational skill set and knowledge of people working in high value-added production are critical and a potential source of competitive advantage. As such, trade and community college curricula need to provide foundational training in measurement, quality assessment, and operations management.

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