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Energy Sector title image page 172: 10 nm TEM of natural abundance (99% ^{12}C) carbon nanotubes synthesized by the electrolysis of carbon dioxide in molten lithium carbonate at 750°C on a 10 cm^2 galvanized steel electrode with a Ni anode. Credit: *Scientific Reports*.

Energy Sector title image page 174 credit: *Economy*.

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MRS Bulletin

Toward a circular materials economy

The circular economy is a simple and alluring concept, a marketing coup, with broad appeal to policymakers and the general public. It has become a modern catchall phrase for many of the environmental strategies we already pursue. For some, it means reducing factory waste, for others, improving recycling rates. Some are motivated by reducing raw resource input, while others see a way to grow profits with less environmental impact. How is a circular economy more than just recycling? What is the difference? Like most good concepts—justice, good will, or perhaps courage—an exact definition is hard to pin down. Some would argue that a circular economy, much like its analogue sustainability, should remain amorphous: a high-minded ideal that is pursued in principle, but not in specifics.

Achieving an entirely circular materials economy—one in which all waste is eliminated, all material loops are closed, and all products are recycled indefinitely—would require an annulment of the second law of thermodynamics. To maintain materials in perfect condition as they cycle through the economy, without input of new materials or energy, would be to defy the principles of entropy and disorder. We have a name for such an unattainable ideal: a perpetual motion machine. The absence of a concrete definition of circularity results in a nebulous concept overlain with a veneer of elegance. But if we adopt such a premise, then how can we know if we are moving toward circularity? To move toward a destination, one must first know the direction of travel. To make progress, one must be able to measure the distance covered. For "if you can't measure it, you can't improve it" (Peter Drucker).

Despite the buzz around the circular economy, a clear definition is still to emerge, and measurements of circularity remain in their infancy. Attempts to measure circularity tend to bundle a number of existing indicators, drawn from established fields such as life-cycle assessment, resource efficiency, and sustainable production and consumption. Metrics such as waste per output of product (kg/kg), recycling rates (%), and emissions per output of product (CO_2/kg) are combined in various weightings and reported in scorecards in an attempt to provide guidance. Too often, companies simply cherry-pick the metrics that are easiest to implement, while taking full benefit from membership in the "circularity club."

Such a piecemeal approach relies on individual companies to make the good calls and for the economic conditions to be just right, to justify a move away from the status quo of "source, use, and dump." A number of companies are taking this challenge seriously and making genuine attempts to evolve their business practices and product offerings. However, the problem of measuring progress toward circularity is complicated by the number of strategies available to pursue this goal. Unfortunately, these strategies do not always pull in the same direction: a lightweight product will require less resource inputs but may make future reuse less likely; novel materials may deliver an improved product but complicate end-of-life recycling options; targeting recycled content for a product may simply shift the resource burden to another country; designing longer life products may result in a less efficient stock.

The materials science community has a key role to play in defining a future circular materials economy and in establishing sound metrics to measure progress toward circularity. This community will also be required to balance the excitement that comes from developing new improved materials with a new caution to ensure these materials can be maintained in closed-loop cycles. In this way, we might just turn the alluring ideal of a circular economy into a pragmatic approach for achieving a more sustainable materials future.

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