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Research Paper

The S-Cycle Performance Matrix: Supporting Comprehensive Sustainability Performance Evaluation of Technical Systems

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ABSTRACT

In this paper, we present the first generic framework for selecting comprehensive material/energetic sustainability performance indicators (SPIs) for technical systems: the S-Cycle Performance Matrix (S-CPMatrix). This novel matrix is comprised of 6 generic sustainability goals, 11 SPI archetypes, and 23 corresponding metrics identified from our previously developed model of technical system sustainability (the S-Cycle), and is intended to support decision makers in meeting three identified criteria for comprehensive SPI sets: (C1) inclusion of indicators measuring performance at all relevant scales; (C2) inclusion of efficiency and effectiveness indicators; and (C3) coverage of all system sustainability goals. We evaluated the matrix by interpreting and classifying 324 indicators currently applied to assess technical system sustainability performance in the literature, with 94.1% found to be fully classifiable with respect to the proposed goals and SPI archetypes following several refinements. The matrix is applicable to different systems, and may be considered to facilitate the selection of a holistic set of SPIs from different sources and evaluation approaches. Thus, it addresses a need for consistent yet flexible guidance on how to comprehensively assess technical system sustainability performance, mirroring generic guidelines on organizational SPI selection widely available through several international initiatives. In addition to industrial evaluation of the S-CPMatrix, four avenues for future research are proposed: (i) use of the matrix for systems comparison/benchmarking; (ii) further investigation of unsupported metrics; (iii) the nature and measurement of contaminants; and (iv) assessing the comprehensiveness of current SPI sets for technical systems. © 2017 The Authors. Systems Engineering Published by Wiley Periodicals, Inc. Syst Eng 00: 1–26, 2017

Key words: enterprise & environment; measurement; sustainability; sustainability assessment; sustainability performance indicators

1. INTRODUCTION

Encompassing relatively simple consumer products up to large scale, complex machinery and transportation, technical systems fulfill a range of different functions across the economy. At a basic level, the operation of a technical system may be understood as the transformation of materials and energy into useful or valuable outputs that meet the needs of society [Hubka, 1982; Hubka and Eder, 1988]. These material

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and energetic inputs originate in natural systems, whilst the waste that is typically produced alongside intended outputs is ultimately mitigated by natural processes [Meadows, 1998; United Nations Environment Programme, 2012]. Acknowledging this relationship with the natural world, Hubka and Eder [1988: 32] suggested in the 1980s that the "equilibrium of these ecosystems should be respected and considered" in the design and development of technical systems. Today, there is a general consensus that artificial systems may have a considerable impact on the environment and the resource base throughout their life cycle [Ulgiati, Raugei, and Bargigli, 2006; Stasinopoulos et al., 2009]. Consequently, organizations are under increasing consumer and regulatory pressure to monitor and improve the sustainability performance of their technical systems and products [Park, Lee, and Wimmer, 2005; Chapman, 2011].

Information on the sustainability performance of technical systems may be used to support decision making in a variety of contexts. Technical systems constitute the artifact in engineering design, and it is during the design process that the greatest improvements in technical system sustainability may be achieved [Park et al., 2005; Stasinopoulos et al., 2009; Spangenberg, Fuad-Luke, and Blincoe, 2010]. Here, designers may use information on the sustainability performance of their artifacts to identify particular aspects that should be targeted to improve sustainability [Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010], or to select the most sustainable option from a range of alternatives [Azkarate et al., 2011]. At the organizational level, manufacturing organizations may assess the sustainability performance of their technical products as a means to manage business processes [Hussey, Kirsop, and Meissen, 2001; Global Reporting Initiative, 2013a] and the implementation and monitoring of sustainability and corporate social responsibility policies [Marimon et al., 2012; Global Reporting Initiative, 2013a,b]. The information gathered through such an assessment may be published in an organizational sustainability report, where it becomes available to consumers who can subsequently use it to make purchasing decisions on the basis of product sustainability [Chapman, 2011; Koller, Floh, and Zauner, 2011], for example, which product to buy from an organization or which organization's products to buy.

A number of sustainability performance evaluation methods are available to designers and organizations during the design process and in later stages of the technical system life cycle. Prominent examples include life cycle assessment, material flow analysis, energy analysis, emergy analysis, and exergy analysis. All of these may be classified as evaluating the material and energetic performance of technical systems, and similarities may be detected across certain methods with respect to the broad areas being measured. For instance, the majority include performance indicators focusing on various types of emissions and waste products, as well as material and/or energy consumption at different life cycle stages. However, as shown in Section 2.1, the specific indicators applied vary from method to method. Additionally, authors may be seen to define sustainability performance indicators (SPIs) in an *ad hoc* manner, seeming to draw upon their knowledge of the system and sustainability generally rather than any formal method [e.g., Denholm, Kulcinski, and Holloway, 2005; Rotella et al., 2012; Asif and Muneer, 2014]. These observations raise a basic question: what constitutes a comprehensive set of material and energetic SPIs for evaluating the sustainability performance of technical systems? That is, what range of material and energetic aspects should fundamentally be measured in order to gain a holistic view? Given that effective decision making requires comprehensive information on the issue at hand [Dalal-Clayton and Bass, 2002; Wahl and Baxter, 2008; Boyle et al., 2012], this question has ramifications for sustainability decision making in each of the contexts outlined above.

The Global Reporting Initiative (GRI) has developed a set of generic guidelines for organizational sustainability reporting (SR), intended to foster a common and consistent approach worldwide [Hussey et al., 2001; Dalal-Clayton and Bass, 2002; Global Reporting Initiative, 2013a]. Clear guidance on the type and range of SPIs that should be included in a comprehensive assessment of an organization's sustainability performance is provided [Hussey et al., 2001; Morhardt, Baird, and Freeman, 2002]; however, the guidelines do not prescribe the use of any particular evaluation methods, leaving the choice up to the assessor with the caveat that they report any "standards, methodologies, and assumptions used" [Global Reporting Initiative, 2013b: 91]. In contrast, there is a lack of any consistent and flexible guidance of this nature at the level of technical systems [Waage, 2007]. Whilst all of the methods listed above may be considered useful in sustainability performance evaluation, it is not clear whether they yield comprehensive sets of SPIs or what form such a set might take.

Toward addressing the above issues, this paper presents the first generic framework for selecting comprehensive material/energetic SPIs for technical systems: the S-Cycle Performance Matrix (S-CPMatrix). This novel matrix is comprised of 6 generic sustainability goals, 11 SPI archetypes, and 23 corresponding metrics identified from our previously developed model of technical system sustainability (the S-Cycle [Hay, Duffy, and Whitfield, 2014; Hay, 2015]). It is intended to support decision makers in addressing three identified criteria for comprehensive SPI sets (Section 2): (C1) coverage of all relevant spatiotemporal scales; (C2) inclusion of efficiency and effectiveness indicators; and (C3) coverage of all sustainability goals defined for a system. To provide an initial evaluation of the S-CPMatrix, we examined a sample of 324 SPIs used in various assessment methods currently applied to different technical systems. We found that 94.1% of these indicators were classifiable with respect to the matrix following several refinements. Furthermore, all of the proposed SPI archetypes and associated metrics were found to be supported in the sample, with the exception of four metrics. Based on these findings, we conclude that the matrix is strongly supported in the literature, is applicable to different systems, and may be considered to facilitate the selection of a holistic set of SPIs from different sources and evaluation approaches. Thus, it addresses the need for consistent, yet flexible guidance on how to comprehensively assess technical system sustainability performance outlined above. As discussed in Section 4, work to evaluate the utility and applicability of the S-CPMatrix in an industrial context, as well as its comparability with existing methods, is ongoing.

The remainder of the paper is organized as follows. First, the findings of a literature review on comprehensiveness in sustainability performance evaluation are presented in Section 2. The S-CPMatrix is introduced in Section 3, and its development (Section 3.1) and evaluation through the classification exercise mentioned above (Section 3.2) are described. The work is discussed in Section 4, where four avenues for future research are highlighted: (i) the application of the matrix to support systems comparison/benchmarking; (ii) further investigation of metrics found to be unsupported by the classification exercise; (iii) the nature of contaminants as an influence on technical system sustainability, and how they may be measured and modeled; and (iv) assessing the comprehensiveness of SPI sets currently applied to technical systems. The paper concludes with a summary of the work in Section 5.

2. COMPREHENSIVENESS IN SUSTAINABILITY PERFORMANCE EVALUATION

As a first step toward developing the S-CPMatrix, we sought to understand the issue of comprehensiveness from two perspectives: (1) a sustainability perspective, focusing on what performance aspects should be measured at what scales and (2) a performance perspective, focusing on the nature of performance and performance indicators. The three criteria for comprehensive SPI sets that we identified from this body of work are elaborated in the following sub-sections.

Literature from area (1) was gathered by searching major engineering databases (e.g., Compendex and the Technology Research Database), as well as several multidisciplinary databases via the Web of Science service. Search terms relating to sustainability and the environment were applied, in combination with a range of terms reflecting: (i) performance measurement, for example, assess*, eval*, indicator, measur*, and metric and (ii) technical systems as conceptualized by Hubka and Eder [1988], for example, product, system, and engineer*. Regarding area (2), sources by authors generally considered to be influential in performance measurement research were selected for review, including: Kaplan and Norton [1992, 1996]; Neely, Gregory, and Platts [1995]; Bourne et al. [2000]; O'Donnell and Duffy [2002, 2005]; Neely, Adams, and Kennerley [2002a]; Neely et al. [2002b]; Duffy [2005]; and Bourne and Bourne [2007]. The literature on sustainability is reviewed in Section 2.1 below, and performance measurement is covered in Section 2.2.

2.1. Sustainability and the Technical System Life Cycle

A range of methods may be applied to evaluate the sustainability performance of technical systems, falling into two broad categories: (i) *ad hoc* approaches and (ii) formal evaluation methods. In *ad hoc* approaches (Table I), evaluators appear to define SPIs based on their own knowledge of sustainability and the technical system in question rather than any predefined method. Although the specific material and energetic aspects measured often differ as shown in Table I, similarities may be detected with respect to the broad areas being measured, for example, emissions and waste products, energy efficiency, and material/energy consumption.

With respect to formal methods, Ness et al. [2007] highlight several product-related assessment methods that are commonly applied to technical systems, namely: life cycle assessment; material flow analysis; energy analysis; exergy analysis; and emergy accounting. The indicators typically associated with each method are presented in Table II below. None of the methods are positioned as comprehensive with respect to sustainability performance. However, they all focus on the material and/or energetic flows associated with a technical system, and are therefore frequently presented as useful for assessing the sustainability performance of technical systems [e.g., Brown and Ulgiati, 1997; Rosen, Dincer, and Kanoglu, 2008; Gasparatos, El-Haram, and Horner, 2008; Ulgiati et al., 2011; Liao, Heijungs, and Huppes, 2011; Buonocore, Franzese, and Ulgiati, 2012]. As shown in Table II, the nature of the indicators associated with each method depends primarily upon its particular material and/or energetic perspective.

As indicated in Tables I and II, different evaluation methods measure sustainability performance at different scales, ranging from local (L) to regional (R) and global (G). The notion of scale in this context may be understood in terms of the technical system life cycle, which is generally considered to consist of four key stages: (i) extraction and processing of raw materials required to manufacture the system; (ii) manufacturing (including design and development, and also transportation of components); (iii) system operation; and (iv) recycling and disposal [Blanchard and Fabrycky, 1981; Stasinopoulos et al., 2009; Ulgiati et al., 2011]. As shown in Figure 1, each stage is supported by the Earth system's material and energetic resource base, as well as waste sinks and processing activities.

Sustainability performance may be evaluated across different portions of the life cycle. For instance, certain authors focus upon the operation phase only [e.g., Caliskan, Dincer, and Hepbasli, 2012; Rotella et al., 2012; Aydin et al., 2013], whilst others apply methods such as life cycle assessment to evaluate performance across the full life cycle [e.g., Ulgiati et al., 2011; Adams and McManus, 2014; Ofori-Boateng and Lee, 2014]. Ulgiati et al. [2011: 177] highlight that life cycle stages are closely tied to the spatial scale at which material and energetic flows are evaluated, with each scale "characterized by well-specified processes" occurring at different stages:

- The local scale involves "final resource use," that is, the operation of the technical system—here, only the direct material and energetic inputs to and outputs from the system need to be considered;
- The regional scale involves "manufacturing and transport of components" —here, the indirect material and energetic inputs/outputs associated with manufacturing and transporting system components must be considered in addition to the direct inputs/outputs above; and
- The global scale involves "resource extraction and refining" —here, the indirect inputs/outputs resulting from the extraction and processing of the raw materials consumed to manufacture the components must additionally be considered.

Table I. A Selection of Authors Applying *Ad Hoc* Approaches to Evaluating the Sustainability Performance of Technical Systems

Source	Technical System	Indicators	Scale
Denholm et al. [2005]	Baseload wind energy system, including turbines & storage)	• Fuel consumption rate • GHG emission rate • NOx emission rate • Primary energy efficiency • SO2 emission rate	R
Hondo [2005]	A range of different power production systems	• Life cycle GHG emission factor	R
Evans, Strezov, and Evans [2009]	Photovoltaic, wind, hydro, & geothermal energy production systems	• Efficiency of energy generation • Greenhouse gas emissions • Land use • Price of electricity generation • Social impacts • Water consumption	R
Onat and Bayar [2010]	Power production systems generally	• Carbon dioxide emissions • Efficiency • Fresh water consumption • Land use • Social effects • Unit energy cost	L
Rotella et al. [2012]	Hard machining system	• Cutting force • Material removal rate • Mechanical power • Thrust force • Wear rate • White layer thickness	L
Coelho, Lange, and Coelho [2012]	Ten different waste-to-energy plants	• Area required by treated waste • Chemicals and additives consumption by treated waste • CO_2 emissions by treated waste • Dust emissions by treated waste • Electricity consumption by treated waste • Electricity generation by treated waste • Fossil fuel consumption by treated waste • Greenhouse gas emissions by treated waste • Liquid effluents generated by treated waste • Other gases emitted by treated waste • Other materials consumed by treated waste • Soil used by treated waste • Thermal energy generation by treated waste • Waste or sub products generated by treated waste • Water consumption by treated waste • Water vapor consumption by treated waste	L
Chandrasekaran and Guha [2012]	Turbofan engine	• Emission index of carbon dioxide • Emission index of carbon monoxide • Emission index of hydrocarbons • Emission index of NOx • Inlet mass flow • Net thrust • Overall efficiency • Specific fuel consumption • Thermal efficiency	L
Abdel-Salam and Simonson [2014]	Membrane liquid desiccant air conditioning system	• CO emissions • CO_2 emissions • NOx emissions • PM emissions • Primary energy consumption • SOx emissions	L

(*Continued*)

Table I. Continued

Source	Technical System	Indicators	Scale
Asif and Muneer [2014]	Window (panel & frame)	• Annual CO_2 emission—electricity • Annual CO_2 emission—gas • Annual electricity cost • Annual gas cost • Annual heat loss • Life cycle CO_2 emission—electricity • Life cycle CO_2 emission—gas • Life cycle cost—electricity • Life cycle cost—gas • Life cycle heat loss	L
Rahman et al. [2014]	Compression ignition engine	• Brake specific fuel consumption • Carbon monoxide (emission parameter) • Exhaust gas temperature • Hydrocarbons (emission parameter) • Nitrogen oxides (emission parameter) • Particulate matter (emission parameter) • Thermal efficiency	L
Singh, Singh, and Agarwal [2014]	Biodiesel-fuelled HCCI engine	• CO_2 emissions • Hydrocarbon emissions • Indicated specific fuel consumption • Indicated thermal efficiency • NO emissions • Smoke opacity	L

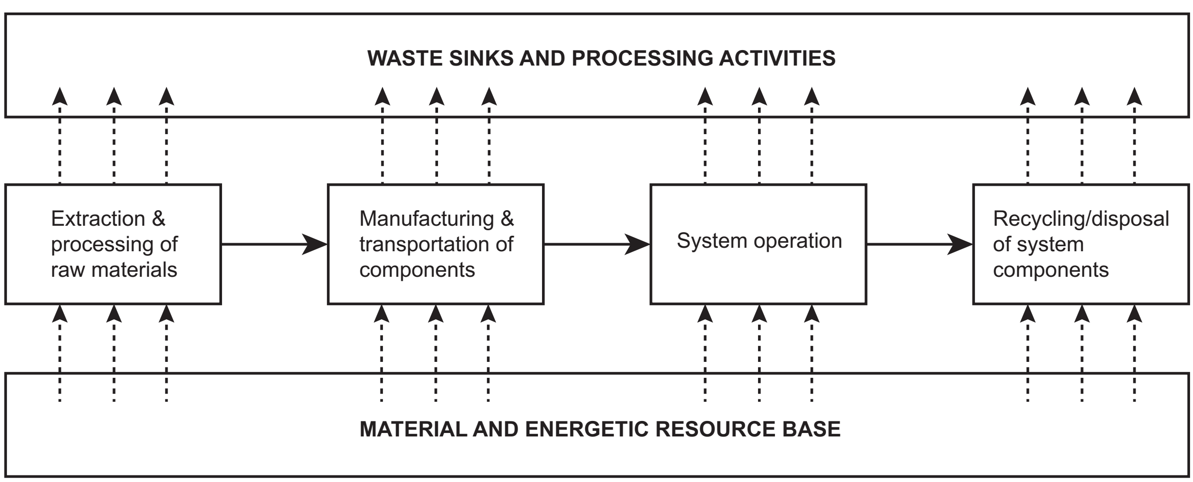

Figure 1. The technical system life cycle.

Recycling and disposal processes also occur at the regional scale, essentially mirroring manufacturing processes with a focus on system deconstruction as opposed to construction. However, data on the material and energetic flows associated with recycling and disposal are generally rather limited. Thus, in certain cases this phase may be excluded from a regional or global scale performance evaluation [Gurzenich and Wagner, 2004; Hondo, 2005; Raugei, Bargigli, and Ulgiati, 2005].

The different spatiotemporal scales delineated above may be illustrated by considering the notion that all of the activities involved in the technical system life cycle, including the operation of the system *per se*, occur within a wider system of interest (SoI) that provides inputs to activities and receives the outputs produced [Blanchard and Fabrycky, 1981; Hubka and Eder, 1988; Tully, 1993; Stasinopoulos et al., 2009]. Essentially, increasing the spatial scale over which sustainability performance is to be evaluated means that: (i) more of the Earth system is included in the technical system's wider SoI and (ii) the technical system's interactions with this SoI must be considered across a broader portion of the system life cycle, as shown in Figure 2.

Ulgiati et al. [2011: 177] highlight that the "value of a given indicator is only 'true' at the scale at which it is calculated."

Table II. Formal Sustainability Performance Evaluation Methods Applied to Technical Systems, and Associated Indicators

Evaluation Method	Associated Indicators	Scale	Sources
Embodied energy analysis	• CO_2 release • Cumulative energy demand • Embodied energy per unit of output • Energy efficiency • EROI of material and/or energetic output • GER of outputs • Oil equivalent of outputs • Oil equivalent intensity per unit of output • Total oil equivalent applied • Total embodied energy applied	G	Raugei et al., 2005; Ulgiati et al., 2011; Buonocore et al., 2012; Cellura et al., 2014
Emergy accounting	• Adjusted yield ratio • Emergy efficiency index • Emergy from imported resources • Emergy from local nonrenewable resources • Emergy from local renewable resources • Emergy Sustainability Index • Emergy Yield Ratio • Environmental Loading Ratio • Renewable fraction • Total emergy • Transformity of outputs	G	Raugei et al., 2005; Ulgiati et al., 2011; Buonocore et al., 2012; Moss et al., 2014
Energy analysis	• CO_2 emissions • Coefficient of Performance • Cooling capacity • Energetic renewability ratio • Energy efficiency • Energy input rate • Energy losses • Energy storage rate • Wet bulb effectiveness • Work output	L	Balta, Dincer, and Hepbasli, 2010; Caliskan et al., 2011b; Caliskan et al., 2012; Li et al., 2012; Söğüt et al., 2012; Waheed et al., 2014
Exergy analysis	• Entropy generation • Environmental effect factor • Exergetic renewability ratio • Exergetic sustainability index • Exergy destruction rate/factor • Exergy efficiency • Exergy input rate • Exergy losses • Exergy output rate • Exergy storage rate • Recoverable exergy ratio • Sustainability index [exergetic] • Thermodynamic efficiency • Total exergy input • Waste exergy ratio	L	Raugei et al., 2005; Balta et al., 2010; Caliskan et al., 2011a; Caliskan et al., 2011b; Ulgiati et al., 2011; Caliskan et al., 2012; Li et al., 2012; Söğüt et al., 2012; Aydin et al., 2013; Waheed et al., 2014
Life cycle assessment	• Abiotic depletion potential [I] • Acidification potential (overall & per unit of output) [I] • Carbon footprint (overall & per unit of output) [I] • CH4 emissions • Chemical oxygen demand [I] • Climate change [I]	R – G	Pacca, Sivaraman, and Keoleian, 2007; Shah, Debella, and Ries, 2008; Ulgiati et al., 2011; Buonocore et al., 2012; Thiers and Peuportier, 2012; Adams and McManus, 2014;

(*Continued*)

Table II. Continued

Evaluation Method	Associated Indicators	Scale	Sources
	• CO emissions • CO_2 emission intensity • CO_2 emissions • CO_2 payback time • Dissolved organic carbon • Ecotoxicity potential [I] • Electricity generation • Energy gain ratio • Energy intensity • Energy payback time • Eutrophication potential [I] • Fossil depletion [I] • Global warming potential [I] • Human toxicity (overall & per unit of output) [I] • Land use [I] • Life cycle embodied energy • Life cycle GHG emissions • Metal depletion [I] • Net CO_2 reduction • Net energy ratio • Nonradioactive waste creation [I] • Nonrenewable energy [I] • NOx emissions • Odor • Ozone depletion potential [I] • Particulate matter formation [I] • Photochemical oxidation (overall & per unit of output) [I] • PO4 emissions • Potable water consumption [I] • Primary energy consumption [I] • Radioactive waste creation [I] • Respiratory inorganics [I] • SOx emissions • Water consumption/resource depletion [I]		Antony et al., 2014; Kim et al., 2014; Ofori-Boateng and Lee, 2014; Russell-Smith et al., 2014; Shahabi et al., 2014; Uddin and Kumar, 2014
Material flow accounting	• Abiotic material intensity per unit of output • Global to local ratio of abiotic material • Global to local ratio of water demand • Material intensity, air factor • Material intensity, biotic factor • Total abiotic material requirement • Total water demand • Water demand per unit of output	G	Raugei et al., 2005; Ulgiati et al., 2011; Buonocore et al., 2012

To illustrate, consider the use of nonrenewable resources by a solar panel. A solar panel may be viewed as a relatively simple technical system that converts solar energy into electrical energy. At the local scale, we may evaluate the panel's consumption of nonrenewable resources and find that it uses none—the only energetic input to the system during its operation is renewable solar energy. As discussed further in Section 3.1, for sustainability, the use of nonrenewable resources should be minimized, ideally to zero. Thus, at the local scale, the panel appears to be sustainable. However, if we evaluated the same aspect of performance at the regional scale, we would likely obtain a rather different picture. The manufacture of solar panels involves nonrenewable and scarce metals [Fthenakis, 2009] and is likely to be driven by fossil fuels [Kim et al., 2014], which are also nonrenewable. Furthermore, recycling and/or disposing of solar panels at the end of their life cycle requires intensive processing [Fthenakis, 2009], which is again likely to be driven by fossil fuels [Kim et al., 2014]. Thus, whilst the panel's performance appears to be sustainable at the local scale, it seems less so at the regional scale.

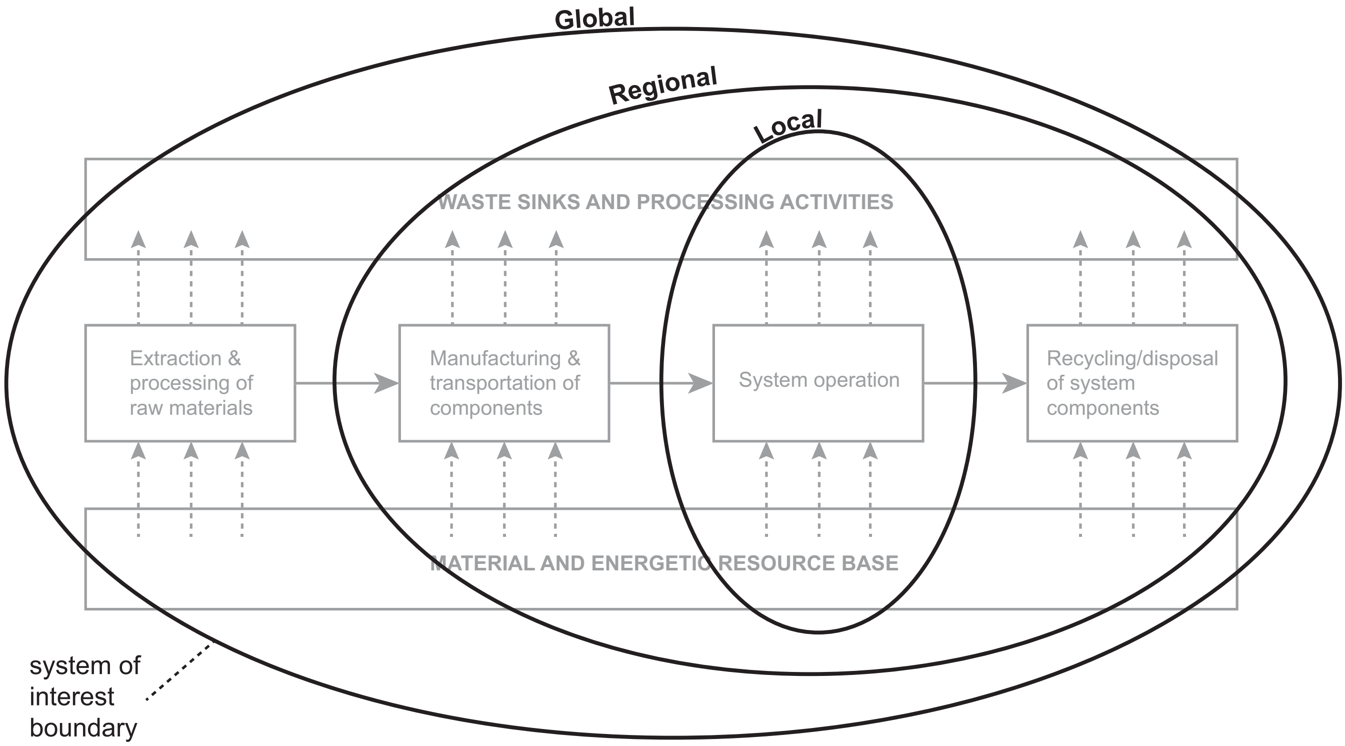

Figure 2. The spatiotemporal scales of sustainability performance evaluation.

It can be seen from the above that a technical system's sustainability performance may be interpreted differently depending on the spatiotemporal scale of the evaluation. Thus, in order to gain a comprehensive view, it may be necessary to measure a set of SPIs providing information on performance at different scales. This is supported by Ulgiati et al. [2011: 187], who suggest that "a selection of many indicators is needed in order to have a comprehensive evaluation across space and time scales." As mentioned in Section 1, information on sustainability performance is used for different purposes. For example, a designer may wish to identify areas where changes could potentially be made to a technical artifact to improve aspects such as energy efficiency and consumption during its life in service [Aydin et al., 2013]. In this case, evaluation at the local scale is likely sufficient, given the relationship between temporal and spatial scale outlined above. In other cases, information may be used to understand what phase in a system's life cycle is associated with the worst sustainability performance, and should therefore form the focus of redesign efforts [Park et al., 2005]. This is likely to entail evaluation at the regional and possibly also global scales. Thus, it may not be necessary to evaluate SPIs at every scale outlined above in all cases; however, it is necessary to ensure coverage of all scales that are relevant given the purposes of the evaluation. On this basis, we may define an initial criterion for comprehensive SPI sets:

- *Criterion 1 (C1).* A comprehensive set of SPIs for a technical system should include indicators measuring performance at all relevant spatiotemporal scales, given the purposes of the evaluation.

2.2. Performance Axioms

In Section 2.1, the range of methods and indicators applied to measure sustainability performance was outlined. In a general sense, Neely et al. [2002b: 12] suggest that performance measurement can be understood as "the process of quantifying purposeful action." In this paper, we are concerned with the purposeful action a technical system is involved in during its life cycle. Purposeful action may be quantified in terms of two basic elements: *efficiency* and *effectiveness* [Neely et al., 2002a,b]. These are formalized in the generic E^2 performance model developed by O'Donnell and Duffy [2005: 77] in their work on design performance (Fig. 3). The authors conceptualize purposeful action as a goal-directed activity, and suggest that: (i) efficiency may be viewed as the ratio of what has been materially gained from an activity to the level of resource used and (ii) effectiveness refers to the degree to which the result or output from an activity meets the activity's goal. They also argue that whilst effectiveness "cannot be measured without specific knowledge of the activity goals," efficiency is inherent in a particular activity. That is, it exists whether it is evaluated or not, and may be measured without knowing the goals of the activity. However, the goals may affect "the behaviour of resources used in the activity and consequently the level of efficiency resulting from their use" [O'Donnell and Duffy, 2005: 77].

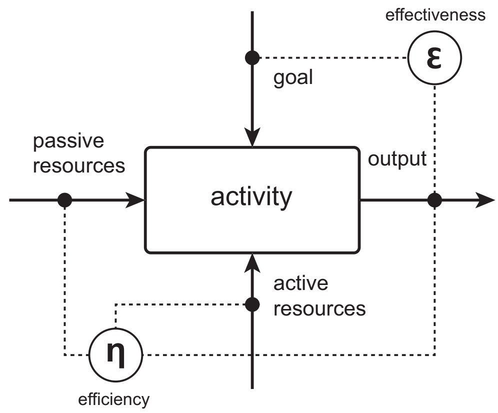

Figure 3. The E^2 performance model (adapted from O'Donnell and Duffy [2005: 79]).

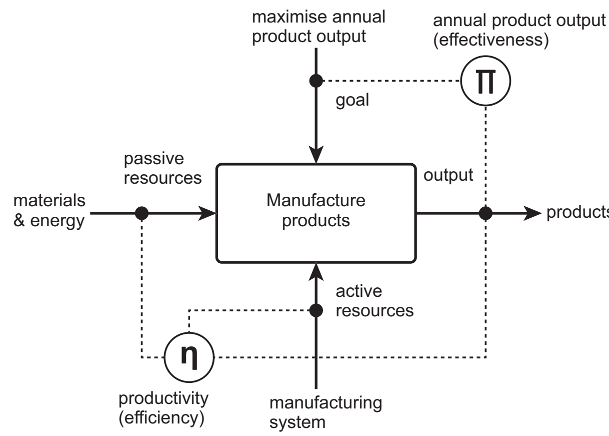

Figure 4. Activity carried out by a manufacturing system.

Two criteria for comprehensive SPIs may be identified by considering a set of performance axioms derived from the E^2 model by O'Donnell and Duffy [2002]. Briefly, these state that: "activities are the fundamental means that create performance, activities and their management are inextricably linked, and [. . .] all metrics [i.e. indicators] can be typified to efficiency or effectiveness indicators" [O'Donnell and Duffy, 2002]. The axioms are elaborated in Sections 2.2.1 and 2.2.2 below. We shall adopt the following terminology throughout, noting instances where other authors may be describing the same concept using different terms:

- A *performance indicator* is taken to be a parameter used to quantify the efficiency or effectiveness of an activity [Neely et al., 2002b].
- A *performance metric* is defined here as a specification for a broadly based performance indicator [Neely et al., 2002a].
- A *measure* is considered to be an item of data required to compute a value for a performance indicator [Duffy, 2005].

2.2.1. Efficiency and Effectiveness

The first axiom posited by O'Donnell and Duffy [2002] states that: "All performance can be measured by efficiency and/or effectiveness. That is, no matter the metric(s) or aspect(s) under consideration, all indicators of performance, no matter how general or specific, will indicate either an efficiency or effectiveness measure" [O'Donnell and Duffy, 2002: 1218]. In turn, O'Donnell and Duffy [2005: 79] argue that performance "is completely described within the elements of efficiency and effectiveness," and therefore both elements must be measured to obtain "a fully informed view of activity performance." This is supported by others. For instance, Kennerley and Neely [2002: 149] state that a set of performance indicators should include both efficiency and effectiveness measures in order to be "balanced." Neely et al. [1995: 81] define a performance measurement system as "the set of metrics used to quantify *both* the efficiency and effectiveness of actions" (emphasis ours).

A one-eyed focus on efficiency may mean that gains are achieved at the expense of effectiveness, and vice versa. To illustrate this, consider the performance of a manufacturing system as an example. As shown in Figure 4, the manufacturing system (a collection of resources) carries out an activity whereby materials and energy (inputs) are transformed into some kind of product (output), with the goal of maximizing the annual output of products.

The efficiency of the activity may be measured by an indicator such as productivity, that is, the number of products produced per unit of materials and/or energy consumed. Given the activity goal, effectiveness may be measured by the number of products produced in a year. In isolation, we may set a target level for the effectiveness measure that appears to be appropriate given our knowledge of the system, the wider business, the customer, and so on. However, without considering the potential productivity inherent in the activity—that is, the potential level of productivity that could be obtained given the activity's attributes—this level of effectiveness may be produced in a grossly inefficient manner. In contrast, we may evaluate the activity's productivity, without any knowledge of the target level for the effectiveness measure, and find that it is highly efficient in producing products from materials/energy. However, beyond our knowledge, the activity may be producing an output of products either far below or exceeding the target level considered adequate by decision makers. In both cases, it may be seen that measuring one performance component in isolation can yield a misleading view on overall activity performance.

Given that high efficiency does not necessarily equate with high effectiveness and vice versa, it is necessary to measure both elements to fully understand a system's performance [O'Donnell and Duffy, 2005]. In a sustainability context, this is supported to some extent by McDonough and Braungart [2002], who suggest that sustainable systems must be both ecoeffective and ecoefficient. As we will show in Section 3.2, the majority of SPIs currently applied to technical systems may indeed be typified to efficiency or effectiveness indicators, although the sets of SPIs used may not always cover both elements. On this basis, we may define a second criterion for comprehensive SPI sets:

- *Criterion 2 (C2).* A comprehensive set of SPIs for a technical system should include indicators measuring both efficiency and effectiveness.

2.2.2. The Relationship between Indicators and Goals

The next two performance axioms defined by O'Donnell and Duffy [2002: 1217–1218] are stated thus:

i. "Activities are the fundamental means that create performance. [. . .] Other aspects influence the type, definition and behavior of an activity but it is the activity itself that realises performance."
ii. "Activities and their management are inextricably linked. Carrying out an activity will always involve an element of management. Thus, every activity, even at an individual cognitive level, will involve its management."

In short, it is fundamentally activities that produce performance [Lebas and Euske, 2002; Neely et al., 2002a; Bourne and Bourne, 2007], and these activities are managed by a decision maker (be it a human or an artificial intelligence system).

A key element of activity management is setting performance goals [Neely et al., 2002b; O'Donnell and Duffy, 2005]. These essentially define the behavior required to deliver a desired level of performance [Hubka and Eder, 1988; O'Donnell and Duffy, 2005; Hay et al., 2014]. For example, the production of waste is a key sustainability consideration for technical systems, as discussed further in Section 3. The ideal performance to be achieved in this area is a waste output level of zero (we make no claims about whether this is actually achievable). Thus, a goal such as "minimize waste production" may be defined for the system. We may then take action by, for instance, making changes to the system or its support environment to ensure that it produces less waste in the future [Hay et al., 2014]. Note that performance goals can be defined for existing and conceptual systems. For instance, a designer may set the above goal for a conceptual system design and then make changes to the design to minimize its potential waste output [O'Donnell and Duffy, 2005; Russell-Smith et al., 2014].

It may be seen from the above that performance indicators should always be related to performance goals. This is supported in the wider literature on performance. For example, in a business context, Kaplan and Norton [1992: 73] state that in order to apply their balanced scorecard framework, "companies should articulate goals for time, quality, and performance and service and then translate these goals into specific measures." In a similar context, Bourne et al. [2000: 757–758] suggest that "the two requirements of the design phase [for performance indicators] are identifying the key objectives to be measured and designing the measures." Although efficiency may be viewed as an inherent property of an activity that is measurable without knowledge of goals, O'Donnell and Duffy [2005: 73] state that the "selection and application of metrics to determine efficiency allow particular views of efficiency to be created, e.g. cost based efficiency" [O'Donnell and Duffy, 2005: 73]. It is reasonable to suggest that the desired "views" of efficiency are likely to reflect certain goals of the activity being evaluated. For instance, it is unlikely that one would define an indicator to measure the cost-based efficiency of an activity if the activity has no cost-focused goals.

In summary, goals define the behavior required to achieve certain performance, whilst indicators provide information on whether system behavior is shifting in the required direction in response to management actions [O'Donnell and Duffy, 2005; Hay et al., 2014]. Thus, to obtain a fully informed view on the performance of a system from a particular perspective, be it sustainability or something else, we need to select indicators that provide information in relation to all relevant goals. On this basis, we may define a third criterion for comprehensive SPI sets:

- *Criterion 3 (C3).* A comprehensive set of SPIs for a technical system should cover all of the sustainability goals defined for the system, that is, goals governing the aspects of behavior affecting a system's sustainability performance.

The nature of sustainability goals for technical systems is discussed in Section 3, where the S-CPMatrix is introduced.

3. THE S-CYCLE PERFORMANCE MATRIX (S-CPMatrix)

The three criteria for comprehensiveness identified from the literature in Section 2 form the basis of the S-CPMatrix discussed in Section 1. To construct the matrix, we derived the following elements from our previously developed S-Cycle model [Hay et al., 2014]: (i) generic sustainability goals, highlighting the general range of such goals that may be defined for a technical system (C3); (ii) SPI archetypes, highlighting the different types of efficiency and effectiveness indicator at the disposal of evaluators (C2); and (iii) a range of metrics (i.e., essentially, formulae) to measure each type of SPI, highlighting the scale at which different measures may be evaluated (C3). The S-Cycle model describes the general aspects of behavior affecting the sustainability performance of any system. In turn, the S-CPMatrix is intended to support the translation of these general aspects into comprehensive sets of measurable SPIs for specific technical systems.

The S-Cycle model is briefly introduced in Section 3.1, before the S-CPMatrix is presented and the goals, SPI archetypes, and metrics derived from the model are described and explained. Section 3.2 outlines a classification of 324 indicators undertaken to provide an initial evaluation of the matrix. Note that ongoing work to further evaluate the matrix in an industrial context is discussed in Section 4.

3.1. Elements of the S-Cycle Performance Matrix

Whilst a full explication of the S-Cycle model (Fig. 5) is beyond the scope of this paper, readers are referred to Hay et al. [2014] for further information and an exemplary application to a bioethanol production system. As shown in Figure 5, system operation is described using a generic activity formalism similar to that adopted in the E^2 model introduced in Section 2.2. Technical system activities operate within a wider SoI that provides inputs and receives the outputs produced, as discussed in Section 2.1. These activities transform input flows of renewable and nonrenewable resources, originating in stocks within the SoI, into output flows of: (i) intended output, that is, the valuable or useful output produced by a

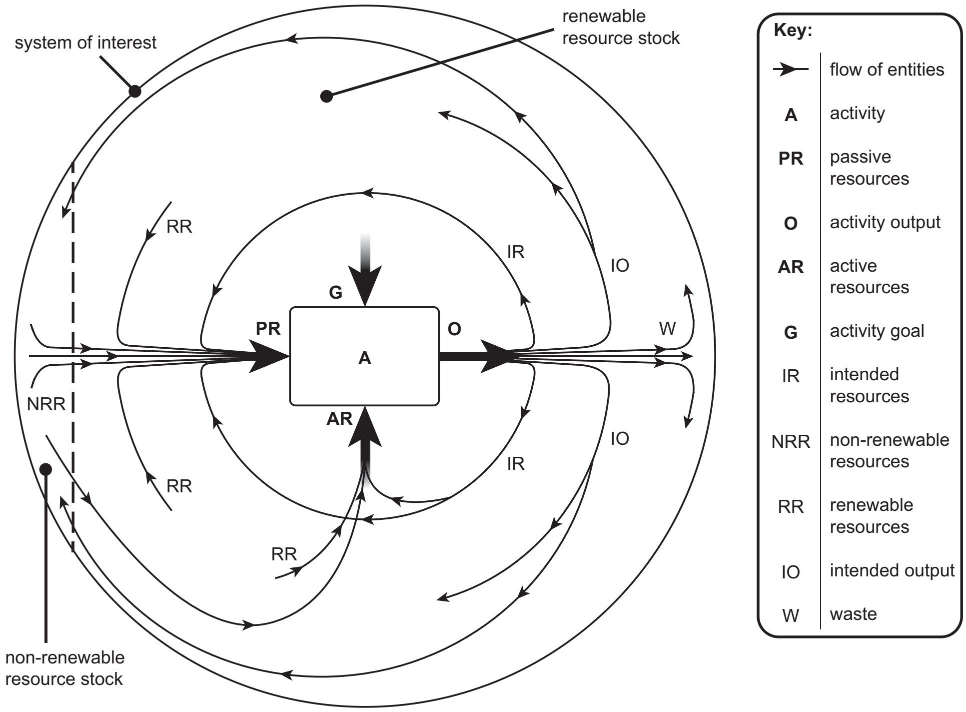

Figure 5. The S-Cycle model. Reprinted from Journal of Environmental Management, Vol. 133, Hay, L., Duffy, A., and Whitfield, R.I., The Sustainability Cycle and Loop: Models for a more unified understanding of sustainability, pp.232–257, Copyright (2013), with permission from Elsevier.

technical system in order to fulfil its function and meet human needs; (ii) intended resources, that is, resources produced by a technical system for its own use and self-sufficiency; and (iii) waste, that is, outputs with no utility to the technical system that produced them. Renewable resources originate from stocks that regenerate over time, whilst nonrenewable resources originate from stocks that do not regenerate significantly along anthropological timescales. Resources may be further sub-divided into: (i) passive resources, that is, the materials and energy being processed by the technical system activity and (ii) active resources, that is, the components of the technical system *per se* that carry out the processing of passive resources. The S-Cycle's validity as a model of technical system sustainability has been evaluated through application to the bioethanol system referenced above plus a further nine distinct systems in an industrial setting [Hay, 2015]. Thus, it may be considered to provide a suitable basis for defining generic, comprehensive SPIs for technical systems.

The initial version of the S-CPMatrix is presented in Table III; a refined version developed following evaluation is presented and discussed in Section 3.2.2. Throughout the following sections, readers are referred to Table IX for the meaning of abbreviations.

Generally speaking, the goals in the matrix were defined on the basis that they should reflect the aspects of behavior affecting system sustainability performance, that is, those aspects described in the S-Cycle model. With respect to measuring effectiveness, we considered what indicators would provide information on the achievement of these goals based on the behavior conveyed by the S-Cycle model. Regarding the measurement of efficiency, we considered what kinds of efficiency are inherent in a technical system's activity from a sustainability perspective given the inputs and outputs described in the S-Cycle model. In defining metrics for the resulting SPI archetypes, we considered how each SPI may be expressed from two perspectives:

i. *Data*, that is, what measures are needed to compute a value for the indicator, how these measures relate, and whether they can be related in different ways.
ii. *Spatiotemporal scale*, that is, whether the measures can be evaluated at local, regional, and/or global scales. As discussed in Section 2.1, both intended output and intended resources are produced during the operation phase of the life cycle and may therefore be measured at the local scale only. Given that direct and indirect resource inputs and waste outputs may be consumed/produced by a system throughout its life cycle, these may be measured at all scales. The scale of each measure in the matrix is denoted by a subscript letter, that is, L = local, R = regional, and G = global.

The rationale behind each goal in the S-CPMatrix and its associated SPI archetypes and metrics is outlined below.

3.1.1. Goal: Produce Intended Output

Based on the S-Cycle model (Fig. 5), the material/energetic sustainability of a system activity may be generally defined as its ability to continue operating within a wider SoI [Hay et al., 2014]. That is, more specifically, its ability to continue producing its intended output over time. Thus, a failure to

Table III. Initial Version of the S-Cycle Performance Matrix (S-CPMatrix)

Generic sustainability goals	ε/η	SPI archetypes	Metrics	S-Cycle metric definitions	Full metric definition
PRODUCE IO	ε	IO production	Absolute IO output	IO_L	Amount of IO produced over some time period (t_{max} = full operation phase).
			IO production rate	IO_L/t	Amount of IO produced per unit of time (t_{max} = full operation phase).
MINIMISE OVERALL RESOURCE USE	ε	Resource consumption	Absolute PR input	$PR_{L,R,G}$	Amount of PR consumed over some time period, including both renewable and non-renewable PR (t_{max} = full life cycle).
			PR consumption rate	$PR_{L,R,G}/t$	Amount of PR consumed per unit of time, including both renewable and non-renewable PR (t_{max} = full life cycle).
	η	Resource efficiency	Resource intensity	$PR_{L,R,G}/IO_L$	Amount of PR consumed per unit of IO produced over some time period (t_{max} = full operation phase).
			Resource productivity	$IO_L/PR_{L,R,G}$	Amount of IO produced per unit of PR consumed over some time period (t_{max} = full operation).
MINIMISE NRR USE	ε	NRR consumption	Absolute NRR input	$P\text{-}NRR_{L,R,G}$	Amount of non-renewable PR consumed over some time period (t_{max} = full life cycle).
			NRR consumption rate	$P\text{-}NRR_{L,R,G}/t$	Amount of non-renewable PR consumed per unit of time (t_{max} = full life cycle).
			NRR fraction	$P\text{-}NRR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is non-renewable (t_{max} = full life cycle).
	η	NRR efficiency	NRR intensity	$P\text{-}NRR_{L,R,G}/IO_L$	Amount of non-renewable PR consumed per unit of IO produced over some time period (t_{max} = full operation phase).
			NRR productivity	$IO_L/P\text{-}NRR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full operation phase).
MINIMISE RR USE	ε	RR consumption	Absolute RR input	$P\text{-}RR_{L,R,G}$	Amount of renewable PR consumed over some time period (t_{max} = full life cycle).
			RR consumption rate	$P\text{-}RR_{L,R,G}/t$	Amount of renewable PR consumed per unit of time (t_{max} = full life cycle).
			RR fraction	$P\text{-}RR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is renewable (t_{max} = full life cycle).
	η	RR efficiency	RR intensity	$P\text{-}RR_{L,R,G}/IO_L$	Amount of renewable PR consumed per unit of IO produced over some time period (t_{max} = full operation phase).
			RR productivity	$IO_L/P\text{-}RR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full operation phase).
MAXIMISE SELF-SUFFICIENCY	ε	IR production	Absolute passive IR output	$P\text{-}IR_L$	Amount of passive IR produced over some time period (t_{max} = full operation phase).
			Passive IR production rate	$P\text{-}IR_L/t$	Amount of passive IR produced per unit of time (t_{max} = full operation phase).
		IR consumption	Passive IR fraction	$P\text{-}IR_L/PR_L$	Fraction of PR consumed over some time period that was self-produced (t_{max} = full operation phase).
MINIMISE WASTE PRODUCED	ε	W production	Absolute W output	$W_{L,R,G}$	Amount of W produced over some time period (t_{max} = full life cycle).
			W intensity	$W_{L,R,G}/IO_L$	Amount of W produced per unit of IO produced over some time period (t_{max} = full operation phase).
			W production rate	$W_{L,R,G}/t$	Amount of W produced per unit of time (t_{max} = full life cycle).
	η	Resource inefficiency	Wastefulness	$W_{L,R,G}/PR_{L,R,G}$	Amount of W produced per unit of PR consumed over some time period (t_{max} = full operation phase).

continue producing intended output over time may be interpreted as a loss of sustainability. Effectiveness against the goal may be evaluated by measuring the level of intended output produced by a system over time. That is, *intended output production* as an absolute value or a rate. We did not define an efficiency measure for this goal, although intended output is involved in computing efficiency for resource-focused goals below.

3.1.2. Goals: Minimize Use of (i) Nonrenewable and (ii) Renewable Resources

As shown in Figure 5, a technical system's ability to continue producing intended output over time is fundamentally dependent upon the continued availability of the resources it requires, and may also be affected by its waste production behavior. Since the continued availability of nonrenewable resources cannot be guaranteed, their consumption should be minimized/eliminated where possible. It is also desirable to minimize the use of renewable resources given that stocks are depleted if consumption rates exceed regeneration rates [Hay et al., 2014]. At the very least, stock regeneration rates should be respected. Effectiveness against these goals may be evaluated by measuring the level of passive nonrenewable and renewable resources consumed by a system over time, respectively. That is, *nonrenewable resource consumption* and *renewable resource consumption* as absolute values, rates, or fractions of the total passive resource input. Efficiency may be evaluated via the indicators *nonrenewable* and *renewable resource efficiency*, defined as the ratio of intended output produced to passive nonrenewable or renewable resources consumed over time, respectively.

3.1.3. Goal: Minimize Overall Resource Use

As discussed above, it is desirable to minimize the consumption of resources derived from external stocks, that is, renewable and nonrenewable resources. Thus, a parent goal to minimize overall resource use may be defined for the above goals. Effectiveness against this goal may be evaluated by measuring the total level of passive nonrenewable and renewable resources consumed by a system over time. That is, *resource consumption* as an absolute value or rate. Efficiency may be evaluated via the indicator *resource efficiency*, defined as the ratio of intended output produced to the total passive nonrenewable and renewable resources consumed over time.

3.1.4. Goal: Maximize Self-Sufficiency

In other words, maximize the fraction of the passive resource input that was self-produced (intended resources) as opposed to externally derived (nonrenewable and renewable resources). Reducing an activity's reliance upon external resource stocks can reduce the impact of external shocks and disturbances (e.g., the sudden loss of a resource stock) on intended output production and in turn, sustainability. Effectiveness against this goal may be evaluated by measuring the level of intended resources produced by a system over time. That is, *intended resource production* as an absolute value or a rate. Alternatively, the fraction of the total passive resource input that was self-produced may be measured. That is, *intended resource consumption*.

3.1.5. Goal: Minimize Waste Produced

Waste production rates exceeding the waste processing capacity of the wider SoI may cause waste to accumulate in the SoI (i.e., pollution). Unintended consumption of waste products by system activities may disrupt their functioning and therefore, compromise their sustainability. Effectiveness against this goal may be evaluated by measuring the level of waste produced by a system over time. That is, *waste production* as an absolute value, a rate or a value per unit of intended output produced over time (i.e., waste intensity). Efficiency may be evaluated via the indicator *resource inefficiency*, defined as the ratio of waste produced (i.e., undesired gain) to passive resources consumed over time. Resource inefficiency may be considered to indicate how inefficiently a system uses resources to produce output—that is, what fraction of a system's resource input is transformed to waste rather than intended output. Summing the values obtained for the resource efficiency (above) and resource inefficiency indicators should always yield a value of 1 or less.

It may be seen in Table III and from the above discussion that there is often more than one way of computing a particular SPI, hence, an SPI may have more than one associated metric. The intention is not that every single metric in the S-CPMatrix should be applied in every assessment effort—rather, decision makers may select a subset of these metrics that best aligns with their interests and the audience for the results, as long as the resulting set of SPIs meets the three criteria for comprehensiveness identified herein. The matrix simply highlights the range of different types of metric at the disposal of decision makers. For instance, consider the resource intensity and productivity metrics associated with the resource efficiency SPI and the goal to minimize overall resource use. These are both defined as the ratio between intended output and resource consumption; however, they are expressed as the inverse of one another as shown in Table III. Thus, measuring both does not inherently provide any more information than measuring one alone. However, the format of the information provided by each one may be more useful in different contexts. For example, engineers involved in assessing a power generation system may be more interested in how much electricity is produced per unit of resource consumed (resource productivity) given economic concerns. However, the resource intensity metric may be more effective at communicating the environmental impacts associated with electricity generation to consumers, who may then be motivated to reduce their personal electricity consumption.

3.2. Classification of Current Sustainability Performance Indicators

The S-CPMatrix outlined in Section 3 is a product of induction from the literature covered in Section 2 and the S-Cycle model introduced in Section 3.1. To provide an initial evaluation of the matrix, 324 indicators currently applied to evaluate technical system sustainability performance were interpreted and classified with respect to the matrix elements. In doing so, we sought to determine:

Table IV. Nomenclature

Abbreviation	Meaning
S-cycle abbreviations	
AR	Active resource
IO	Intended output
PR	Passive resource
P-IR	Passive intended resource
P-NRR	Nonrenewable passive resource
P-RR	Renewable passive resource
W	Waste
Performance abbreviations	
$\mathcal{E}$	Effectiveness
η	Efficiency
Subscripts	
L	Denotes indicator/metric/measure that may be evaluated at the local scale.
R	Denotes indicator/metric/measure that may be evaluated at the regional scale.
G	Denotes indicator/metric/measure that may be evaluated at the global scale.
Other	
t	Time
t_{max}	Denotes the maximum time period a metric may be evaluated over.

i. whether current indicators align with and reflect the proposed SPI archetypes and metrics in the matrix, thus providing support for the latter; and
ii. whether there are any indicators currently applied to technical systems that are *not* described in the matrix, which may be suggestive of additional sustainability goals, SPI archetypes, and metrics.

It should be noted that the classification exercise was largely qualitative in nature, and focused on mapping indicators described in the literature to the proposed goals and SPI archetypes in the S-CPMatrix rather than statistical analysis of the sample. We were not concerned with differences between groups of authors or evaluation methods, or the extent to which different types of indicator are applied in the sample. Rather, we sought qualitative evidence relating to our argument that the generic goals and SPIs in the matrix constitute indicators of sustainability performance, which may be translated to different technical systems and are compatible with existing evaluation methods.

The approach to the classification is briefly outlined in Section 3.2.1, before the outcome and a refined version of the S-CPMatrix are presented in Section 3.2.2.

3.2.1. Approach

A sample of 43 sources (Table IV) evaluating the sustainability performance of technical systems (or elements thereof) was identified from the literature reviewed in Section 2. To arrive at a sample of indicators that is representative of current evaluation approaches (see Tables I and II), we selected sources based on their adopted methods (including both formal evaluation methods and *ad hoc* approaches). Table IV shows the approaches represented in the sample.

To carry out the classification, we first extracted descriptions of the indicators applied in each source along with their associated metrics and units as reported by the authors. A total of 390 indicators were initially identified. In several cases, we observed indicators that were applied by different authors but had similar descriptions/metrics. For instance, numerous life cycle assessment (LCA) indicators were found to be applied by multiple authors providing similar descriptions, including: (i) global warming potential [Thiers and Peuportier, 2012; Russell-Smith et al., 2014; Antony et al., 2014; Ofori-Boateng and Lee, 2014; Kim et al., 2014]; (ii) ozone depletion potential [Cellura et al., 2014; Russell-Smith et al., 2014; Ofori-Boateng and Lee, 2014]; (iii) acidification potential [Thiers and Peuportier, 2012; Cellura et al., 2014; Antony et al., 2014; Ofori-Boateng and Lee, 2014]; and (iv) eutrophication potential [Thiers and Peuportier, 2012; Cellura et al., 2014; Antony et al., 2014; Ofori-Boateng and Lee, 2014]. We did not systematically identify and remove similar/overlapping indicators, largely for the purposes of completeness and thoroughness given nuances between different authors. However, 66 indicators were excluded from the classification exercise for the following reasons:

- Not enough information was provided to classify the indicator, for example, no formal definition or units
- The indicator focused on purely technical aspects rather than those relevant from a sustainability perspective (this was to be expected given that a number of sources openly aim to evaluate both sustainability/environmental performance and technical performance)
- Rather than material and/or energetic performance, the indicator focused on a technical system's contribution to sustainable development (e.g., a focus on social and economic impacts) or socio-economic development generally (e.g., a focus on financial aspects)
- The indicator focused on measuring something that may influence system performance, but is not performance *per se*, for example, the availability of an energy resource [Onat and Bayar, 2010]

We attempted to classify the remaining 324 indicators with respect to the S-CPMatrix (Table III). In classifying the indicators, we interpreted their descriptions and associated metrics to identify: (i) which of the generic sustainability goals they may relate to, if any; (ii) what element of performance they measure, that is, efficiency or effectiveness, based on the definitions provided in Section 2.2; and (iii) whether their metrics and measures align with those proposed in the S-CPMatrix. Table VI presents several illustrative examples of the classification process.

3.2.2. Outcome

In total, 88.6% (287) of the indicators considered were found to be immediately classifiable with respect to both the SPI archetypes and metrics proposed in the initial S-CPMatrix. Of the remaining 11.4% (37), 48.6% (18) were found to be classifiable with respect to the SPI archetypes, but not the metrics. Thus, in total, 94.1% (305) of the indicators

Table V. Indicator Classification Sample

Source	Technical System	Evaluation Method/Approach	Scale
Buildings and structural systems:			
Antony et al., 2014	Biomimetic ceiling structure	Life cycle assessment	G
Asif and Muneer, 2014	Window (panel & frame)	*Ad hoc* approach	L
Russell-Smith et al., 2014	Mixed-use university campus building (design)	Life cycle assessment	G
Thiers and Peuportier, 2012	High energy performance building	Life cycle assessment	G
Energy conversion systems			
Adams and McManus, 2014	Biomass gasification combined heat & power plant	Life cycle assessment	G
Balta et al., 2010	Heat pump (ground-source)	• Energy analysis • Exergy analysis	L
Bianchi et al., 2014	Three different types of combined heat and power plant	• Avoided heat generator • Pollution savings	L
Buonocore et al., 2012	Combined heat & power plant	• Embodied energy analysis • Emergy accounting • Material flow analysis • Life cycle assessment	G
Caliskan et al., 2011b	Solar ground-based heat pump with thermal energy storage	• Energy analysis • Exergy analysis	L
Cellura et al., 2014	Two different types of biomass-fuelled energy production systems	• Embodied energy analysis • Life cycle assessment	G
Chicco and Mancarella, 2008	Poly-generation system	Primary energy saving	L
Coelho et al., 2012	Ten different waste-to-energy plants	*Ad hoc* approach	L
Denholm et al., 2005	Baseload wind energy system, including turbines & storage)	*Ad hoc* approach	R
Evans et al., 2009	Photovoltaic, wind, hydro, & geothermal energy production systems	*Ad hoc* approach	L – G
Hondo, 2005	A range of different power production systems	*Ad hoc* approach	R
Kim et al., 2014	PV systems composed of sc-Si/mc-Si modules with a 100 kWp power conditioning system	Life cycle assessment	G
Liu, 2014	Renewable energy systems generally	*Ad hoc* approach	L – G
Maxim, 2014	Energy generation systems generally	Multi criteria assessment	G
Onat and Bayar, 2010	Power production systems generally	*Ad hoc* approach	L
Pacca et al., 2007	Roof mounted solar photovoltaic system	Life cycle assessment	G
Raugei et al., 2005	Molten carbonate fuel cell, & three different types of gas turbine system	• Embodied energy analysis • Emergy accounting • Material flow analysis • Exergy analysis	G L
Rosato et al., 2013	Three different types of combined heat and power plant	*Ad hoc* approach	L
Rosato et al., 2014a	Building-integrated cogeneration system	*Ad hoc* approach	L
Rosato, Sibilio, and Scorpio, 2014b	Building-integrated cogeneration system	An emissions factor approach	L
Uddin and Kumar, 2014	Horizontal & vertical axis wind turbines	Life cycle assessment	G
Ulgiati et al., 2011	Six different types of cogeneration system	• Embodied energy analysis • Emergy accounting • Life cycle assessment • Material flow analysis • Exergy analysis	G L

(*Continued*)

Table V. Continued

Source	Technical System	Evaluation Method/Approach	Scale
Fuel production systems:			
Moss et al., 2014	Anaerobic digestion system	Emergy accounting	G
Ofori-Boateng and Lee, 2014	Biorefinery producing cellulosic ethanol & phytochemicals	• Exergetic life cycle assessment • Life cycle assessment	G
Heating and cooling systems:			
Abdel-Salam and Simonson, 2014	Membrane liquid desiccant air conditioning system	*Ad hoc* approach	L
Balta et al., 2010	Condensing and conventional boilers, and a solar collector	• Energy analysis • Exergy analysis	L
Caliskan et al., 2011a	Four different types of air cooling system for buildings	Exergy analysis	L
Caliskan et al., 2012	Three different types of M-cycle air cooler	• Energy analysis • Exergy analysis • Emission factor approach	L G
Shah et al., 2008	Three different residential heating and cooling systems	Life cycle assessment	G
Machining and industrial processing systems:			
Rotella et al., 2012	Hard machining system	*Ad hoc* approach	L
Söğüt et al., 2012	Coal preparation unit for cement production	• Energy analysis • Exergy analysis	L
Propulsive and transportation systems:			
Agarski et al., 2012	Five different car models	Multi criteria assessment	L
Aydin et al., 2013	Turboprop engine	Exergy analysis	L
Chandrasekaran and Guha, 2012	Turbofan engine	*Ad hoc* approach	L
Rahman et al., 2014	Compression ignition engine	*Ad hoc* approach	L
Singh et al., 2014	Biodiesel-fuelled HCCI engine	*Ad hoc* approach	L
Refining and distillation systems:			
Li et al., 2012	Heterogeneous azeotropic distillation partitioned distillation column	• Energy analysis • Exergy analysis	L
Shahabi et al., 2014	Seawater reverse osmosis desalination plant	Life cycle assessment	R
Waheed et al., 2014	Crude oil distillation unit	• Energy analysis • Exergy analysis • IPCC CO_2 emissions guidelines	L

analyzed were found to be classifiable to some extent. An overview of the archetypes found to be supported and unsupported is provided in Table VII alongside examples where applicable.

Upon closer examination, the 18 indicators whose metrics did not align with any of those proposed in the S-CPMatrix were seen to suggest additional metrics that had been overlooked. These are presented in Table VIII, alongside the indicators from the sample that they were based on. Furthermore, additional formulae were identified for two proposed metrics. First, in one source [Ofori-Boateng and Lee, 2014], it was observed that the wastefulness metric was computed as the ratio of passive resources to waste produced rather than the ratio of waste produced to passive resources consumed as proposed in the matrix (although the latter formula was found to be supported as shown in Table VII above). Second, it was also observed that the resource productivity metric was computed via the following equation rather than as the ratio of intended output produced to passive resources consumed: $1 - (\frac{W_L}{PR_{L,R,G}})$, where W_L is the amount of a particular type of waste produced by the system at the local scale, and $PR_{L,R,G}$ is the amount of a particular passive resource consumed at the local, regional, or global scale. Note that whilst the authors measure waste production at the local scale, it may also be measured at regional and global scales as noted in Section 3.1.

The 19 indicators (5.9%) that we were unable to immediately classify were found to suggest additional SPI archetypes and a sustainability goal that were not initially identified from the S-Cycle model in Section 3.1. First, one indicator was seen to suggest an additional SPI in relation to the goal *minimize overall resource use*. Rotella et al. [2012] evaluate

Table VI. Examples from the Indicator Classification Process

Evaluation Method	Reported Indicator	Reported Definition	Source	Performance Element	S-CPMatrix Goal	SPI Archetype	S-CPMatrix Metric
Material flow analysis	Total abiotic material requirement	Grams of abiotic material consumed per year	Buonocore et al., 2012	Effectiveness	Minimize external resource use	Resource consumption	Resource consumption rate
Exergy efficiency	Exergy efficiency	Ratio of total useful exergy output to total exergy input	Aydin et al., 2013	Efficiency	Minimize external resource use	Resource efficiency	Resource productivity
Exergy efficiency	Recoverable exergy ratio	Ratio of recoverable exergy to total exergy input	Aydin et al., 2013	Effectiveness	Maximize self-sufficiency	Intended resource consumption	Intended resource fraction
Emergy accounting	Emergy from local renewable resources	Sum of all local renewable emergy inputs to system per year	Buonocore et al., 2012	Effectiveness	Minimize renewable resource use	Renewable resource consumption	Renewable resource consumption rate
Energy analysis	Total energy loss	Sum of energy losses from the system in megawatts	Waheed et al., 2014	Effectiveness	Minimize waste produced	Waste production	Absolute waste output
Ad hoc approach	Thermal efficiency	Ratio of thermal energy produced to primary energy consumed	Rosato et al., 2014a	Efficiency	Minimize external resource use	Resource efficiency	Resource productivity
Ad hoc approach	Fossil fuel consumption by treated waste (system output)	Kilowatt-hours of electricity consumed per tonne of waste treated	Coelho et al., 2012	Efficiency	Minimize nonrenewable resource use	Nonrenewable resource efficiency	Resource intensity

Table VII. List of Supported and Unsupported SPI Archetypes and Metrics

SPI Archetypes	Metrics	Examples	Sources
IO production	Absolute IO output	Total exergy output	Ofori-Boateng and Lee, 2014
	IO production rate	Exergy output rate	Caliskan et al., 2012
	Relative IO production	Electricity generation by treated waste	Coelho et al., 2012
Passive resource consumption	Absolute PR input	Cumulative energy demand	Thiers and Peuportier, 2012; Antony et al., 2014
	Energy payback time	Energy payback period	Adams and McManus, 2014; Kim et al., 2014
	Relative PR consumption	Environmental loading ratio	Ulgiati et al., 2011; Buonocore et al., 2012; Moss et al., 2014
	PR consumption rate	Energy consumption per day	Caliskan et al., 2012
Active resource consumption	N/A (future research)	Wear rate	Rotella et al., 2012
Passive resource efficiency	Resource intensity	Material intensity, abiotic factor	Raugei et al., 2005
	Resource productivity	Primary energy efficiency	Denholm et al., 2005
		Exergy efficiency	Ofori-Boateng and Lee, 2014
NRR consumption	Absolute NRR input	Fossil fuel consumption	Kim et al., 2014
	NRR consumption rate	Emergy from local nonrenewable resources (per year)	Buonocore et al., 2012
	NRR fraction	Currently unsupported	–
NRR efficiency	NRR intensity	Embodied energy per MJ of electricity	Buonocore et al., 2012
	NRR productivity	EROI of electricity	Buonocore et al., 2012
RR consumption	Absolute RR input	Water consumption	Thiers and Peuportier, 2012
	RR consumption rate	Total water demand (per year)	Buonocore et al., 2012
	RR fraction	Energetic renewability ratio	Balta et al., 2010
RR efficiency	RR intensity	Water demand per MJ of electricity generated	Buonocore et al., 2012
	RR productivity	Currently unsupported	–
IR production	Absolute passive IR output	Currently unsupported	–
	Passive IR production rate	Currently unsupported	–
IR consumption	Passive IR fraction	Recoverable exergy ratio	Aydin et al., 2013
Waste production	Absolute W output	Carbon dioxide equivalent emissions	Rosato et al., 2014b
	W concentration (new)	NOx concentration	Bianchi et al., 2014
	W intensity	CO_2 emission intensity	Uddin and Kumar, 2014
	W production rate	CO_2 emissions rate	Waheed et al., 2014
Resource inefficiency	Wastefulness	Waste exergy ratio	Aydin et al., 2013
		Thermodynamic sustainability index	Ofori-Boateng and Lee, 2014

an indicator termed "wear rate," measuring the amount of material worn off the cutting component of a hard machining system during operation. The cutting component may be viewed as an active resource in the machining system's activity, transforming a workpiece (i.e., passive resource) into a machined component (i.e., intended output). Thus, the wear rate indicator appears to measure the consumption of active resources during the operation phase of the life cycle (i.e., at the local scale). This is suggestive of an additional SPI archetype, that is, *active resource consumption* in relation to the goal *minimize overall resource use*.

Second, as discussed in Section 3.1, accumulations of waste within a SoI may potentially disrupt the functioning of system activities. Specifically, excess waste can contaminate an activity's resource input, which may in turn lead to unexpected behavior that could be harmful to active resources driving the activity [Hay et al., 2014]. This can occur in technical system activities and other anthropogenic activities, but also natural activities, leading to issues such as acidification and eutrophication of ecosystems [United Nations Environment Programme, 2012]. The intended output from system activities may also have the potential to contaminate in this way. For example, plastics produced as an intended output of a manufacturing system may be toxic to humans and therefore viewed as potential contaminants in certain human activities. In this respect, a number of LCA impact indicators identified in the sample appear to focus on the contaminating potential of system activity outputs, for example, indicators such as human toxicity, acidification, eutrophication, etc. Thus, it seems that the following sustainability goal may also be relevant

Table VIII. Additional Metrics Suggested by the Classification Sample

New Metric	SPI Archetype	S-Cycle Metric Definition	Full Metric Definition	Indicators Used as Basis	Sources
Energy payback time	Passive resource consumption	$PR_{e'R,G}/IO_{e'annual}$	Number of years required for the energetic IO produced by a technical system to equal the energetic PR it consumes over its full life cycle.	Energy payback period	Pacca et al., 2007; Adams and McManus, 2014; Uddin and Kumar, 2014; Kim et al., 2014
Relative IO production	IO production	$IO_{a'L}/IO_{b'L}$	Amount of IO type a produced per unit of IO type b produced over some time period (t_{max} = full operation phase).	• Electricity generation by treated waste • Thermal energy generation by treated waste	Coelho et al., 2012
Relative PR consumption	Passive resource consumption	$P\text{-}NRR_{L,R,G}/P\text{-}RR_{L,R,G}$	Amount of nonrenewable PR consumed per unit of renewable PR consumed over some time period (t_{max} = full life cycle).	Environmental loading ratio	Buonocore et al., 2012
W concentration	W production	$W_{a'L,R,G}/W_{L,R,G}$	Amount of W type a produced as a fraction of the total W produced over some time period (t_{max} = full life cycle).	• Emission index of carbon dioxide • Emission index of carbon monoxide • Emission index of hydrocarbons • Emission index of NOx	Chandrasekaran and Guha, 2012
				Smoke opacity	Singh et al., 2014

for technical systems: *minimize the contaminating potential of outputs.* Future work required to explore this aspect of behavior is discussed in Section 4.

Finally, whilst all of the SPI archetypes proposed in the initial S-CPMatrix were found to be supported in the indicator sample along with the majority of the proposed metrics, there are certain metrics that do not appear to be supported as shown in Table VII above. Namely, these are: (i) *nonrenewable resource fraction*; (ii) *renewable resource productivity*; (iii) *absolute passive intended resource output*; and (iv) *intended resource production rate*. Additionally, the basic nature of several indicators was found to be unclear; these were deemed unclassifiable with respect to the matrix in its present form. Broadly speaking, they may be split into two categories:

- Indices that seem to relate output to resources in some way, but do not appear to be classifiable as efficiency indicators. For example, the Emergy Sustainability Index [Buonocore et al., 2012; Moss et al., 2014] is essentially the ratio of system yield to environmental burden; however, it relates two other emergy indices measuring resource efficiency and resource consumption and thus, from a performance perspective, it is unclear what the overall index is measuring. Furthermore, there exist indicators such as the exergetic sustainability index [Caliskan, Dincer, and Hepbasli, 2011a,b; Caliskan et al., 2012; Aydin et al., 2013] that include efficiency as a term, but do not measure efficiency *per se*.
- Indices that appear to benchmark the performance of one system against another system, some theoretical level of performance, or performance at another scale. That is, they provide a means to compare aspects of system sustainability performance against a datum. For example, the Primary Energy Saving index [Chicco and Mancarella, 2008; Rosato, Sibilio, and Ciampi, 2013; Rosato, Sibilio, and Scorpio, 2014a] compares the primary energy consumption of a proposed energy generation system with a conventional system, to calculate how much primary energy resource may be saved by switching to the proposed system. A considerable body of research is dedicated to benchmarking in the performance literature, but it is not the focus of the work documented in this paper.

A refined version of the S-CPMatrix, taking into account the observations discussed above, is presented in Table VIII below. Areas requiring clarification through further research, along with additional goals, SPI archetypes, and metrics that were revealed during the indicator classification, are highlighted in grey.

4. DISCUSSION

The S-CPMatrix is the first generic framework for selecting comprehensive material/energetic SPIs for technical systems. It is intended to support decision makers in meeting the three criteria for comprehensiveness identified in Section 2, by highlighting: (C3) the general range of sustainability goals that may be defined for a technical system; (C2) the different types of efficiency and effectiveness indicator at the disposal of evaluators; and (C1) the spatiotemporal scales that different SPIs may be evaluated at.

The classification exercise reported in Section 3.2 provides an initial, qualitative evaluation of the S-CPMatrix, demonstrating its applicability to different technical systems and compatibility with different evaluation methods. In this respect, the work may be viewed as a step toward more consistent, yet flexible guidance on the selection of comprehensive SPI sets for technical systems as discussed in Section 1. The basic principles underlying the matrix have been tested in two case studies focused on a ship's heating and cooling systems [Hay, 2015]. Further work is currently under way to incorporate the S-CPMatrix into a set of guidelines for sustainability performance evaluation, facilitating its application to real-world technical systems in industry. This will enable an exploration of issues such as how to select the most useful SPIs and metrics given the interests of the assessors and other stakeholders, and the overall utility of the matrix for decision makers. This work constitutes a significant undertaking, and the findings will be reported in future papers.

In addition to the ongoing industrial work discussed above, the research undertaken thus far may be seen to highlight four avenues for future work. First, indices that appear to benchmark the performance of systems were identified during the indicator classification exercise. Whilst not the focus of the work reported herein, benchmarking and systems comparison are argued to be important activities for realizing improvements in sustainability performance [Pascual and Boks, 2004; Wever et al., 2005; Ulgiati et al., 2011; Chiang and Roy, 2012]. For instance, Boks and Stevels [2003: 131] describe product environmental benchmarking as a "powerful tool," highlighting its role in improving the environmental performance of products and raising awareness of environmental considerations in manufacturing organizations. A key issue in this context is the comparability of results obtained from performance evaluations of different systems [Ulgiati et al., 2011; van Zeijl-Rozema, Ferraguto, and Caratti, 2011], for example, if different indicators are used and different areas measured. In this respect, the generic nature of the S-CPMatrix means that it could provide a common and consistent basis for future sustainability benchmarking approaches in a technical systems context. We plan to develop and incorporate guidance to this effect into the guidelines discussed above.

Second, a limited number of the proposed metrics were found to be unsupported in the indicator classification sample (Table VII): (i) *nonrenewable resource fraction*; (ii) *renewable resource productivity*; (iii) *absolute passive intended resource output*; and (iv) *intended resource production rate*. It is possible that there were simply no examples of these metrics in our sample. With respect to (i) and (ii) in particular, the metrics *renewable resource fraction* and *nonrenewable resource productivity* were found to be supported and thus, there is no immediately apparent reason why (i) and (ii) may not also be measured. Similarly, in the case of (iii) and (iv), the metric *passive intended resource fraction* was found to be supported, suggesting that this area at least is measured. However, the lack of support for intended resource metrics may also suggest that technical systems are not typically designed to produce

Table IX. Refined Version of the S-Cycle Performance Matrix (S-CPMatrix)

Generic sustainability goals	ε/η	SPI archetypes	Metrics	S-Cycle metric definitions	Full metric definition
PRODUCE IO	ε	IO production	Absolute IO output	IO_L	Amount of IO produced over some time period (t_{max} = full operation phase).
			IO production rate	IO_L/t	Amount of IO produced per unit of time (t_{max} = full operation phase).
			Relative IO production [new]	IO_{a_L}/IO_{b_L}	Amount of IO 'type A' produced per unit of IO 'type B' produced over some time period (t_{max} = full operation phase).
MINIMISE OVERALL RESOURCE USE	ε	Passive resource consumption	Absolute PR input	$PR_{L,R,G}$	Amount of PR consumed over some time period, including both renewable and non-renewable PR (t_{max} = full life cycle).
			Energy payback time [new]	$PR_{e\_R,G}/IO_{e\_L\_annual}$	Number of years required for the energetic IO produced by a technical system to equal the energetic PR it consumes over its full life cycle.
			Relative PR consumption [new]	$P\text{-}NRR_{L,R,G}/P\text{-}RR_{L,R,G}$	Amount of non-renewable PR consumed per unit of renewable PR consumed over some time period (t_{max} = full life cycle).
			PR consumption rate	$PR_{L,R,G}/t$	Amount of PR consumed per unit of time, including both renewable and non-renewable PR (t_{max} = full life cycle).
		Active resource consumption (new)	Future research	Future research	Future research
	η	Passive resource efficiency	Resource intensity	$PR_{L,R,G}/IO_L$	Amount of PR consumed per unit of IO produced over some time period (t_{max} = full oepration phase).
			Resource productivity	$IO_L/PR_{L,R,G}$	Amount of IO produced per unit of PR consumed over some time period (t_{max} = full operation phase).
				$1 – (W_L/PR_{L,R,G})$ [new]	Amount of PR transformed to IO rather than W over some time period (t_{max} = full life cycle)
MINIMISE NRR USE	ε	NRR consumption	Absolute NRR input	$P\text{-}NRR_{L,R,G}$	Amount of non-renewable PR consumed over some time period (t_{max} = full life cycle).
			NRR consumption rate	$P\text{-}NRR_{L,R,G}/t$	Amount of non-renewable PR consumed per unit of time (t_{max} = full life cycle).
			NRR fraction	$P\text{-}NRR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is non-renewable (t_{max} = full life cycle).
	η	NRR efficiency	NRR intensity	$P\text{-}NRR_{L,R,G}/IO_L$	Amount of non-renewable PR consumed per unit of IO produced over some time period (t_{max} = full operation phase).
			NRR productivity	$IO_L/P\text{-}NRR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full operation phase).
MINIMISE RR USE	ε	RR consumption	Absolute RR input	$P\text{-}RR_{L,R,G}$	Amount of renewable PR consumed over some time period (t_{max} = full life cycle).
			RR consumption rate	$P\text{-}RR_{L,R,G}/t$	Amount of renewable PR consumed per unit of time (t_{max} = full life cycle).
			RR fraction	$P\text{-}RR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is renewable (t_{max} = full life cycle).
	η	RR efficiency	RR intensity	$P\text{-}RR_{L,R,G}/IO_L$	Amount of renewable PR consumed per unit of IO produced over some time period (t_{max} = full operation phase).
			NRR productivity	$IO_L/P\text{-}RR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full operation phase).
MAXIMISE SELF-SUFFICIENCY [future work required to clarify SPI archetypes and metrics]	ε	IR production	Absolute passive IR output	$P\text{-}IR_L$	Amount of passive IR produced over some time period (t_{max} = full operation phase).
			Passive IR production rate	$P\text{-}IR_L/t$	Amount of passive IR produced per unit of time (t_{max} = full operation phase).
		IR consumption	Passive IR fraction	$P\text{-}IR_L/PR_L$	Fraction of PR consumed over some time period that was self-produced (t_{max} = full operation phase).
MINIMISE WASTE PRODUCED	ε	W production	Absolute W output	$W_{L,R,G}$	Amount of W produced over some time period (t_{max} = full life cycle).
			W concentration [new]	$W_{a\_L,R,G}/W_{L,R,G}$	Amount of W 'type A' produced as a fraction of the total W produced over some time period (t_{max} = full life cycle).
			W intensity	$W_{L,R,G}/IO_L$	Amount of W produced per unit of IO produced over some time period (t_{max} = full operation phase).
			W production rate	$W_{L,R,G}/t$	Amount of W produced per unit of time (t_{max} = full life cycle).
	η	Resource inefficiency	Wastefulness	$W_{L,R,G}/PR_{L,R,G}$	Amount of W produced per unit of PR consumed over some time period (t_{max} = full operation phase).
				$PR_{L,R,G}/W_{L,R,G}$ [new]	Amount of PR consumed per unit of W produced over some time period (t_{max} = full operation phase).
MINIMISE CONTAMINATING POTENTIAL OF OUTPUTS	ε	Future work	Future work	Future work	Future work

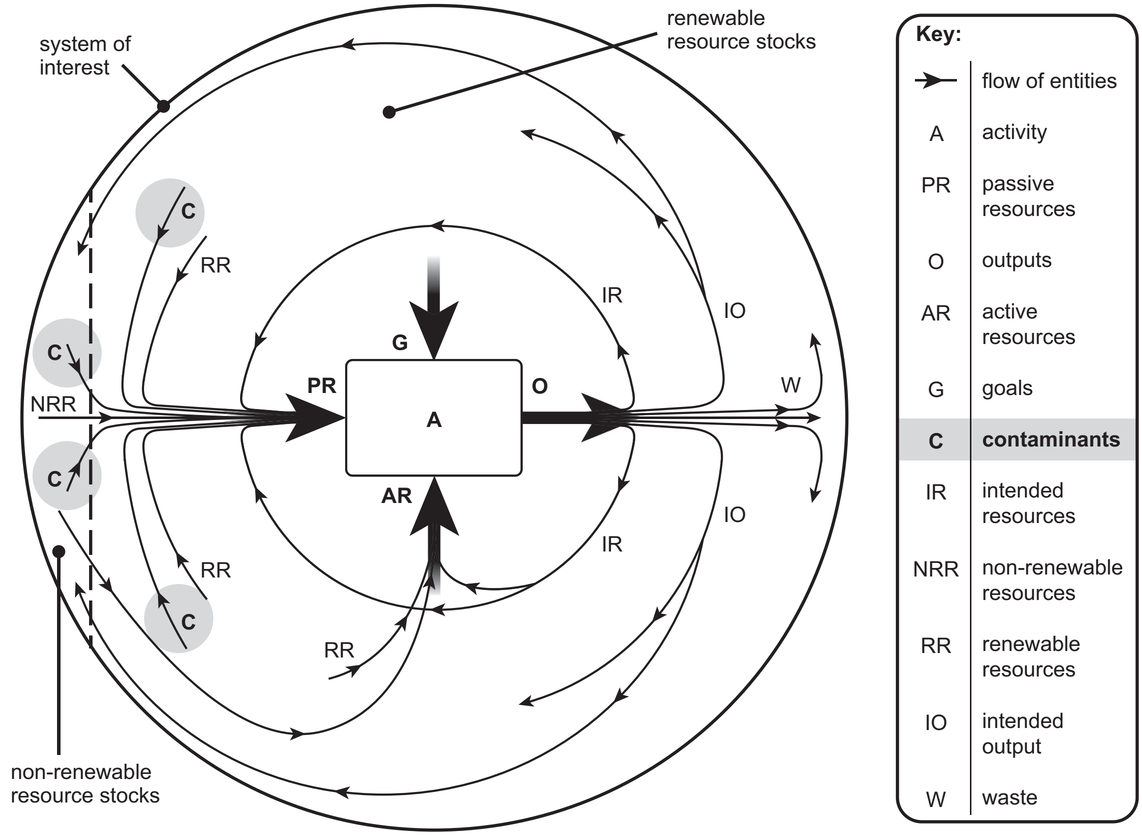

Figure 6. Refined version of the S-Cycle model including contaminants.

and consume intended resources in the first place. In any case, future research involving more extensive application of the S-CPMatrix to technical systems is required to further investigate unsupported metrics. Further refinements to the matrix may in turn be necessary.

Third, the findings of the indicator classification highlighted an additional sustainability goal that may be relevant for technical systems: *minimize contaminating potential of outputs*. This aspect of a technical system's behavior is not immediately apparent in the S-Cycle model, from which goals in the S-CPMatrix were derived. This raises the question of whether the model should be refined to incorporate it. As discussed in Section 3.2.2, the outputs produced by a system activity (that is, intended output and waste) may contaminate the resource inputs of other activities operating within the same SoI. As such, it is proposed that one means of incorporating the notion of contaminants into the S-Cycle model may be to include an additional contaminant input element as illustrated in Figure 6. However, further research is needed to explore the nature of contaminants and how they may be measured. Again, more extensive application of the S-CPMatrix to different technical systems may provide insight into these aspects, and facilitate refinements to both the matrix and the S-Cycle model if appropriate.

Finally, the S-CPMatrix may be considered to provide a framework for assessing the comprehensiveness of SPI sets currently used in sustainability performance evaluation of technical systems. The focus of the study reported in this paper was development of the matrix and as such, the comprehensiveness of individual evaluation efforts was not explored. This may form the focus of future studies, potentially leading to insights regarding the completeness of the information currently used in sustainability decision making in a technical systems context.

5. CONCLUSION

A range of methods focusing on material and energetic performance are considered useful in sustainability evaluation of technical systems. However, it is not clear whether they yield comprehensive sets of sustainability performance indicators (SPIs), or what form such a set might take for a technical system. Generic guidelines provided through international initiatives such as the GRI provide a consistent approach to comprehensive organizational SPI selection, whilst leaving the precise choice of evaluation methods up to the assessors. However, guidance of this nature is lacking at the technical system level.

Toward addressing the above issues, we have presented the first generic framework for selecting comprehensive material/energetic SPIs for technical systems: the S-Cycle Performance Matrix (S-CPMatrix). To construct the matrix, we defined 6 generic sustainability goals, 11 SPI archetypes, and 23 corresponding metrics using our previously developed model of technical system sustainability (the S-Cycle

[Hay et al., 2014; Hay, 2015]). The matrix was then evaluated by interpreting and classifying 324 SPIs used in various assessment methods currently applied to different technical systems. 94.1% of the indicators in the sample were found to be fully classifiable with respect to the S-CPMatrix following refinements, with the remaining 5.9% highlighting additional SPIs and a goal that were not initially identified. Furthermore, all of the proposed SPI archetypes and metrics were found to be supported in the sample, with the exception of four metrics. Based on these findings, we conclude that the matrix is strongly supported in the literature, is applicable to different systems, and may be considered to facilitate the selection of a holistic set of SPIs from different sources and evaluation approaches.

The S-CPMatrix is intended to support decision makers in addressing three criteria for comprehensive SPI sets identified from the literature: (C1) coverage of all relevant spatiotemporal scales; (C2) inclusion of efficiency and effectiveness indicators; and (C3) coverage of all sustainability goals defined for a system. Research is currently under way to apply the S-CPMatrix to real-world systems in industry in order to assess its utility for decision makers in practice. Additionally, the findings of the work reported herein highlight four avenues for further research: (i) the application of the matrix to support systems comparison/benchmarking; (ii) further investigation of metrics found to be unsupported by the classification exercise; (iii) the nature of contaminants as an influence on technical system sustainability, and how they may be measured and modeled; and (iv) assessing the comprehensiveness of SPI sets currently used in sustainability performance evaluation of technical systems.

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