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Economic modelling and indicators in life cycle sustainability assessment

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Abstract
Purpose Sustainability assessment in life cycle assessment (LCA) addresses societal aspects of technologies or products to evaluate whether a technology/product helps to address important challenges faced by society or whether it causes problems to society or at least selected social groups. In this paper, we analyse how this has been, and can be addressed in the context of economic assessments. We discuss the need for systemic measures applicable in the macro-economic setting.
Methods The modelling framework of life cycle costing (LCC) is analysed as a key component of the life cycle sustainability assessment (LCSA) framework. Supply chain analysis is applied to LCC in order to understand the relationships between societal concerns of value adding and the basic cost associated with a functional unit. Methods to link LCC as a foreground economic inventory to a background economy wide inventory such as an input–output table are shown. Other modelling frameworks designed to capture consequential effects in LCSA are discussed.
Results LCC is a useful indicator in economic assessments, but it fails to capture the full dimension of economic sustainability. It has potential contradictions in system boundary to an environmental LCA, and includes normative judgements at the equivalent of the inventory level. Further, it has an inherent contradiction between user goals (minimisation of cost) and social goals (maximisation of value adding), and has no clear application in a consequential setting. LCC is focussed on the indicator of life cycle cost, to the exclusion of many relevant indicators that can be utilised in LCSA. As such, we propose the coverage of indicators in economic assessment to include the value adding to the economy by type of input, import dependency, indicators associated with the role of capital and labour, the innovation potential, linkages and the structural impact on economic sectors.
Conclusions If the economic dimension of LCSA is to be equivalently addressed as the other pillars, formalisation of equivalent frameworks must be undertaken. Much can be advanced from other fields that could see LCSA to take a more central role in policy formation.

Keywords Attributional · Consequential · Economic assessment · Economic indicators · Life cycle costing

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1 Introduction

Sustainability assessment in life cycle assessment (LCA) addresses societal aspects of technologies or products to evaluate whether a technology/product helps to address important challenges faced by society or whether it causes problems to society or at least selected social groups. The term sustainability was introduced to reconcile the conflict between environmental protection and economic development (World Commission on Environment and Development 1987). The concept of sustainability is often broken down into contributions of economic, social and environmental concerns, known as the three pillars (BMU 1998), and this form has been proposed as a basis for life cycle sustainability assessment (Kloepffer 2008; Guinée et al. 2011).

Sustainability implies prospering in a long-term perspective and requires both adequate economic production to provide for livelihoods and a functioning environment. Long-term economic sustainability depends on both natural and human resources, on ecosystem services and social harmony to produce the material goods that humans require for a decent life, so what appears as contradictions in the short term aligns in the long term. In the discussion of economic sustainability, the necessity for environmentally friendly alternatives to be economically advantageous, i.e. profitable for the investor/user also in the short term and hence selected over less environmentally friendly alternatives, is often emphasised (Hawken 1993; Schmidheiny 1992). The full degree of economic benefits, however, becomes only apparent when alternatives are assessed beyond the focus of the single investor or user, i.e. the full costs and benefits to others are properly considered in the decision (Van Den Bergh et al. 2011; Dandres et al. 2012). The current costs, which are influenced by externalities, taxes, and subsidies, are hence a poor guidance to sustainability; however, they still have a significant descriptive value as we show in this paper.

Key to economic sustainability is the functioning of the economic system on the macro-level. Conceptually, the influence of a small component (a product system) on the total system is difficult to grasp, and it is convenient to define such an effect as being outside the system. However, recent studies of rebound and ripple effects (Hertwich 2005b), Jevons' paradox (Alcott 2009; Sorrell 2009) and peak oil (Murphy and Hall 2011) have shown that the interplay between individual products or technologies and the macro-level are potentially significant. These effects relate to producer or consumer changes in demand for related or un-related products to the functional unit when an efficiency improvement is realised (e.g. increase in efficiency of coal use saw spike in demand; savings in fuel used in local transport may be re-spent on overseas holidays). There has been a keen interest to include rebound effects in environmental LCA (Takase et al. 2005; Girod et al. 2011b). Further, technological innovations, such as the product innovations and efficiency gains, are often assessed with LCA and are a key candidate for life cycle sustainability assessment (LCSA). In economics, technological innovation is universally accepted to be an important cause for economic growth (Barro and Sala-i-Martin 1994; Aghion and Howitt 2009; 1998; Solow 1956; Ayres and Warr 2005) and thus should be addressed in LCSA. Growth, again, is seen as important means/enabler for lifting large parts of the population out of poverty (Kuznets 1955).

The question hence arises to what degree and in what form macro-economic considerations can and should be included in LCSA. The sustainability effect of a product or technology in a consequential sense will depend on institutions and properties of the system it is employed in, rather than being an inherent property of the product viz. technology. The product system as unit of analysis in LCA may hence not be suitable to determine the ultimate sustainability in consideration of macro-level concerns (Hertwich 2012). This paper follows the development of micro-level analysis as used in LCSA, starting from life-cycle costing (LCC) to later situate the discussion within the domain of macro-level analysis and consequential considerations. Relevant indicators for economic aspects of sustainability are then changed when looking at macro-level analysis and the role of prospective technologies (Hertwich et al. 2011). Furthermore, making the connection of LCC to economy wide models, such as with the theory of input–output economics, allows LCC to be used for much wider analysis of economic attributes.

In this paper, we review the current standing of economic assessments in LCSA in Section 2. The central role that LCC has played, and has been proposed to play is analysed in Section 3. When considering LCC, perhaps more reflection is required on some of its innate attributes such as system boundary (Section 3.2), aggregation of unlike costs (Section 3.3) and the conflicting nature of user verse social goals (Section 3.4). The situation of LCC within a more general modelling framework is discussed in Section 4.1, and extended to discuss the role of consequential modelling requirements in Section 4.2 and 4.3. Modelling frameworks are of course only relevant if we can draw information from them, and as such, Section 5 discusses what indicators are relevant in economic assessment. A simple example application is provided to show the link between a life cycle cost and economy wide analysis in Section 6 before conclusions a drawn in Section 7.

2 Economic assessment in LCA

Whilst LCA has grown out of a field concentrating on the assessment of environmental impacts, the broadening of the scope of LCA has occurred in order to incorporate the broader notion of sustainability. Much of this work in the economic dimension has focussed on cost assessment and its application or comparison to the results of environmental LCA. Studies range from single user problems such as car driving (e.g. Granovskii et al. 2006) to economy wide studies on infrastructure such as electricity generation (e.g. Gujba et al. 2010).

Much work has been empirical, but there has also been considerable theoretical work since the 1990s. Weidema (1993) started discussing market aspects, but more in the light of their implications for environmental LCA. Norris (2001a) went further in trying to integrate LCC into LCA. Similarly, Weidema (2006) focused on cost–benefit analysis in order to capture the economic impacts of a technology. Whilst LCC is targeted at direct costs of the functional unit, cost–benefit analysis provides a more encompassing view of the broader economic implications of an investment (Weidema 2006). Cost–benefit analysis attempt to quantify the complete costs (and benefits) to *all* stakeholders. Rebitzer and Hunkeler

(2003) discuss a framework for LCC within LCM, focussing on the different perspectives of actors in the supply chain, effects of different types of costing, including, for example, taxes and subsidies; the division of internal and external costs —and the applicability of external costs. They argue that externalities should only be included when there is a reasonable chance that they will become internal costs (e.g. through a carbon price).

The issue of whether to include external costs (such as valued costs of denying a nice view) often depends on whether the study is part of a sustainability assessment, or seeks to only quantify impacts in economic terms, as in Total Cost Assessment (less quantifiable costs) and Full Costs Assessment (all externalities; Norris 2001a, b; Parikh 2002). Kloepffer (2008) restricts LCC to real monetary flows (i.e. excluding externalities and other hidden costs borne by other stakeholders), in general agreement with other literature (Norris 2001a, b) and practice (Bracciali et al. 2008; Stölting and Spengler 2005; Vendrusculo et al. 2009; Schwab Castella et al. 2009; Benko et al. 2006). The combination of full cost assessment and environmental LCA in a LCSA framework would lead to a double counting of the environmental impacts, which would be counted in the environmental domain, as well as costed in the economic domain. Hence, we no longer pursue the issue of externality costing in this paper.

More formally, Kloepffer (2008) has defined LCSA to be composed of three components—an (environmental) LCA, an LCC and a social life cycle assessment (SLCA). The economic sphere of sustainability in that work is thus sought to be captured purely by the life cycle costing associated with a functional unit (and system boundary) analogous at least to the LCA and preferably to the SLCA. Much work has recently been done on refining the application of LCC in the LCSA, including developing experiences (Hunkeler et al. 2008) and a code of practice (Swarr et al. 2011a, b).

Guinée et al. (2011) and Heijungs et al. (2010) take a broader view of the subject, giving a general overview of possibilities in LCSA. Their contributions focus on linking the broadened scope of a LCSA with modelling frameworks, and on the links between normative and empirical aspects. As such, these viewpoints are less restrictive on applications of LCSA principles, and allow more ground to be covered in the framework. In reviewing the modelling requirements, Heijungs et al. discuss the occurrence of price mechanisms and induced volume changes in considering micro-economic effects, and productivity (with induced leisure or spending outcomes) as a major consideration of macro-economic effects. Some examples of applications include such as May and Brennan (2006), where a broader assessment of the three pillars of sustainability occurs for electricity generation. In economic assessment, they broaden a range of costing indicators to separately report the value added to the economy. Similarly, Thomassen et al. (2009) use gross value added as well as labour productivity as indicators of dairy farms.

However, as the current state of the art in LCSA largely focuses on the role of LCC, reflecting the framework postulated by Kloepffer (2008), we start from here in discussing how we should move forward in economic assessment in LCA. Hence, the first question we would like to focus on is if LCC is a comprehensive indicator for the economic dimension of LCSA. Before exploring this question, some of the intrinsic properties of LCC need to be addressed first.

3 LCSA and life cycle costing

3.1 Introduction

We do not seek to give guidelines on how to do an LCC for LCSA, which is very well covered elsewhere (Swarr et al. 2011b), but rather reflect on some of the key attributes of LCC and its relevance for economic assessment in LCA.

The integration of LCC into an LCA framework has been discussed for some time (Norris 2001a, b). And whilst LCC and LCA can have similar modelling structures (Heijungs et al. 2010) and a common functional unit definition (Swarr et al. 2011b), there are some critical conceptual differences (refer to Norris 2001b, Table 1). Apart from the issues of timing (such as the common discounting of future costs in LCC, compared to the rarely performed discounting of future environmental emissions) and obviously valuation (physical valuation, verse monetary valuation), we consider the most critical aspects to be regarding objectives and scope. Whilst the focus of LCA is on societal impacts, LCC's focus is on a select group of stakeholders directly affected by the supply of the functional unit. In terms of scope, LCA analyses production chains, whereas LCC focuses on direct costs of the stakeholders in obtaining the functional unit. We focus on these properties, as they become important for later consideration of the role of LCC.

3.2 System boundary in LCC

The cost of a product (or more precisely a functional unit) is related to the economic actor(s) at the place of the functional unit. As such, only direct costs associated with the functional unit need to be estimated in LCC (Swarr et al. 2011b). However, if we are looking at assessing economic impacts, which, we have argued is the purpose of the economic dimension of LCSA, then it is worthwhile considering what is implicit in a final product cost. The relationship of a final product cost to raw inputs is well known, and explained nicely in Nakamura and Rebitzer (2008). Here, we use matrix notation for the life cycle inventory (LCI; Heijungs and

Suh 2002), in common with usage in input–output analysis (Miller and Blair 1985).

That is, when we start from the basic accounting identity or monetary balance in the economy that revenue must balance with expenditure:

Cost of output = cost of inputs

Switching to an algebraic representation of this we have

$$p_j x_j = \sum_i p_j T_{ij} + \sum_k V_{k,j} \tag{1}$$

at the whole of economy level, where x_j represents the total output for all products j in the economy; T_{ij} are the inputs of goods and services i required to produce product j. p_j are the prices of product j (€/unit, or simply unit prices if product j is represented in monetary terms already). $V_{k,j}$ is the components of type k of Value added for product j. The components of value added cover the primary factors of production (inputs that are not goods and services, such as labour and capital), as well as surpluses and taxes, already in monetary terms (although it is possible to extend the price vector to also include these items in physical terms, such as in employee hours). The summation over the components of value added k and across all product types j gives the gross domestic product (GDP).

$$\text{GDP} = \sum_j \sum_k V_{k,j} \tag{2}$$

Using functional relationships, we can replace T_{ij} with $A_{ij}x_j$, where A_{ij} is the direct requirements matrix, i.e. the inputs of goods and services of product j per unit output of product j. That is:

$$p_j x_j = \sum_i p_i A_{ij} x_j + \sum_k V_{k,j} \tag{3}$$

Dividing both sides by x_j:

$$p_j = \sum_i p_i A_{ij} + \sum_k F_{k,j} \tag{4}$$

Where we define $F_{k,j} = \frac{V_{kj}}{x_j}$ as the components of value added per unit output. In matrix format, this becomes

$$\mathbf{p} = \mathbf{pA} + \mathbf{eF} \tag{5}$$

where $\mathbf{e}$ is a summation vector (vector of 1s) over the k components of value added (already in monetary terms). Further re-arranging gives

$$\mathbf{p} = \mathbf{eF}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{eFL} \tag{6}$$

with $\mathbf{I}$ as the identity matrix, and where $\mathbf{L}$ is the so called "Leontief inverse". In supply chain format, we can use the Taylor series expansion of the Leontief inverse (Defourny and Thorbecke 1984):

$$\mathbf{p} = \mathbf{eFL} = \mathbf{eF}\left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots\right) \tag{7}$$

For a particular functional unit f, we define the volume of direct inputs required to be $\mathbf{x}^f$ (referred to elsewhere as the *cost breakdown structure*). Here, the direct inputs need to be defined as per the system boundary of the LCC (Swarr et al. 2011b), including production, use and end-of-life requirements.

Hence the LCC of a particular functional unit becomes:

$$\mathbf{px}^f = \mathbf{eFLx}^f = \mathbf{eF}\left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{L}\right)\mathbf{x}^f \tag{8}$$

If we represent impact on the economy as the sum of value added, it is then easy for us to unravel the economic impact along the full production chain (Fig. 1). Especially in firm-level studies, this is often referred to as value chain analysis (Dahlström and Ekins 2007). Impact on the economy associated with the cost of the direct inputs is the 0th order production $\mathbf{eFx}^f$ whilst impact from the production of these inputs are the first order production $\mathbf{eFAx}^f$, and the impacts of the production of the products in the second order of the production chain are $\mathbf{eFAAx}^f$. As is clear from the Taylor series expansion, the economic impacts are traced all the way back through the infinite production chains (because of production feedback loops).

Hence whilst the analysts in a LCC only concerns themselves with collecting direct costing data associated with a functional unit ($\mathbf{px}^f$ in this notation), the economic impact is *implicitly* calculated along the full production chain. Hence, the *upstream* system boundary is *necessarily* complete in LCC (i.e. there is no truncation error up the supply chain), whereas this may not be the case in LCA, where truncation error is common (Lenzen and Treloar 2003). This holds true for activities with any economic impact, i.e. activities that are part of the "formal" economy.

3.3 Aggregation of inventories in LCI versus LCC

Whereas an LCC by definition sums up all factor costs $V_{k,j}$ along the supply chain, these factor costs must not necessarily be aggregated in the supply chain context. That is, if we can relate the final LCC $\mathbf{px}^f$ to the supply chain $\mathbf{eF}\left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{L}\right)\mathbf{x}^f$ we can maintain the delineation of the components of value added k. We can thus distinguish the components of the final LCC that are due to labour costs, profit taking, capital depreciation, and taxes.

Hence, our summation vector $\mathbf{e}$, is in fact a normative (or social) construct—it implicitly states that we value each type of factor input equally. We aggregate remuneration of employment with profit taking. Employment serves many, and can easily be defended as being a positive economic outcome, whereas profit taking serves only a few, and is

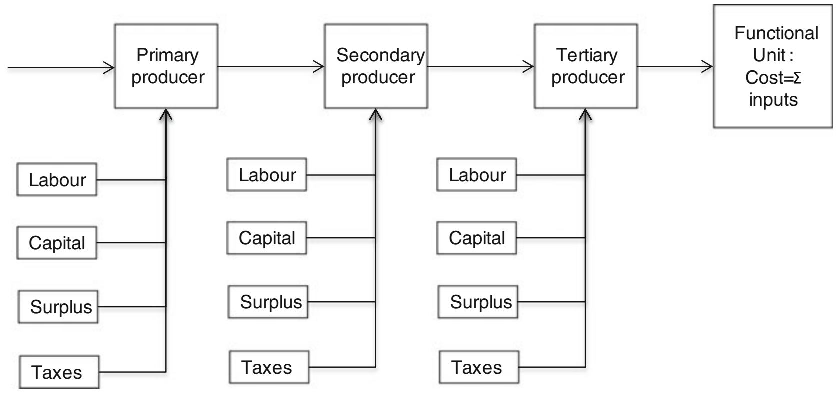

Fig. 1 Supply chain representation of components of value added required in the delivery of a functional unit

debatable whether growth in profit is necessarily good or bad. This is one of the criticisms of using GDP as an economic indicator—it is a sum of positive and negative social impacts (Stiglitz et al. 2009).

In environmental LCA, the inventory section is clearly delineated from the impact assessment. No aggregation of elemental flows occurs in the inventory stage, but instead aggregation is a focus of the impact assessment. This is not generally the case in LCC, where different types of factor costs are usually aggregated. Whilst the factor costs may have the same unit (e.g. Euro or dollar; Seuring et al. 2008), this does not mean they have the same intrinsic quality. Hence, whilst aggregation has been advocated (Seuring et al. 2008), we maintain that the aggregation of different types of factor costs is equivalent to an impact assessment, and not an inventory. If we are to align LCC with LCI and LCA, then this needs to be considered.

However, the aggregation of factor costs is not a necessary evil for LCC. As per environmental LCI, it is possible to create a monetary inventory along the supply chain, with aggregation to occur in the impact assessment stage. The authors' are not aware of many studies which take this approach, however (an example which goes part way can be found in Linnanen et al. (2002)). One reason is the lack of data available from a life cycle perspective on factor costs of different processes. Whilst the price of a product can be estimated, the breakdown of this price into direct profit, labour, taxes and upstream supply chain inputs is not available in any life cycle database. Practitioners then need to look elsewhere for this kind of data. Two obvious choices include input–output tables, which have aggregated sector level data, but with specific primary and intermediate inputs, or engineering costing tools (e.g. Ereev and Patel 2012).

3.4 Inherent contradictions in LCC applied to LCSA

We have shown that LCC as represented by the costing of direct requirements for a functional unit is equivalent to the summation of the components of value added along the upstream supply chain of these requirements. Here is the fundamental contradiction of using life cycle cost as a sole indicator of economic impacts in a sustainability assessment. From an individual user's perspective, life cycle cost should be minimised (life cycle cost is often used to normalise environmental impact against, so that the smallest environmental impact per dollar cost is taken as the best option). However, from society's perspective, the sum over the components of value added should generally be maximised. As such, the life cycle cost is not an indicator of economic well-being at all. If we want to design sustainability assessments that realistically try to include perspectives of economic well-being, then we clearly need other indicators than life cycle cost. In fact, the only way a reduced life cycle cost can be seen to be synonymous with economic growth (and even here it is still a stretch to equate economic growth to economic well-being) is where reduced costs has a rebound effect on commodity consumption—that is reduced unit expenditure leads to overall increased sales volume (Jevons 1866; Hertwich 2005a). This type of effect is clearly consequential, and beyond the computational structure of attributional LCA to begin with, and LCC in particular. We return to this point later.

4 Economic modelling approaches in LCSA

4.1 Introduction

Despite these criticisms, we do not say that LCC is not a very useful tool—it clearly is. We only state that LCC is one approach that can be applied, and that by itself, it does not give a full reflection of many interesting economic phenomena. LCC does not by itself reflect the purpose of LCSA in assessing societal concerns. Hence in order to adequately address the economic dimensions of LCSA, we then propose that we go beyond LCC. Without repeating the derivations of Section 3.2, it is clear that LCC can be directly applied in the macro-economic setting of input–output analysis (Eq. (8)). Reforming LCC as a foreground monetary inventory by means of the cost breakdown structure of a LCC allows the connection of LCC to product chain analysis in the whole of economy context. As such, the limitation here is not methodological, but access to relevant data such as input–output tables. However, as is well known, there are limitations to the scope of issues that can be addressed in a static input–output framework.

4.2 Methods applicable to consequential and attributional LCA

The discussion on LCC has been limited to the attributional setting (i.e. when describing the fixed relationships that contribute to the impact of a functional unit, often applicable in current or historical analysis). However, more and more focus in LCSA is not on what has happened in the past, but how LCSA can help provide insight into consequences of decisions. Introducing nanotechnologies to the economy, or scaling up renewable power generation, will all have far greater implications on the economy than what can be assessed based on the attributional impacts of a single functional unit.

In microeconomic terms, we have the costing of a functional unit reflecting a single object, but any technology necessarily operates in a broader market. Microeconomics examines how the presence of a new technology affects prices in the market, and hence the quantity changes in supply and demand of related products and services. Microeconomics does not provide indicators per se, but focuses on modelling behaviours. As Heijungs et al. (2010) point out, microeconomic theory has been used in life cycle assessment mainly to understand or model the rebound effect from a consumer's perspective (Thiesen et al. 2008; Girod et al. 2011a); or on potential shifts in market structure within the supply chain. Analysing the consequential price shifts on related products is rare in a LCA context, and is often the domain of partial equilibrium models, whereas economy wide non-marginal changes in prices require computable general equilibrium models (Dandres et al. 2011, see below; Berck and Hoffmann 2002).

If we return to the objective of LCC, of assessing and attributing costs to a single-product oriented functional unit, we see that the indicator is not adequate in a consequential setting. There is simply no mechanism in LCC to include the impact of re-expenditure of any potential cost savings. Life cycle cost is purely an attributional indicator. For a consequential-type assessment, a broader cost/benefit analysis of multiple stakeholders is required. In microeconomics, we limit our viewpoint to impacts on related goods and services, ignoring economy-wide changes. In practice, this means developing supply/demand models for estimation of prices and consequentially volumes of related products associated with a change to the marketplace—i.e. models to include the rebound effect (Thiesen et al. 2008). Price elasticities of demand and cross price elasticities of demand are ideally utilised here (Ekvall and Andrae 2006). Thus, from Eq. (8), we replace our single stakeholder variable on volumes $\mathbf{x}^f$ with a multiple stakeholder variable $\mathbf{x}^{f*}$ and a modified price vector $\mathbf{p*}$ utilising whichever applicable model to estimate this variable. As this creates disequilibrium in the broader economy, (i.e. $\mathbf{p}^*\mathbf{x}^{f*} \neq \mathbf{eFLx}^{f*}$), we can take a very basic assumption that price differences only affect profit margins of existing sectors (with inputs of goods and services, capital, labour and tax rates fixed in the short term). Mathematically, with fixed intermediate inputs ($\mathbf{L}$), we can split our summing relationship over components of value added (the vector $\mathbf{e}$=[1 1 1 1], for 4 components with no scaling) into fixed inputs $\mathbf{e}^1$=[1 1 1 0], and profits $\mathbf{e}^2$=[0 0 0 r], (with r, the only variable input, showing the scaling factor on profits required to adjust for the inequality).

$$\mathbf{p}^*\mathbf{x}^{f*} = \mathbf{e}^1\mathbf{FLx}^f + \mathbf{e}^2\mathbf{FLx}^f \tag{9}$$

Rearranging,

$$\mathbf{e}^2 = \frac{\mathbf{p}^*\mathbf{x}^{f*} - \mathbf{e}^1\mathbf{Flx}^f}{\mathbf{Flx}^f} \tag{10}$$

Implicit in this construction is that the scaling factor on profit margin r applies equally to all supply chain inputs. Whilst this assumption has no impact on aggregate indicators (contribution to GDP, etc.), it will impact structural indicators, and could be refined where additional information is known.

4.3 Macroeconomic concerns

In macroeconomics, we are interested in the long run dynamics of a whole economy. As such, shifts in productivity and structure are paramount. The introduction or upscaling of technologies are expected to change labour requirements, more efficiently use capital, and more efficiently use inputs of goods and services. LCSA is perhaps not adequately equipped to handle these problems yet, and recommendations to use computable general equilibrium or similar models (European Commission 2010) are arguably not linked closely enough to modelling of technical change in environmental LCA.

Whilst much is still to be done in this area, we can approach the problem in the same LCSA framework, albeit with a different arrival point for the inventory stage—instead of using existing IO databases, we need to apply dynamic models to the economy under the introduction/upscaling of the production system associated with the functional unit.

5 Proposed economic indicators in LCSA

In utilising frameworks that address the full supply chain and economy-wide interactions (the use of input–output and general equilibrium frameworks, as above and in Heijungs et al. (2010)), it is then possible to extend well beyond the single indicator of life cycle cost and instead calculate a wealth of other economic indicators. We hence turn our attention to what indicators are relevant to extract from these more general modelling frameworks.

Numerous LCAs and integrated assessments seek to include indicators of interest to the broader economic system. Such an example is Kruse et al. (2009), where production costs, gendered and migrant labour costs, value added, employment hours are used as quantitative indicators. Other examples looking at economy-wide impacts due to such things as employment compensation, profit generation, tax expenditure can be found in Foran et al. (2005) and Wood and Garnett (2010). The EU (EUROSTAT 2005) uses four headline indicators made up of subsidiary indicators for measuring economic performance. This includes GDP/capita, per capita wealth (World Bank 2011), investment (regional breakdown, investment, net saving, total consumption expenditure), competitiveness (labour productivity, unit labour cost, price competitiveness, lifelong learning, research and development (R&D) expenditure) and employment/unemployment. The UN (UN 2001) looks at headline indicators of GDP, investment share, balance of trade, debt ratios and aid, but also include a range of consumption and production indicators that border on investigating environmental sustainability (energy use, waste generation, etc.). Resource productivity, defined as the economic output achieved relative to resource inputs, is used, but represents a problem for LCSA when utilising the three pillar approach. Resource productivity clearly crosses the environmental and economic domain, such that if it is to be included, it needs to be addressed at the integration stage of the various indicators, that is, it is an endpoint indicator that is not relevant to be categorised in a pillar-type approach. There are further hundreds of potential indicators of economic well-being. It is not the purpose of this paper to review these all here.

What is clear, and is the purpose of this paper, is that several themes are used to represent economic well-being outside LCSA that could equally well be applied within LCSA (Hertwich et al. 2011). Firstly, GDP, or at least contribution to GDP, is used extensively, which we have already shown how it can be consistent with current LCC approaches in an attributional setting. Secondly, investments are treated specifically. With various ways of examining the issue, indicators that relate to investments are the total capital expenditure, the annual capital depreciation, the capital productivity, the investment share of current expenditure, the expenditure on R&D. Thirdly, labour is also of interest. Whilst crossing the boundary to social assessment, labour productivity is clearly of economic concern, whilst labour costs contribute both to product costs and measures of GDP. Fourthly, geographic specification is important—reliance on imports and contribution to exports affects the strength of an economy.

As most sustainability assessment frameworks are drawn up on the national level, we believe they can overlook some economic attributes associated with particular functional units or technologies. We would thus like to draw on commonly used indicators in economics relating to technologies that in particular investigate structural aspects.

Firstly, we would like to consider the role of innovation. We define process innovations as innovations that give us the ability to produce more of the same product for less/different inputs, whilst product innovations we define to result in qualitatively different products, either totally new or with new and improved features, which may have new applications than the ones that existed before. Process innovations can be adequately captured in an attributional assessment, and the previously mentioned indicators of productivity, cost, import dependency, etc. describe the contribution of process innovations to the economy. Product innovations necessarily shift demand to the new products and should generally be considered within the scope of consequential assessments. They are often seen as playing a key role in economic growth (Barro and Sala-i-Martin 1994), and as such the "novelty" of the output of a technology can be seen as an important dimension to cover in the economic assessment. Novelty can be quantified as the percentage of new markets compared to existing markets of a technology, measured in terms of economic production.

Secondly, we would like to extend this reasoning by investigating the pervasiveness of a product system, and to measure the pervasiveness on two aspects—how important the output of the product system is for the rest of the economy, and how much inputs are drawn from the rest of the economy for the particular product system. For a product innovation with pervasive qualities, such as the development of the computer, we would expect strong demand for the product from many other economic sectors. For a process innovation, we can reflect on the required changes in supply from other sectors to service the demand of the product system. These concepts can be quantified by the use of measures for economic linkages (Chenery and Watanabe 1958; Rasmussen 1956). Linkage measures look at the relative importance (looking at coefficients) of the product system for other sectors. Forward linkages measure the importance of the product for other sectors of the economy, whilst backward linkages measure the relative contribution of other products to the operation of the technology. Linkages can be measured within the hybridised input–output framework. Forward linkages based on the supply-driven Ghosh (1958) model, whilst backward linkages can be based on the demand driven Leontief model (Leontief 1941). Production systems with strong forward and backward linkages can be considered to be key

Table 1 An indication of indicators relevant for economic LCSA

Type	Meaning	Aggregate indicators	Indicators	Calculation
Absolute measures	Associated value adding	Contribution to GDP/LCC	Components of value added capital	Supply chain summation
			labour	
			profit	
			tax	
	Self-sufficiency	Trade	Imports	Supply chain summation
Relative measures	Innovative capacity	Product innovation	Novelty	New/existing markets
	Efficiency of production	Productivity	Capital	Output/capital input
			Labour	Output/labour input
	Complexity of production	Structure	Linkages	Ratio—inputs/outputs of goods and services
			Industry distribution	Ratio

processes within an economy and play an important role in economic development (Sohn 2004).

Finally, the structural requirements of a production system are of interest (e.g. in the IMAGE model Alcamo 1994). Generally, it is of concern to policy makers if a production system is heavily reliant on agricultural or mined goods, or whether they play a large role in the service sector of the economy. Whilst the desired outcome (primary or service sector reliance) may differ from region to region, the structural effects of different technologies are of interest to anticipate, because they will bring economic benefit to some sectors and hardship to others. For example, the case of bio-fuels will clearly benefit agricultural producers—useful if your country has excess agricultural production, but detrimental if this increases reliance on overseas production. The anticipation of structural changes also allows policy makers to change education and rules, and to provide infrastructure necessary for new sectors to prosper (Moe 2010).

In summary, we provide a list of select indicators (see Table 1) that fulfil the above objectives and which are of interest in a life cycle or technology assessment. We combine the reviewed indicators from the sustainability literature that cover value adding (including contribution to GDP and life cycle cost), trade and productivity with our proposed indicators to cover product innovations (novelty), pervasiveness (linkages) and economic structure. The list of indicators in Table 1 is not extensive or comprehensive, and that is not our purpose—just as in environmental LCA indicator selection is done based on situational importance to be as comprehensive as desired, the same can be done in economic assessment. What is important is stressing that these indicators are all manipulations of basic (monetised) inventory data. We thus have a clear link to environmental LCA where the calculation of indicators occurs within impact assessment whilst costing methods are applied firmly in the inventory stage (given appropriate scoping).

6 Case study—wind power

We show here a simple example. In order to keep it simple and manageable, we focus on demonstrating the application of a basic costing in an economy-wide framework and do not go into consequential assessment. The main purpose is

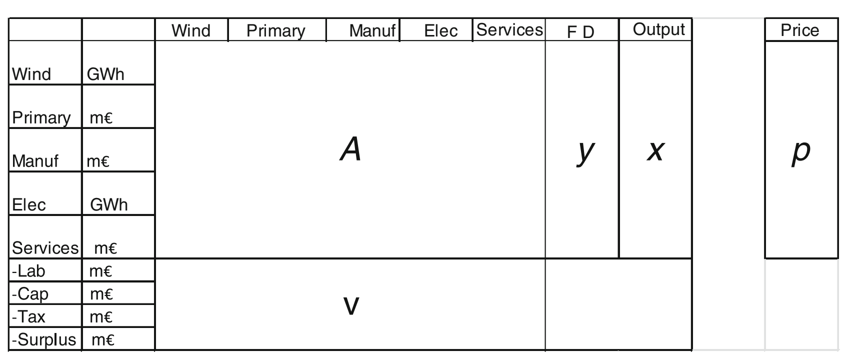

Fig. 2 Representation of variables in a hybrid IO LCA model. FD refers to final demand, Output is the gross output of each product

Table 2 Values of variables in a hybrid IO LCA model

		Wind	Primary	Manufacturing	Electricity	Services	FD	Output	Price	
Wind	GWh	–	0.00	0.00	0.00	0.00	7,503	30,157	0.045	m€/GWh
Primary	m€	–	0.12	0.08	0.01	0.01	766,492	3,290,382	1.000	m€/m€
Manufacturing	m€	0.00	0.12	0.39	0.00	0.10	7,282,522	19,415,060	1.000	m€/m€
Electricity	GWh	–	0.27	0.26	0.03	0.13	3,928,522	15,773,586	0.045	m€/GWh
Services	m€	0.00	0.15	0.20	0.01	0.29	25,740,753	42,552,802	1.000	m€/m€
Lab	m€	0.00	0.17	0.17	0.00	0.32				
Cap	m€	0.04	0.11	0.04	0.01	0.08				
Tax	m€	0.00	0.04	0.04	0.00	0.04				
Surplus	m€	0.00	0.28	0.07	0.00	0.15				

The values of the **v** and **A** matrices are per unit output for each product, i.e. per gigawatt hour for wind and electricity, and per million Euro for other product groups

hence to show the breadth of analysis that can be done by marrying different frameworks. The example is real world—based on the EXIOPOL database[1] aggregated to one region and four sectors, and hybridised into mixed units. We investigate wind power, as it has the nice property that an attributional LCA can be performed on it, as it currently exists, whilst it is also expected to undergo significant growth in the coming decades. The functional unit is 1GWh of electricity. At the outset, we assume an equal price for wind power to other types of electricity. This price includes differential tax rates and different profit margins of the different types of electricity generation—so essentially it is saying that the user price is the same, not the generation price. Figure 2 shows the format of the model, filled with data in Table 2.

We perform a comparative LCA based on the functional unit of 1 GWh of electricity generated. For wind power, our functional unit is hence x^{wind}=[1 0 0 0 0], whilst for all other types of electricity generation our functional unit is x^{elec}=[0 0 0 1 0].

Contributions to components of value added are then calculated for each component k as (see Eqs. (6)–(8)):

$$\mathbf{V}_k^{\mathbf{wind}} = \mathbf{F}_k(\mathbf{I}-\mathbf{A})^{-1}\mathbf{x}^{\text{wind}} \quad (11)$$

$$\mathbf{V}_k^{\mathbf{elec}} = \mathbf{F}_k(\mathbf{I}-\mathbf{A})^{-1}\mathbf{x}^{\text{elec}} \quad (12)$$

Results (Table 3) show a significantly higher capital input per gigawatt hour required for wind power, with lower inputs of labour, tax and profits (surplus). As expected, the summation over the components of value added gives the cost of a gigawatt hour of electricity (Eq. (8)).

As we are only employing a single region (global) model in this example to keep it as simple as possible, there are no imports. However, it is straightforward to generalise the model to have imports as additional inputs into the domestic production processes. Equation (8) then becomes:

$$\mathbf{M}^f = \mathbf{M}\mathbf{x}^{(-1)}\left(\mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots\right)\mathbf{x}^f$$

Where $\mathbf{Mx}^{-1}$ are the total imported goods and services per unit of output of each product group, and the calculated imports per functional unit are $\mathbf{M}^f$. It can be seen that this calculation is equivalent to the calculation for the components of value added—that is, they are both considered as primary inputs in the domestic economy, as imported goods and services have no upstream impact on the domestic economy.

In terms of productivity, we calculate productivity as the ratio of output per factor input, i.e. $\frac{\mathbf{x}}{\mathbf{V}_k}$. As such, the results for the labour and capital productivity measures shown in Table 4 reflect the lower output relative to the capital requirements of wind power, and the higher output relative to labour requirements. Electricity in general has higher labour productivity and lower capital productivity than other sectors in the economy.

Wind power is a demonstration of a pure process innovation, with product output being identical to an existing product (electricity). Hence, the novelty of the technology is zero. We can reflect further on this through the linkage indicators. For linkages, different weighting options are available, here we follow the current convention (discussed in Wood and Lenzen

Table 3 Indicator results on components of value added

		Wind	Electricity
Labour	m€/GWh	0.005	0.016
Capital	m€/GWh	0.037	0.013
Tax	m€/GWh	0.001	0.006
Surplus	m€/GWh	0.002	0.010
Contribution to GDP (total cost)	m€/GWh	0.045	0.045

[1] www.exiobase.eu

Table 4 Indicator results on productivity measures

		Wind	Primary	Manufacturing	Electricity	Services
Labour productivity	€/€	11.22	5.78	6.01	9.12	3.09
Capital productivity	€/€	1.22	9.11	24.57	5.17	12.23

2009) with backward linkages being the column sum of the Leontief Inverse $(\mathbf{I}-\mathbf{A})^{-1}$ (see Eqs. (5) and (6)), and forward linkages being the row sum over the Ghosh Inverse—a representation of sales $\left(\mathbf{I}-\mathbf{T}'*\mathbf{x}^{(-1)}\right)^{(-1)}$ (see Eq. (1)).

As the novelty is zero, the forward linkages (Table 5) are the same (there is no known difference in the use of the different types of electricity in the economy), whilst the backward linkages show that wind has lower linkages back through the economy—that is, it has lower requirements on the production of other industries. This would be seen as negative trait (Section 5). However, as capital is considered a primary input (no current year production is required to produce it), these results are in a sense an artefact of the way investment is treated in national accounts. If we endogenise investment, we would see a higher backward linkage due to the construction of the turbine.

Indicators of structure are taken as the relative importance of intermediate inputs (measured by the Leontief Inverse; see Eqs. (5) and (6)) from primary, manufacturing and services. As could be expected, wind has significantly less demand for outputs of the primary sector of the economy (Table 6). Whether this result would be considered a positive or negative attribute of wind technology would depend on the policy orientation of the region (e.g. whether there was a need for employment opportunities in the primary sector).

7 Conclusions

LCA is a powerful tool that is being broadened in scope into other areas of sustainability assessment. In including economic assessments under the umbrella of LCSA, there is much scope for aligning modelling frameworks and indicator assessments to have greater consistency between the different pillars of environmental, economic and social sustainability. Economic assessments should be consistent with the relationships covered in environmental LCA, and should also focus on issues of societal concern. Economic assessments need to be able to cover the innovative capacity of a product system, and to reflect on economy wide implications of a technology beyond the direct costs associated with a functional unit. Whilst the use of LCC has been used extensively to address the economic dimension of LCSA, it is arguable if by itself, it is fully fit for purpose. LCC as a unique tool has little to say on economy wide impacts and the relative contribution of different types of value adding, etc. However, tying a LCC to an economy wide model can begin to contribute to this discussion, much as in environmental LCA, a foreground process system (object of study) is tied to a background inventory of requirements (using LCA databases). Applying an LCC in an economy wide supply chain context makes two things apparent. Firstly, that embedded in LCC is a normative construct that is usually reserved for impact assessment, not inventory compilation, and that this is driven by the aggregation of different types of (positive and negative) social costs. Secondly, LCC (when applied in an attributional setting—the only setting where it is meaningful), has the contradiction that a user will try to minimise life cycle cost, whilst society will try to maximise value adding. This contradiction is compounded by the fact that for a particular product system, the functional unit life cycle cost and the supply chain value adding are equivalent. As LCC does not consider any dynamic effects of behavioural or price relationships, it is a method that is limited to the attributional setting. Methods drawing on rebound effects, equilibrium analysis and the like are required to address consequential questions.

Moving beyond modelling frameworks to the objectives of our assessment, we consider what properties of a product system are relevant in an economic assessment. Whilst the cost of a product system is clearly an important concern, the more general applications of sustainability assessment clearly focus on contributions to GDP and value adding in the economy; the self-sufficiency of an economy or otherwise perceived as the reliance on imports; the role of investments, both in terms of research and development and capital infrastructure; and the role of labour. In addition, we feel

Table 5 Indicator results on linkages (dimensionless)

	Wind	Electricity
Forward linkages	2.595	2.595
Backward linkages	1.003	1.086

Table 6 Indicator results on Structure (dimensionless)

	Wind	Electricity
Primary	0.037	0.229
Manufacturing	0.300	0.300
Services	0.663	0.471

that from the economic literature, when analysing product systems or technologies, we are interested in whether we are looking at a qualitative change to the types of goods and services being produced in the economy—that is, if we are seeing product innovations. Likewise measures of linkages reflect on the relative importance of a single-product system for the rest of the economy, and structural effects represented by sector demand are necessary considerations for regional development. A simple example for wind power is then used to demonstrate these indicators.

In conclusion, much can be taken from existing modelling frameworks and assessments that can be used in LCSA to more adequately cover the economic dimension. If LCSA wants to be able to provide adequate coverage of economic impacts so that it is used directly in policy formation itself (rather than alongside other methodologies) then we feel LCSA needs to go beyond LCC. Further, as we move from attributional to consequential assessments, it is clear that we are going to need indicators of economic impact that apply to multiple stakeholders and the dynamic relationships between them, and that these indicators should be able to address long-term economic sustainability and not just short term economic cost.

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