# Location-specific sustainability metrics: measuring sustainability space

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**Abstract**
Achieving sustainability – the balance between economic and social development and environmental viability – is one of the key goals of industry, society and government. To measure sustainability, numerous indicators or "metrics" have been developed. However, they do not typically incorporate any information about a local region: they relate equally to a power station in Antarctica or in the middle of the Amazon rainforest. This paper describes a new approach to sustainability metrics that brings local conditions into the assessment of sustainability. We introduce a general mathematical and theoretical model for deriving such metrics and then demonstrate on one specific metric – soil acidification – that provides a useful and well known example. The metrics are applied to differentiate between four sites for the same power station in Australia. The methodology demonstrates a marked difference to existing sustainability metrics, in that it is able to distinguish between different receiving environments, something that cannot be achieved with previously described sets of metrics. These "location-specific sustainability metrics" offer a model to improve the information upon which decisions about future development strategies are made, and to evaluate sustainability in a way that better represents the real world.

**Keywords**
Sustainability metrics, sustainable development, indicators, environment, acidification.

## Introduction

Sustainability, defined generally as a state of social and economic prosperity in which the ecological balance is not disturbed beyond its ability to regenerate, has become a catchword for industry, government and other institutions across the globe and the importance of related concepts, underlying values and principles cannot be underestimated. It is, however, a term that is vague, conceptually complex and involves highly interrelated subsystems that make it difficult to solidify into a comprehensible form. As related concepts become more widespread and the interpretations of sustainability become more diverse, there is a growing need for defining, measuring and capturing essential elements of sustainability with logical, practical and widely applicable methodologies.

The measurement of sustainability is a concept that has led to the development of various general and empirical sets of metrics or indicators, measurable quantities – such as emissions of pollutants, usage of water and number of jobs created – that aim to cover at least the three pillars of social, economic and environmental impact and benefit that are typically associated with sustainability. Sustainability metrics have, perhaps, been the most widespread response to the challenge of sustainable development because governments, companies, scientists and society in general want to be able to quantify progress in the same way that profit can be quantified.

The Global Reporting Initiative (GRI 2006) is perhaps the most widely used set of metrics and the thousands of companies that report each year using this framework are a testament to the importance that companies place on sustainability metrics. The main drivers for companies to report against such metrics tend to be corporate social responsibility and the need to retain a social license to operate (meeting community expectations so a company is allowed to continue operating). The existing sets of metrics have been developed internally, in stakeholder consultations or by consultants or scientists for specific communities (Scerri and James 2010), for specific industries (Azapagic 2004) or industry more generally (GRI 2006; IChemE 2003; Pinter et al. 2005; Azapagic and Perdan 2000). However, the significant omission from all of these metrics is that they do not directly incorporate the specific environment in which the process or plant is located (Jin and High 2004; Diniz da Costa and Pagan 2006; Durucan et al. 2006). Rather, there is an implicit or generalised environmental connection that arises from the particular selection of metrics and any weighting of a contributing component, such as the weighting of methane emissions as 21 times the contribution of the equivalent mass of carbon dioxide for its impact on climate change.

Every environment in which a plant could be located is unique in terms of its combination of soil properties, climatic conditions, vegetation, human and animal populations. In some cases, the environment can process, buffer or recycle plant emissions or provide plant inputs without significant loss of environmental quality. However, in other cases, the level of industrial impact is irreversible or unsustainable in the long term. If the environment can sustain such processes without breaching its “carrying capacity” then, in principle, anthropogenic impacts can be perceived as sustainable (in reality, public and government opinion may see even theoretically sustainable processes as unsustainable, thus eliminating the plant’s social licence to operate). Currently, the sole potential consideration of carrying capacity is undertaken before a plant is built in an environmental impact assessment. However, most of the information involved in such studies goes unused after legislative approval is granted.

Existing sustainability metrics do not include the carrying capacity or the specific environment either. Typical sustainability metrics models may be considered “loading” models, in which the only judgment of greater or lesser sustainability is based on the relative rate of emissions as they leave the plant. They provide relative measures of sustainability (Jin and High 2004) that do not include the contextual elements that binary models of sustainability would be required to employ (McElroy et al. 2008). There are many merits in these models because they provide a yardstick for comparing different processes and impacts for a generalised location. However, by not taking into consideration environmental processes that result in temporal and spatial variations, they can lead to a false comparison of different plant locations.

In this work we develop a new methodology for sustainability metrics within the scope of environmental impacts and test the idea of incorporating location-specific environmental parameters to create a more realistic indicator of ecological sustainability. The main focus of our model is emissions within the environmental dimension of a "sustainability space", which is physically and chemically limited by baseline environmental conditions as the lower limit and its carrying capacity as the upper limit. As a case study, the emissions of sulphur dioxide from coal-fired power stations are used to demonstrate the model using a validated emissions transport model reported elsewhere by McLellan et al. (2010: 815-824). This work focuses on the environmental pillar of sustainability for the sake of demonstration, using an environmental impact that is relatively well known and well monitored, and for which comparisons with existing work can be drawn. This testing of the sustainability metrics model proposed here is seen to be an important step prior to expanding the methodology to applications that are less scientifically studied or less understood. The next steps in this work will be to expand to indicators across the triple bottom line of sustainability.

## Sustainability metrics model

Since the 1960s, with the United States and Europe leading the way, emissions of pollutants to air, land and water have been the subject of key environmental legislation and monitoring. Most monitored contaminants have a localised or regional, rather than a global, impact. The notable exceptions to this would be ozone depleting substances and greenhouse gases, where all other legislated environmental reporting regards compounds that make an impact on health or environment in relatively close proximity. This is arguably due to the fact that particular industrial facilities have made drastic and obviously unsustainable impacts on their surrounding communities and environments, whereas climate change and ozone depletion are less immediate and visible effects.

Typical approaches currently in use for assessing the sustainability performance of operations are based on how contaminant emissions contribute to a given defined environmental burden (EB) (IChemE et al. 2003). These methodologies use a set of multipliers (potency factors) to determine the contribution of an emitted substance to a given environmental impact (eg. global warming, photochemical smog, atmospheric acidification). The total weighted contribution to the particular environmental impact is designated the "environmental burden" as per Equation (1).

$$EB_i = \sum_{N=1}^{n} (W_N)(PF_{i,N}) \qquad (1)$$

Where:
$EB_i$ = i-th environmental burden
$W_N$ = weight of substance N emitted, including accidental and unintentional emissions
$PF_{i,N}$ = potency factor of substance N for i-th environmental burden

The EB is thus the sum of the potential impacts of all contributing emissions from a plant. The most widely known use of this approach is perhaps the contribution of different greenhouse gas emissions to global warming – methane is allocated a potency factor of 21 relative to $CO_2$, which has a potency factor of one. The EB of emitting 10 tonnes of methane and 10 tonnes of $CO_2$ would therefore be 21 x 10 + 1 x 10 = 220 tonnes of $CO_2$ equivalent.

This EB approach is general in nature and offers a system of metrics that act mostly as "technology indicators" in that they assess the inherent potential environmental impact of the plant or system only in terms of the quantity of emissions. This omits the connection of the plant to its environment, except by implication in the selection of metrics and indirectly through the potency factor. This approach can be used to compare different processes, or the performance of a given plant over time, with lower emissions being considered more sustainable. However, this approach does not provide much assistance in terms of comparing different processes in different locations because it does not include factors that indicate the sensitivity of the environment to a given impact.

The assumption of a linear relationship between sustainability and emissions or resource use is implicit in the EB-type sustainability metrics (a linear sum of potency-weighted substance emissions). Thus an emission of twice the original amount of sulphur oxides is assumed to decrease sustainability by 50 per cent in terms of the acidification metric. As a measure of technology, this is useful. However, there are a number of reasons why this does not suffice for the sustainability assessment of localised pollutants. First, atmospheric or aquatic emissions are typically dispersed widely throughout the receiving media. In the case of atmospheric emissions, the dispersion and dilution caused by wind mean the impacts are different across the geographical area of influence. Furthermore, the type of soil and vegetation upon which the emission is deposited and the rainfall and runoff characteristics mean that the effect of the emission may be buffered in some locations (eg. basic soils with a pH less than 7) but severe in others (eg. acidic soils). Thus a typical "loading model" of sustainability, where linear impacts are assumed, is not valid for locally dependent elements.

The typical loading model for contaminant increase may be depicted graphically as in Figure 1, with an industrial plant causing deviation from the baseline value at some steady rate that is entirely dependent on the quantity of the emission. Eventually, the local environment is no longer able to process or buffer the impacts and sustainability is breached. The typical sustainability metric would be associated with the gradient of the line. Research groups (Diniz da Costa and Pagan 2006; McLellan 2007) considered that each environment has a different carrying capacity and initial baseline concentration of contaminant, and that the buffering aspects of the environment may lead less towards a continual increase and more towards a new steady state. This environmental behaviour can be depicted graphically in terms of concentration of an emitted substance as in Figure 2. Ultimately, it is important to include both spatial and temporal dimensions. However, for the sake of illustration, only the temporal dimension is shown.

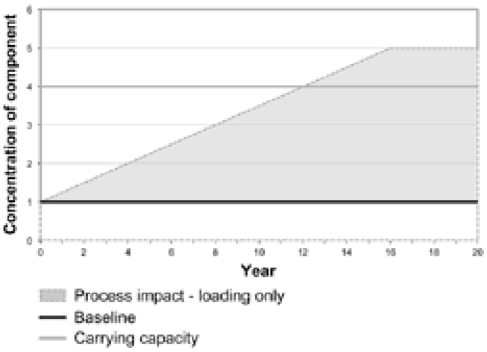


Figure 1. A typical "loading" sustainability model in which a process adds to the environment's contaminant concentration in a linear fashion, from the baseline level up to and beyond the carrying capacity of the environment

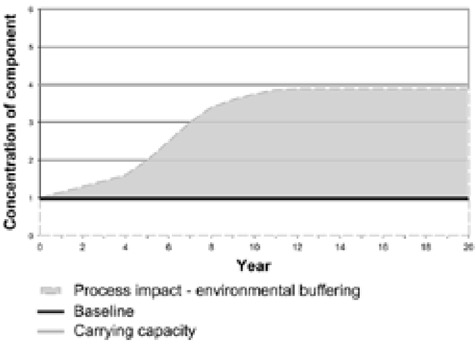


Figure 2. Sustainability with environmental buffering, in which a new process adds to the environmental concentration of a component but the environment buffers the load so it does not breach the carrying capacity

The area or volume between the baseline as the bottom line and the carrying capacity as the top line is nominally called the "sustainability space", which is similar to the concept of "environmental space" proposed elsewhere (Opschoor and Reinders 1991; Spangenberg 2002) but with the inclusion of a baseline. In this approach, we take into consideration the physical and chemical limitations associated with the environment at a specific location. The shaded areas in Figures 1 and 2, which show the effect of a plant on the concentration of a local contaminant, represent the amount of sustainability space that is being used by the plant or process. We propose, therefore, that the sustainability metric (SM) be defined as the ratio of the utilised space to the total sustainability space.

Sustainability in the location-specific sense is a function of space and time, as are the baseline and carrying capacity. With suitable assumptions and data availability, a mathematical function (or sometimes an elaborate mathematical model) can be obtained for each of the carrying capacity, baseline and emission. Thus the sustainability metric can be derived from knowledge of the baseline, carrying capacity and the equation or form of the contaminant contribution curve by determining the percentage overall breaching of the carrying capacity over the two spatial dimensions over time. To address this problem, we propose a general equation to describe sustainability metrics as follows:

$$SM_i = \left\{ 1 - \frac{\iiint_{x,y,t} \left[ f(x,y,t)_i - B(x,y,t)_i \right] dt.dy.dx}{\iiint_{x,y\ t} \left[ CC(x,y,t)_i - B(x,y,t)_i \right] dt.dy.dx} \right\} \times 100\% \qquad (2)$$

Where:

$SM_i$ = the sustainability metric with regard to the *i*-th impact or component

*x* and *y* = two dimensions of distance (m or km)

*t* = time (s or yrs)

*f*(*x*,*y*,*t*) = the variation in emission or potential impact of the project as a function of distance (x and y) and time (t)

*B*(*x*,*y*,*t*) = the baseline value as a function of distance and time

*CC*(*x*,*y*,*t*) = the carrying capacity limit as a function of distance and time

Comparing Equation (2) to Equation (1), the function *f*(*x*,*y*,*t*) incorporates $W_N$ (the amount of emissions) and substitutes the potency factor ($PF_{i,N}$) for a mathematical relationship or model that incorporates the environmental transport, reaction and deposition of the emitted substance (or, in the case of social or economic factors, a relationship of impact as a function of distance from the plant and time from initial commissioning). The addition of the baseline and the carrying capacity, which are both functions of distance and time, incorporates the baseline conditions and the potential of the environment to absorb the impact. This is not found in Equation (1).

If this approach is applied using environmental monitoring data or where suitable emission transport models are not readily available, discrete methods can be applied in lieu of the integral equation. For example, the area around the plant can be broken down into a grid, and data for each grid element entered from measured data or from interpolation using environmental or mathematical modelling. The grid values can be calculated at set, discrete, time intervals, for example, yearly. The sustainability metric can then be calculated at each time and grid point, replacing the integrals in Equation (2) with a summation in the form of Equation (3), which then represents the SM value averaged over the area of the grid or over time.

$$SM_{D,i} = \left\{ 1 - \frac{\sum_{x=-X}^{X} \sum_{y=-Y}^{Y} \sum_{t=0}^{T} \left[ f_{i(x,y,t)} - B_{i(x,y,t)} \right]}{\sum_{x=-X}^{X} \sum_{y=-Y}^{Y} \sum_{t=0}^{T} \left[ CC_{i(x,y,t)} - B_{i(x,y,t)} \right]} \right\} \times 100\% \qquad (3)$$

Where:
$SM_{D,i}$ = (discrete) sustainability metric with regard to the *i*-th impact or component over a given time period (0 – T) and area delineated by the grid of *x* and *y* values
*x* and *y* = grid coordinates of distance (m or km) around the facility of interest
*t* = time (s or yrs)
$f_{i(x,y,t)}$ = the value of the emission or potential impact of the facility with respect to the *i*-th impact at the grid location (x,y) at a given time (t)
$B_{i(x,y,t)}$ = the baseline value as at the grid location at a given time
$CC_{i(x,y,t)}$ = the carrying capacity limit at the grid location at a given time

The discretised data can also be plotted without summing over the total area, which could then produce graphs such as those shown later in this paper (Figure 5). This would avoid the potential problem of "hiding" areas of low sustainability that can occur in the aggregation of impacts across a wide area (particularly in areas with large variability of local environment). Ideally, the data would be kept disaggregated to the greatest extent to avoid this problem, although, in practice, a comparison may require aggregation. If aggregation is undertaken, then the lowest practical level of aggregation is preferred. As a guide, the level of aggregation should be the same as the level of variability of the environmental conditions – ie. if the environment is largely homogeneous then aggregation is acceptable up to a higher level. If the local environment is considered to be within a radius of 50 km to 150 km of the plant, aggregation on the scale of the entire local environment would be questionable and a scale of 5-10 km radius may be acceptable (from experience with the case study described here).

Special cases of contaminant increase are the globally important substances such as greenhouse gases and ozone depleting substances. In such cases, the spatial dimensions become unimportant because the effect is assumed to be equivalent regardless of location. Thus Equation (2) may be simplified down to Equation (4).

$$SM_{G,i} = \left\{ 1 - \frac{\int_t \left[ f(t)_i - B(t)_i \right] dt}{\int_t \left[ CC(t)_i - B(t)_i \right] dt} \right\} \times 100\% \qquad (4)$$

Where: subscript G in $SM(t)_{G,i}$ indicates a global sustainability metric

However, the magnitude of the total global carrying capacity in comparison to a single process is vastly larger, thus the metric would diminish in comparison to the overall global capacity. Therefore, in the case of impacts on a global scale, it is deemed most useful to use the local, national or industry-level targets as pseudo-carrying capacities. Similar approaches have been applied elsewhere (McElroy et al. 2008; Yossapoll et al. 2002).

The overall conclusion of the sustainability metrics approach taken here is that the higher the SM percentage value, the closer the plant is to 100 per cent sustainable. The carrying capacity indicates the value of the contaminant level beyond which the environment can no longer buffer the effects of the plant impact and, hence, when the SM value is 0 per cent or below (ie. where $\frac{f - B}{CC - B} \geq 1$) the sustainability can be considered to be zero. Negative sustainability values indicate the magnitude of the carrying capacity breach (or level of unsustainability), which others have considered useful (McElroy et al. 2008; Pope et al. 2004). However, in this case, we assume that once the carrying capacity is breached, the plant is unsustainable and, therefore, we assign a 0 per cent value for all SM less than or equal to 0 per cent.

The three graphs in Figure 3 demonstrate the metrics equation proposed in this work using arbitrary units of contaminant concentration. Graph (a) shows a pristine environment with a carrying capacity of 4 and baseline (natural) concentration of 1. The metric calculation is trivial for this situation, as the SM will be 100 per cent, with the area under the emissions curve being 0. In Graph (b), a power plant is placed in this environment and, over the 20-year period, the concentrations of contaminant rise to 2.5 units after six years, then stabilise at that level (1.5 units above the baseline). The value of the SM is calculated:

1 – (1.5 x 6/2 + 1.5 x 14) / (4 x 20 – 1 x 20) = 1 – 25.5 / 60 = 57.5 per cent

So over the period in question, the plant is considered to be sustainable, with an SM of 57.5 per cent indicating almost half of the available carrying capacity has been used.

In Graph (c), a plant has been placed in the same environment but with emissions rising to an extent that breaches the carrying capacity. The value of the SM is thus:

1 - (5 x 20 / 2) / (4 x 20 – 1 x 20) = 1 - 50 / 60 = 16.7 per cent

In this case, while the average sustainability metric over the period is still positive, the trend indicates that this will become negative within five years unless changes are implemented.

Using this model, any SM above 0 per cent is classified as sustainable. However, there are, naturally, limitations based on inherent error in measurement, modelling and estimation of environmental systems that must be taken into account. Considering the current study, the areas that would most likely bring error into the results are: sampling of soil, measurement of soil parameters, measurement of meteorological parameters and model errors. It is widely recognised that the largest error in environmental modelling is introduced by the natural variability of environmental systems (Budden and Collins 1998). The development of the model applied in this study indicated that variability across a 25 $m^2$ sampling area could be up to 50 per cent of the mean value (Plenderleith 1989; McLellan 2007). Unfortunately, this natural variation is unavoidable and it will affect all types of environmental impact measures similarly. The smaller the mesh of the measurement grid available the better, in terms of accuracy, but the worse in terms of strains on computational time and cost. By contrast, a larger grid mesh gives lower precision but perhaps greater accuracy when averaged over a wider area. This source of error can propagate through the critical load calculations and needs

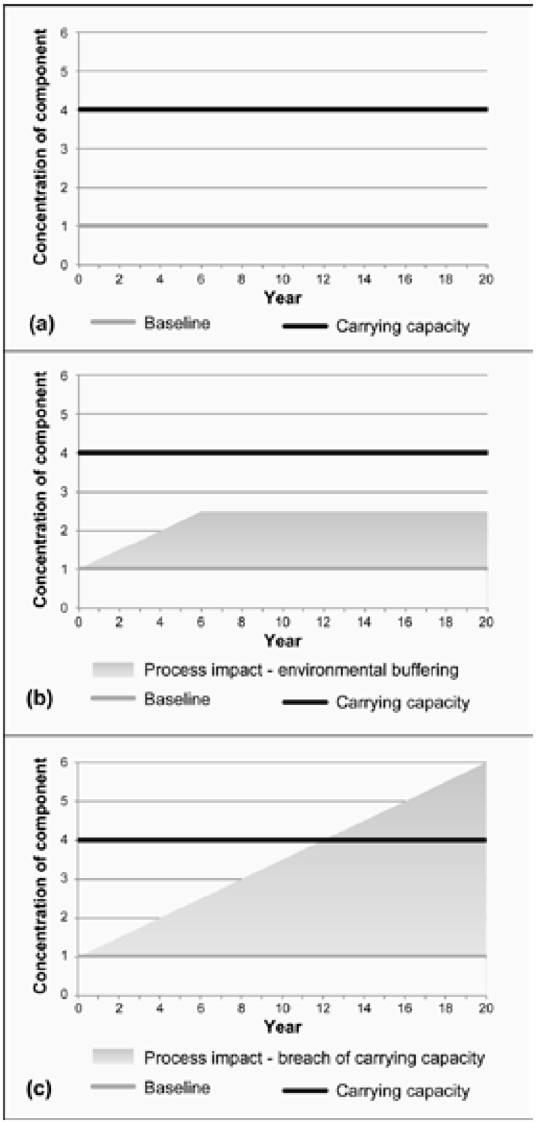


Figure 3. Three situations to demonstrate the metrics: (a) pristine environment; (b) environment with power plant emissions buffered below the carrying capacity; (c) environment with power plant breaching the carrying capacity

to be kept in mind (Thomas and Reynolds 1998).

Errors in sampling and measurement are most critical for low concentration sites, where the error of measurement can be similar in magnitude to the measured value (McLellan 2007). However, this was not the case in the current study. Furthermore, with regard to modelling error, the atmospheric transportation and deposition models generally applied can be expected to have an error of 10-20 per cent (Alcamo and Bartnicki 1987), with this case being no exception. For non-environmental sustainability metrics, the error would be a factor of the available data and the scientific understanding of factors relating the impact of the operation to its social or economic environment.

The key conclusions of this discussion of error are that the largest contributor to error at any specific grid point will be natural variability of environmental systems, while the model itself may contribute only a relatively small proportion of the error and this error will be largely comparable across alternative measures of environmental impact. Most crucial in terms of the SM is the carrying capacity: if the error in estimation of carrying capacity is 50 per cent, for example, then an SMt of 50 per cent could be in the range of 0 per cent through to almost 100 per cent (where the exact change is dependent on the ratio of the baseline to the carrying capacity and the ratio of the measured or modelled concentration to the baseline). So, while the SM is a useful measure, it is important to also recognise the limitations by estimating the error inherent in the modelling used to calculate it. In the case study described here, we used a sensitivity analysis to identify whether the results were sufficiently robust and concluded that they were within a range of error of input parameters of 20 per cent, as reported in McLellan et al. (2010).

A breach of carrying capacity (SM of 0 per cent) is broadly interpreted as an indication that the plant or process will be unsustainable in the given environment if the local environmental conditions do not change or, more importantly, if the plant in question is not changed to reduce the environmental impact. The implications of a breach of carrying capacity for a specific impact will be dependent upon that particular impact and its ability to be naturally or artificially reversed. In the current example, soil acidification could be reversed without significant harm to the environment if the exceedance has been for a short period, such as a year. However, if the period of carrying capacity breach has been longer, the soil may never recover to its initial state (as has been witnessed in Europe, where acid rain has affected the environment irreversibly in some countries). A longer-term trend of exceedance will tend to degrade the environment gradually over time, making it unsustainable. The implications of the breach in capacity are also relevant to the magnitude of the breach – minor breaches are less likely than larger breaches to cause permanent harm. The key value of using a methodology such as the SM is to enable monitoring and modelling to flag such potentially unsustainable events and to enable preventative action.

## Case study application

To verify the applicability of this methodology to a real-world situation, a case study was undertaken using an Australian coal-fired power plant. Soil acidification from sulphur oxide ($SO_x$) emissions was taken as the demonstration sustainability metric. To apply the metrics, an empirically verified emissions transportation model was developed, as reported by McLellan (2010). This model gave the balance of sulphur compounds (considered to be $SO_2$) in the soil around the plant (the *f* function). The baseline values were taken from a historical monitoring study (Plenderleith 1989) at a number of sites around the plant. The carrying capacity for the specific metric of soil acidification was taken from the literature.

Much research has been done on the topic of acidification, especially in Europe, so methodologies for measuring the carrying capacity of soil in relation to acidification are available. For this example, the critical load assessment work of Kuylenstierna et al. (1995), Cinderby et al. (1998:1-19) and the International Institute for Applied Systems Analysis (2001) was used to estimate the carrying capacity. In fact, the work examining deposition gap closure analysis and accumulated exceedance – calculating how much compound has been deposited on an area, what the "critical load" that can be environmentally buffered is for that area and how much (if at all) that limit has been exceeded – is an established and relatively mature field of research (especially in relation to acidification and, more recently, other compounds such as ozone). This has been useful in the current example for the estimation of carrying capacity. However, this previous work is not applied to the wider context of sustainability and remains very specifically within the field of environmental impacts of airborne pollutants. While the current study employs acidification as an example, the general SM methodology can be applied more generally than these earlier methods. Moreover, the current methodology does not seek to overturn such methods. Instead, it aims to use the results of such modelling as part of the growing global trend of sustainability reporting in a way that makes the results more directly applicable at the level of an individual operation. It also aims to make the results easier to understand by expressing the impacts on a common indicator rather than giving each impact its own units, which non-specialists might not comprehend.

Figure 4 shows the sustainability metric as calculated for one particular monitoring site around the plant at different levels of emission of $SO_x$ (base case is 22.6 kt $SO_x$ / yr). The major importance of this site for this study is its unique position. The site is a pristine forest in a sparsely populated area. In addition, the only atmospheric emission in the airshed of this site is the coal power station that we are considering. This means any change in soil sulphur could notionally be attributed to $SO_x$ emissions from the coal power plant. Carrying capacities as reported in mmol eq H+ / $m^2$ / yr were converted to mg $SO_4^{2-}$ / kg (assuming this is the form of sulphur deposition, Norris 2003), assuming a bulk soil density of 1600 kg / $m^3$, and examining the top 10 cm of soil as the initial "vessel" over which the mass balance is taken. The resulting carrying capacities are shown in Table 1.

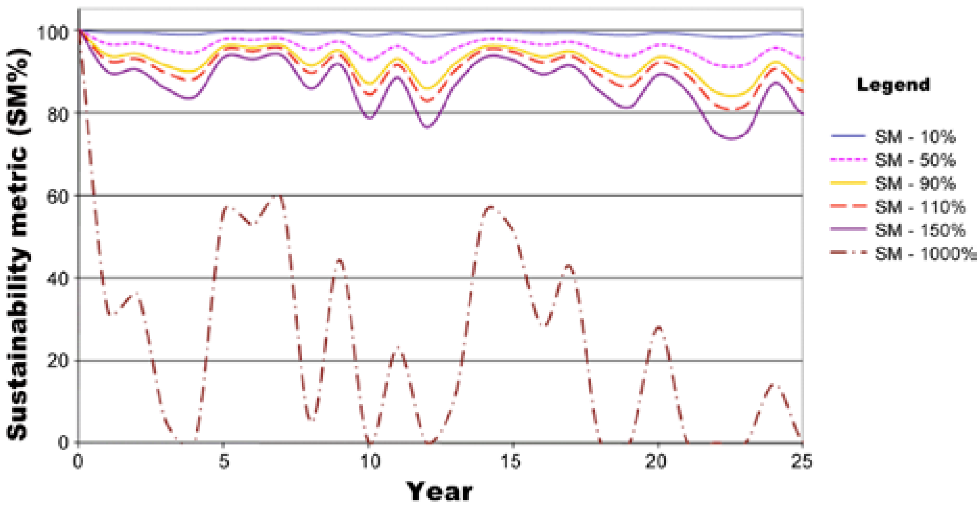


Figure 4. Acidification sustainability metric sensitivity to SOx emission rate from plant at various rates of emissions as a percentage of the base case (as indicated in the legend)

Baseline sulphur concentrations, pH and other soil characteristics were available for 32 monitoring sites around the power plant (Plenderleith 1989). Sulphur content ranged from 2 mg S / kg to 33 mg S / kg with the general soil (at non-monitored locations throughout the airshed) assumed to have initial soil sulphur content of 21 mg S / kg. Only four of the monitored sites around the test case were identified as having "category three" carrying capacities, while the remainder were "category four", which meant the site was expected to be quite resilient to sulphur acidification.

Table 1. Carrying capacities for the deposition of sulphur dioxide, calculated for the case study

| Category | Carrying capacity mmol eq H+ / $m^2$ / yr (25 years) | mg $SO_4^{2-}$ / $m^2$ / yr | mg $SO_4^{2-}$ / kg / yr | mg $SO_4^{2-}$ / kg (25 years) |
|---|---|---|---|---|
| 1 | 25 | 1200 | 7.5 | 187.5 |
| 2 | 50 | 2400 | 15 | 375 |
| 3 | 100 | 4800 | 30 | 750 |
| 4 | >200 | 9600 | 60 | 1500 |

The sustainability metric equation was applied for a period of 25 years, integrating the emissions transportation model reported by McLellan et al. (2010) in place of the function *f*. The results for a single monitoring site are shown in Figure 4. This figure shows the change in sustainability (as measured by the SM) starting from 100 per cent (assumed as the site in its pristine condition before the power plant was commissioned). Over time, the SM varies in response to the annual rainfall conditions as the main parameter. Sulphur deposition in the relatively dry climate of the test case is dominated by dry deposition. Years of high rainfall have the effect of removing some of the sulphur from the soil, hence increasing the SM, as the distance to the carrying capacity threshold is increased. The last five years of the period of testing show a decrease in the SM because of decreased rainfall, leading to higher sulphur retention. The figure also shows sensitivity of the SM to changes in the rate of emissions from the plant. It is apparent that the current emission rate is within the carrying capacity of the site, as the SM does not drop below 85 per cent. Although, with an increase in the emissions of SOx from the plant by a factor of 10, there are indicated periods where the carrying capacity would be exceeded. Such a situation is unlikely to happen on the basis of a single plant due to the availability of SOx removal technology and preventative legislation.

The calculation of the SM for discrete sites within an airshed is useful for monitoring and modelling the potential sustainability performance in a location-specific sense. In order to give a meaningful contextual value to our proposed model, we decided to interpolate our results to different sites of interest using typical graphing software – Mathematica™ and D-Plot™. To illustrate this point, we produced contour maps of sustainability in the plant vicinity (Figure 5). This gives an easy method of viewing the variation in sustainability performance over the local area.

Figure 5 shows the results of calculating and graphing the SM for the same plant emissions at the site of four existing power plants in Australia (Tables 2 to 4 give some of the relevant data on carrying capacity and rainfall at each of the sites). Plot (d) is the original case study. Examining plots (a) to (d) shows that the pattern of sustainability performance is significantly different around each of the plant locations. These differences are caused by different climatic conditions and soil carrying capacities. The level of sustainability performance graphed in this way can be a powerful tool for comparing potential sites for industrial operations.

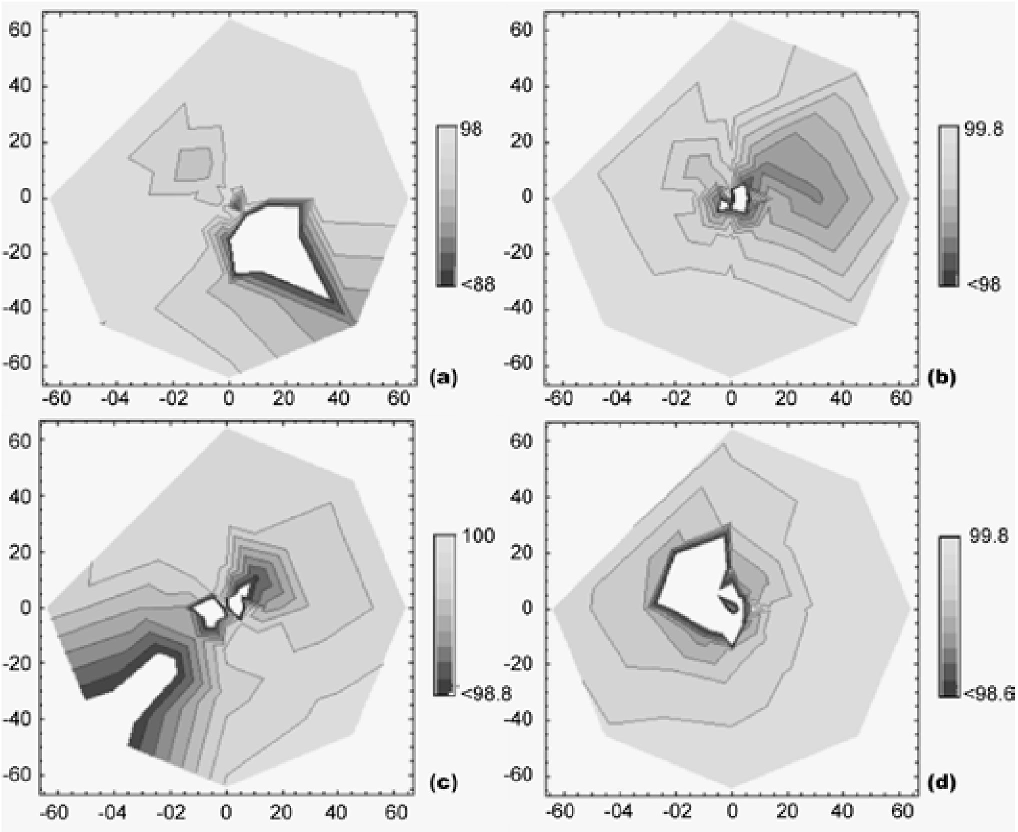


Figure 5. Sulphur soil acidification sustainability contours for coal-fired power generation, transposing the modelled plant to the location of four existing Australian power plants.
*(Note: unshaded areas indicate an SM per cent of 100 per cent; the shading of contours has been set by the graphics software and could not be changed by the authors. Care must be taken in comparing the four graphs, each of which has a different range of SM per cent as indicated by the legends)*

Table 2. Historical rainfall data from 1983 to 2008 at the four power-plant sites

| | Year | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall (mm / yr) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | Historical average |
| Site (a) | 594 | 660 | 626 | 519 | 821 | 989 | 799 | 927 | 658 | 747 | 582 | 475 | 686 | 730 | 613 | 813 | 561 | 720 | 318 | 319 | 488 | 515 | 371 | 371 | 867 | 660 |
| Site (b) | 1039 | 812 | 752 | 638 | 598 | 1066 | 759 | 866 | 996 | 951 | 780 | 647 | 874 | 1184 | 704 | 843 | 932 | 848 | 608 | 719 | 780 | 718 | 968 | 568 | 933 | 943.5 |
| Site (c) | 729 | 713 | 913 | 773 | 695 | 785 | 888 | 743 | 927 | 808 | 897 | 826 | 917 | 810 | 562 | 751 | 587 | 735 | 774 | 571 | 624 | 626 | 481 | 464 | 933 | 729.3 |
| Site (d) | 947 | 855 | 633 | 659 | 713 | 791 | 858 | 668 | 667 | 758 | 579 | 399 | 919 | 1089 | 555 | 753 | 601 | 489 | 479 | 388 | 487 | 514 | 517 | 385 | 360 | 730 |

From the graphs, it is apparent that there are areas of higher or lower sustainability in some areas. These represent bands of particularly high or low carrying capacity or particularly low or high deposition. This information can be used as a powerful tool in environmental management where the sustainability of "hot spot" areas needs to be ascertained properly and managed over time. The white areas in the middle of each figure are areas of 100 per cent SM. In these areas, deposition is minimal because of the design of exhaust stacks, which lead to deposition in areas further from the plant.

Table 3. Airshed soil carrying capacities (mg $SO_4^{2-}$ / kg for the period of 25 years)

Site (a)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 1500 | 1500 | 1500 | 750 | 750 | 750 |
| NE | 1500 | 1500 | 1500 | 750 | 750 | 750 |
| E | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| SE | 1500 | 1500 | 1500 | 187.5 | 187.5 | 187.5 |
| S | 1500 | 1500 | 1500 | 187.5 | 187.5 | 187.5 |
| SW | 1500 | 1500 | 1500 | 750 | 750 | 750 |
| W | 1500 | 1500 | 1500 | 750 | 750 | 750 |
| NW | 1500 | 1500 | 1500 | 750 | 750 | 750 |

Site (b)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| NE | 1500 | 1500 | 1500 | 1500 | 750 | 750 |
| E | 1500 | 1500 | 1500 | 1500 | 750 | 750 |
| SE | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| S | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| SW | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| W | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| NW | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |

Site (c)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| NE | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| E | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| SE | 1500 | 1500 | 1500 | 1500 | 375 | 187.5 |
| S | 1500 | 1500 | 1500 | 1500 | 375 | 187.5 |
| SW | 1500 | 1500 | 1500 | 1500 | 375 | 187.5 |
| W | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| NW | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |

Site (d)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| NE | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| E | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| SE | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| S | 1500 | 1500 | 750 | 1500 | 1500 | 1500 |
| SW | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| W | 1500 | 1500 | 1500 | 750 | 1500 | 1500 |
| NW | 1500 | 750 | 1500 | 750 | 1500 | 1500 |

| | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Centre of circular sub-airshed (km from central emissions point) | 0 | 3.62 | 7.24 | 14.92 | 30.9 | 64.06 |

Table 4. Average wind speed and direction at the power-plant sites

| Site (a) | | | Site (b) | | | Site (c) | | | Site (d) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction of impact | Wind in direction (per cent of day) | Average wind speed (km/h) | Direction of impact | Wind in direction (per cent of day) | Average wind speed (km/h) | Direction of impact | Wind in direction (per cent of day) | Average wind speed (km/h) | Direction of impact | Wind in direction (per cent of day) | Average wind speed (km/h) |
| N | 5.4 | 9.24 | N | 4.5 | 10.51 | N | 2.6 | 9.43 | N | 10.2 | 10.22 |
| NE | 2.7 | 6.26 | NE | 9.0 | 6.57 | NE | 11.5 | 12.24 | NE | 6.7 | 13.00 |
| E | 11.1 | 9.73 | E | 13.5 | 8.52 | E | 12.6 | 13.62 | E | 6.2 | 14.29 |
| SE | 21.4 | 13.08 | SE | 13.2 | 9.90 | SE | 1.5 | 11.27 | SE | 7.1 | 12.81 |
| S | 5.3 | 11.77 | S | 4.1 | 7.22 | S | 2.2 | 10.14 | S | 9.3 | 12.86 |
| SW | 2.2 | 8.47 | SW | 8.4 | 8.45 | SW | 15.9 | 16.33 | SW | 11.3 | 9.90 |
| W | 15.4 | 12.86 | W | 12.2 | 11.82 | W | 34.4 | 21.37 | W | 20.0 | 11.89 |
| NW | 29.2 | 13.52 | NW | 19.0 | 13.32 | NW | 5.3 | 21.80 | NW | 23.9 | 12.78 |

Table 5. Average and minimum sustainability metric (SM per cent) for each power-plant site (assuming the same plant emissions at each site but with local environmental conditions)

| SM per cent key data | | |
|---|---|---|
| | Minimum | Area-based average |
| Site (a) | 59.1 | 97.8 |
| Site (b) | 95.5 | 99.7 |
| Site (c) | 96.1 | 99.7 |
| Site (d) | 95.2 | 99.8 |

It is particularly apparent from Figure 5 and Table 5 that Site (a) has some areas of particularly high impact (lower SM). The contextual reasons for this are that the annual rainfall is quite low and almost a decade of exceptionally low rainfall has allowed soil sulphur to build up (in the model). In addition, there is an area of higher sensitivity (lower critical load capacity) situated towards the south east of the plant, which is downwind of the plant for approximately 20 per cent of the year. These factors combine to give a high load and a low capacity, which result in a relatively low SM (59 per cent to 88 per cent) in the south east compared with the other sites. This conjunction of factors is not as strongly evident in the other locations. However, despite being lower, the value does not become negative, which indicates that the plant would still be within the bounds of sustainability.

The overall average SM for a location may also be obtained by averaging by area from the contour map, or by integration across the entire airshed using the emissions transportation model. However, care must be taken to stipulate appropriate boundaries. The further out from the plant, the lower the deposition, due mainly to atmospheric dispersion; if too wide a radius is taken for averaging, the inner areas where deposition is highest may be hidden from scrutiny. The results of such averaging are shown in Table 5, with comparison of the minimum value for each site (the full set of discrete grid values of the SM are shown in Table 6). The significantly lower minimum value in Site (a) illustrates the potential for lower sustainability points to be hidden by an area-based average

Table 6. Full sustainability metric (SM per cent) data for each power-plant site and for each sub-airshed (assuming the same plant emissions at each site but with local environmental conditions)

Site (a)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 100.00 | 98.21 | 98.46 | 98.47 | 99.33 | 99.81 |
| NE | 100.00 | 97.21 | 98.87 | 98.15 | 99.57 | 99.97 |
| E | 100.00 | 92.49 | 99.92 | 98.60 | 99.36 | 99.75 |
| SE | 100.00 | 89.51 | 95.68 | 59.10 | 80.91 | 91.79 |
| S | 100.00 | 97.13 | 98.80 | 89.00 | 95.19 | 98.62 |
| SW | 100.00 | 98.37 | 99.34 | 99.36 | 99.76 | 100.00 |
| W | 100.00 | 96.36 | 96.84 | 98.57 | 98.53 | 99.39 |
| NW | 100.00 | 99.64 | 97.22 | 94.14 | 97.29 | 98.80 |

Site (b)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 100.00 | 99.43 | 99.52 | 99.78 | 99.90 | 99.98 |
| NE | 100.00 | 96.20 | 98.45 | 98.76 | 98.96 | 99.62 |
| E | 100.00 | 95.53 | 99.95 | 99.16 | 98.75 | 99.50 |
| SE | 100.00 | 96.30 | 98.48 | 99.29 | 99.50 | 99.80 |
| S | 100.00 | 98.43 | 99.35 | 99.71 | 99.88 | 99.97 |
| SW | 100.00 | 97.24 | 98.86 | 99.47 | 99.76 | 99.92 |
| W | 100.00 | 98.61 | 98.83 | 99.73 | 99.75 | 99.90 |
| NW | 100.00 | 99.89 | 99.20 | 99.24 | 99.65 | 99.85 |

Site (c)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 100.00 | 99.47 | 99.55 | 99.80 | 99.92 | 100.00 |
| NE | 100.00 | 96.19 | 98.44 | 98.75 | 99.67 | 99.87 |
| E | 100.00 | 96.21 | 99.96 | 99.29 | 99.67 | 99.87 |
| SE | 100.00 | 99.47 | 99.78 | 99.90 | 99.85 | 100.00 |
| S | 100.00 | 99.14 | 99.64 | 99.84 | 99.72 | 100.00 |
| SW | 100.00 | 96.08 | 98.38 | 99.25 | 98.37 | 98.24 |
| W | 100.00 | 96.87 | 97.32 | 99.39 | 99.41 | 99.73 |
| NW | 100.00 | 99.97 | 99.80 | 99.81 | 99.92 | 99.98 |

Site (d)

| Sub-airshed | Inner | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| N | 100.00 | 98.06 | 98.35 | 99.24 | 99.65 | 99.87 |
| NE | 100.00 | 97.94 | 99.16 | 99.33 | 99.83 | 99.94 |
| E | 100.00 | 98.23 | 99.98 | 99.67 | 99.85 | 99.95 |
| SE | 100.00 | 97.78 | 99.09 | 99.58 | 99.81 | 99.94 |
| S | 100.00 | 97.10 | 95.96 | 99.44 | 99.75 | 99.91 |
| SW | 100.00 | 95.43 | 98.12 | 99.12 | 99.60 | 99.84 |
| W | 100.00 | 96.74 | 97.23 | 98.07 | 99.40 | 99.74 |
| NW | 100.00 | 99.39 | 98.48 | 95.18 | 99.32 | 99.71 |

## Discussion

The case study shows that the proposed sustainability metrics model can be used to differentiate between different locations and to incorporate more information than is possible in typical metrics. The fact that different patterns of impact are shown in Figure 5, and that there is a different SM value for each site in Table 5, indicates that location-based differentiation has been achieved. For standard metrics, the values in Table 5 would be equal and no differentiation would be acknowledged across the sites. This makes a strong argument for including locational aspects as a fundamental element of sustainability metrics. However, it is acknowledged that the aggregation of SM across a wide area can hide some hot-spot areas of impact (for example, the minimum value shown for Site (a) is significantly lower than for the other three sites but the aggregated SM is only marginally lower). Although the aggregated value is still a valid measure of the average sustainability, a lower level of aggregation or graphical representation of the data would be preferable.

Given the graphical expression shown in Figure 5, there is the potential to expand this work into the area of geographical information systems (GIS) because of the ability to store information for a given spatial point on a large number of metrics. The supporting data for this is particularly attractive. Studies have been performed in this area (Backhaus et al. 2002) in relation to groundwater acidity and heavy metals. However, a more complete examination, incorporating atmospheric emissions transportation, would be welcome. GIS would seem to lend itself to this application because it allows numerous data elements to be incorporated into a map of the process locality. Such "sustainability mapping" is of key interest as an area of research because graphical forms of data representation for sustainability are potentially useful to industry, government and society – they enable many people to grasp the concepts and impacts more readily than facts and figures.

It can also be argued that, for new projects in particular, environmental impact assessments (EIA) already include a large amount of modelling and data that could be incorporated into the model. In effect, the function $f$ is given by the atmospheric and hydraulic modelling, the baseline values must be determined in the EIA, and the carrying capacity, $CC$, must be estimated in order to validate a new project's existence or specific design. If the carrying capacity is likely to be breached, this should be identified and mitigated as an outcome of the EIA process. This is another potential area for future research, which could lead to the better benchmarking and monitoring of new projects as well as better use of the modelling that is carried out routinely as a legislative requirement.

The key arguments against the type of model proposed here are in the amount of data and effort required to derive the metrics. Simpler, agglomerated or generalised metrics can reduce the data required (Bossel 1999; Bellekom et al. 2006) but will continue to lack the ability to compare different locations and the absolute sustainability of an activity. The key conclusion of the study presented here is that the incorporation of location-specific factors – including the spatial and temporal factors that are unique to a place – are of vital importance in understanding the real impacts on sustainability. Without these, the metrics are largely an abstraction, separated from the true nature of the environment.

There are, of course limitations to this study. Although the SM model has been demonstrated for sulphur deposition and its contribution to soil acidification, there are numerous other impacts (other emissions, resource use, social and economic effects) that have not been included. The purpose of this paper was to describe and demonstrate the new sustainability metrics model and its advantages. However, in order to truly cover sustainability, multiple other impacts across at least the triple bottom line should be included. Furthermore, it has been shown that the synergistic effects of the variation of a single technological or environmental parameter can vary widely with regard to the associated impacts (McLellan 2009). Therefore, to get a true indication of the sustainability of a process, further work is needed to apply this approach to other aspects of sustainability, including other contaminant emissions, social and economic factors. Covering social factors presents a particular challenge from the perspective of quantification. However, some aspects at least are not beyond the potential of this metrics model (eg. jobs and health statistics over time and space, and the relationship to plant emissions or hiring strategies) and slight modifications could perceivably be used to incorporate qualitative or semi-quantitative social indicators.

## Conclusions

This paper has demonstrated a new model for incorporating location-specific factors into sustainability metrics, applying it to a case study power plant situated in four locations. Each environment, society and economy is unique, leading to the inference that location-specific factors are important for measuring performance with regards to sustainable development. The model offered here is one way of incorporating them. It is has been argued that adding this locational context provides a more absolute than relative measure of sustainability. Incorporating this context also allows comparison across different locations, which is not possible using existing standard methodologies. The case study demonstrates this by showing that the same plant, identical in its impact under current sustainability measurements, has a very different pattern of sustainability and is less sustainable in some cases depending on where it is sited. The use of such a method would help to make current sustainability reporting more meaningful and has the potential to help societies perform more sustainably in the long term by supporting better monitoring and decision making on sustainability issues.

## References

Alcamo, J. and Bartnicki, J. (1987) 'A framework for error analysis of a long-range transport model with emphasis on parameter uncertainty', *Atmospheric Environment*, 21(10): 2121-2131.

Azapagic, A. (2004) 'Developing a framework for sustainable development indicators for the mining and minerals industry', *Journal of Cleaner Production*, 12(6): 639-662.

Azapagic, A. and Perdan, S. (2000) 'Indicators of sustainable development for industry: a general framework', *Process Safety and Environmental Protection*, 78(4): 243-261.

Backhaus, R., Bock, M. and Weiers, S. (2002) 'The spatial dimension of landscape sustainability', *Environment, Development and Sustainability*, 4(3): 237-251.

Bellekom, S., Potting, J. and Benders, R. (2006) 'Feasibility of applying site-dependent impact assessment of acidification in LCA', *International Journal of Life Cycle Assessment* 11(6): 417-424.

Bossel, H. (1999) *Indicators for Sustainable Development: Theory, Method, Applications*, Winnipeg: International Institute for Sustainable Development.

Budden, A. L. and Collins, C. (1998) *Soil Analysis Techniques – the Need to Combine Precision with Accuracy*, Cambridge: the International Fertiliser Society.

Cinderby, S., Cambridge, H. M., Herrera, R., Hicks, W. K., Kuylenstierna, J. C. I., Murray, F. and Olbrich, K. (1998) *Global Assessment of Ecosystem Sensitivity to Acidic Deposition*, York: Stockholm Environmental Institute.

Diniz da Costa, J. C. and Pagan, R. J. (2006) 'Sustainability metrics for coal power generation in Australia', *Transactions of the Institution of Chemical Engineers*, Part B 84, No. B1: 1-7.

Durucan, S., Korre, A. and Munoz-Melendez, G. (2006) 'Mining life cycle modelling: a cradle-to-gate approach to environmental management in the minerals industry', *Journal of Cleaner Production*, 14(12-13): 1057-1070.

Global Reporting Initiative (2006) *GRI Sustainability Reporting Guidelines*, Amsterdam: Global Reporting Initiative.

IChemE, Azapagic, A., Howard, A., Parfitt, A., Tallis, B., Duff, C., Hadfield, C., Pritchard, C., Gillett, J., Hackitt, J., Searman, M., Darton, R., Rathbone, R., Clift, R., Watson S. and Elliot, S. (2003) *The Sustainability Metrics – Sustainable Development Progress Metrics*, Rugby: Institution of Chemical Engineers.

International Institute for Applied Systems (2001) *RAINS-ASIA User's Manual,* Luxemburg: International Institute for Applied Systems Analysis.

Jin, X. and High, K. A. (2004) 'Comparative vs. absolute performance assessment with environmental sustainability metrics', *Proceedings of the American Institution of Chemical Engineering Annual Meeting 2004*, Austin: American Institution of Chemical Engineers.

Kuylenstierna, J. C. I., Cambridge, H., Cinderby, S. and Chadwick, M. J. (1995) 'Terrestrial ecosystem sensitivity to acidic deposition in developing countries', *Water, Air and Soil Pollution*, 85(4): 2319-2324.

McElroy, M. W., Jorna, R. J. and van Engelen, J. (2008) 'Sustainability quotients and the social footprint 7', *Corporate Social Responsibility and Environmental Management*, 15: 223-234.

McLellan, B. C. (2009) 'Potential opportunities and impacts of a hydrogen economy for the Australian minerals industry', *International Journal of Hydrogen Energy*, 34(9): 3571-3577.

McLellan, B. C., Dicks, A. and Diniz da Costa, J. C. (2010) 'Atmospheric and hydrological transport modelling of SOx emissions in a unique verification context', *AICHE Journal*, 56(3): 815-824.

McLellan, B. (2007) *Location-Specific Sustainability Metrics for Hydrogen Energy Systems*, PhD dissertation, Brisbane: University of Queensland.

Norris, G. A. (2003) 'Impact characterization in the tool for the reduction and assessment of chemical and other environmental impacts: methods for acidification, eutrophication and ozone formation', *Journal of Industrial Ecology,* 6(3-4): 79-101.

Opschoor, H. and Reinders, L. (1991) 'Towards sustainable development indicators' in Kuik, O. and Verbruggen, H. (eds.) *In Search of Indicators of Sustainable Development*, Dordrecht: Kluwer Academic Publishers: 7-27.

Pinter, L., Hardi, P. and Bartelmus, P. (2005) *Sustainable Development Indicators: Proposals for the Way Forward*, Winnipeg: International Institute for Sustainable Development: 5-33.

Plenderleith, R. W. (1989) *Tarong Crop and Forestry Study (ETM88/055)*, Brisbane: Queensland Electricity Commission, Generation Technology Department (Environmental Section).

Pope, J., Annandale, D. and Morrison-Saunders, A. (2004) 'Conceptualising sustainability assessment 7', *Environmental Impact Assessment Review*, 24 (6): 595-616.

Scerri, A. and James P. (2010) 'Communities of citizens and "indicators" of sustainability', *Community Development Journal*, 45(2): 219-236.

Spangenberg, J. H. (2002) 'Environmental space and the prism of sustainability: frameworks for indicators measuring sustainable development', *Ecological Indicators*, 2(3): 295-309.

Thomas, A. H. and Reynolds, B. R. (1998) 'Numerical stability considerations in the simple mass balance calculation of critical loads for acidity', *Science of the Total Environment*, 217(3): 257-264.

Yossapoll, C., Caudill, R., Axe, L., Dickinson, D., Watts, D. and Mosovsky, J. (2002) 'Carrying capacity estimates for assessing environmental performance and sustainability', *Proceedings of the IEEE International Symposium on Electronics and the Environment*: 32-7.

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