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Technical impact indicators for materials

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Abstract – The impact of the use of particular materials on the environment and society can be assessed in a number of ways, including through the impact on natural resources, contribution to environmental burden and effects on the quality of human life. In this context, indicators such as embodied energy, exergy, TMR (total material requirement), ecological footprint, social indicators (such as effects on human health) and LCA based on these indicators, are available. We apply the concept of energy networks [1] (quoted in Appendix O), to explore the differences in energy network impact due to processes for the production of various materials, each time with an equivalent end-use in mind. The inventory analysis part of LCA has been carried out on materials, as well as some work on impact assessment (LCIA) for resource use, pollution severity and health impact. The indicators proposed here aid the assessment of the energy system impact, particularly with regards to opportunity costs to society, impact on equity in society and the administrative burden on society due to the current energy networks. The indicators are: embodied energy, the maximum process temperature, the annual use energy, and network reliance. Three case studies are employed to explore the usefulness of the indicators, including a beverage container, a house window frame and a beverage bottle transport crate. These case studies show that for a particular end use, different materials can have wide differences in the proportion of energy sourced from energy networks (a factor of 95 observed in one case). The indicators also offer a quicker indication than life cycle assessment and allow deduction of impacts on a wider social system. The indicators have the potential to change material development and process design trends towards processes which are less burdensome on energy networks.

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In current energy research, the comparison of materials in terms of energy performance commonly involves a survey of one or more of the following characteristics: embodied energy, use of non-renewable energy, CO_2 emissions intensity and exergy, which are all related to the environmental impact of materials. Social impact assessment generally looks at society as a collection of individuals, whose health, wealth and environment are affected by the impacts of energy use. Thus indicators often quantify local and global pollution and safety issues. There are also indicators that look at economic impacts of energy for a material such as GDP energy intensity.

Life cycle assessment (LCA) is a tool that is now widely used to determine the impacts of processes and their products. The inventory analysis part of a life cycle assessment is now well established in worldwide practice. It is well documented in the ISO codes of practice [2]. The assessment part of a life cycle assessment (life cycle impact assessment or LCIA) is not as standard as the inventory analysis. The definition, meaning and interpretation of impacts are varied. They depend not only on the process under consideration but also on the interests of the party conducting the impact assessment.

The impact of the use of particular materials on the environment and society can be assessed in a number of ways, including through the impact on natural resources, contribution to environmental burden and effects on the quality of human life. In this context, indicators such as embodied energy [3], exergy [4], TMR (total material requirement) [5], and ecological footprint [6] exist. Impact assessment indicators which employ the weighting of life cycle inventories to combine resource consumption, pollution severity and health impact include the Dutch Eco-Indicator 95, the Swiss Ecopoint indicator, the Swedish Environmental Priority Strategies for Product Design (EPS), and the LIME indicator from Japan.

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Table 1. Definition of indicators used in the survey.

Indicator	Meaning
Emergy	Input of energy required to produce the material in MJ (used interchangeably with embodied energy in this study)
Temperature	Highest temperature required for processing in K
Relative annual use energy	Average annual amount of energy associated with the use of the product, for the specified purpose in MJ. In relation to the other material options (if all materials equal, value = 1).
Network reliance	% of energy that is derived from an energy network of geographical expanse > 10 km (evaluated for embodied energy only here).

The concept of energy networks, including electricity, crude oil, natural gas, coal etc. supply and use networks ([1], quoted in Appendix O), while rarely considered in energy research can significantly contribute to understanding sustainability. The impact or demand of materials processing, use and disposal on an energy system, and energy networks in particular, is of interest when planning sustainable futures, since man-made energy networks invariably have environmental, economic and social system impacts. The generally larger scale of activity in energy networks confers the potential to greatly increase impacts in general.

This work aims to define and evaluate the usefulness of a system of four indicators designed to show the technical impact of various materials as used in products from an energy perspective, allowing the comparison of different materials, as well as different processes.

The survey conducted here is not a comprehensive life cycle impact assessment exercise. The usual life cycle impact assessments would attempt to make a thorough impact assessment of the energy and other inputs required, as well as other outputs for the processing of the materials. This research focuses on the processing of the materials in relation to the energy supply-related burden on the society, especially with regard to the established energy networks. This is in contrast to considering society as merely a collection of individuals who are vulnerable to impacts. Three social impacts behind the rationale for selecting the four indicators are opportunity costs to society, impact on equity in society and the administrative burden to society. The results of the survey are meant to have relevance to policy-making, as well as to enterprises which process and develop materials, and thus hopefully contribute to the overall objective of sustainable materials use in society.

1 Methodology

Four indicators have been selected, some of them derived especially for the requirements of this research. During the indicator selection process, an original list of 7 indicators was pre-selected. These included embodied energy, processing temperature of the material, the annual use energy for the material in the product form, the intolerance to the interruption of the energy supply during processing, the reliance on energy networks, the indispensability of the process to produce the material, and the indispensability of the material itself in the particular products. After a trial process, where the indicators were tested on case studies, some of the indicators were discarded, and the indicator list was reduced to four indicators described in Table 1: embodied energy (emergy), temperature, relative annual use energy and network reliance.

These indicators have been chosen and defined in such a way as to balance usefulness of the information contained within them with the convenience of evaluating them. The robustness of the indicators is also a factor considered, to prevent excessive ambiguity, which would render the indicators meaningless.

The list of indicators to be used is shown in Table 1.

Three different products, each of which can be made from a possible range of materials, were considered as an initial application of the indicator system. The products were also chosen to be fairly homogeneous in terms of the number of materials used to make them, the ideal being a product made of only one material.

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Firstly, we surveyed a 280 ml container for hot or cold beverages, sold in sealed containers in shops and vending machines. These are commonly known as "cans" or "bottles". The alternative materials in this survey were aluminium and PET (Appendix A). The type of aluminium used for beverage cans is sheet aluminium, which has been hot and cold rolled (Fig. 7 in Appendix D). The type of PET used for beverage bottles has undergone solid state polymerisation (SSP). More details on the data for aluminium and PET are below in the discussion on the ELCD [8] data. Additional data was then sought for the processing of the aluminium sheet into a beverage container. This was done using online reports and media on the manufacture of aluminium beverage containers [Appendix F and Appendix H]. A similar exercise was carried out for PET.

Secondly, we looked at a standard house window frame, as defined in an LCA exercise published by FAO, primarily comparing wood to other products [7]. The dimensions of the window are shown in Figure 5 of Appendix B. The overall dimensions are a height of 1300 mm and length of 1650 mm. The materials surveyed here were spruce timber, aluminium and PVC. For this survey, since the window frames are made of more than one material, the embodied energy had to be a sum of the different embodied energy amounts for the different materials. The other indicators however, were evaluated only for the main material of which the window frame is constructed.

Thirdly, we looked at crates for transporting beverage bottles. The materials considered for these were pine timber, PVC and aluminium. The crate size was standardised to carry 24 beverage bottles, each of size 750 ml. Such a crate is shown in Figure 6 of Appendix C.

The second and third case studies above were chosen because they seemed to be cases where the relative annual use energy would differ for the materials concerned, due to heat flow between the inside and outside of the house in the second case study, and due to transport energy use in the third case study.

The data for the survey was obtained from a number of various sources, including the following:

- LCA inventory data from an EU project with the name ELCD [8], available online. This data included inventory LCA data for a number of materials and processes. This survey made use of the energy input data for a number of the materials.
- LCA inventory data and study report comparing wood with other materials, from the FAO of the United Nations [7].

The ELCD data has a few characteristics which are relevant to the methodology. Firstly, the data contains what appears to be thorough inventory data for various materials. The data is obtained from various entities such as industry associations, including the European Aluminium Association, Plastics Europe Association of Plastics Manufacturers, and PE International GmbH (in the case of wood products) [8]. It is then standardised. One of the standards of the data sets a clear statement of the system boundaries for each material survey. Another standardisation is the horizontal averaging of the inventory data [8], so that for example, production of a kilogramme of aluminium sheet will show a wide range of energy sources from a wide range of geographical locations, which is not literally accurate for any one particular kilogramme of aluminium, but is representative of the input and output inventory amounts of the average kilogramme of aluminium sheet. The survey population is industries in Europe, but supply inputs from around the world are reflected in the inventory data. A third form of standardisation is the disclosure of the percentage of the total production (in the EU), that is included in the ELCD survey. The percentages are high where stated [8].

An outline of the processing of some of the materials is included in Appendix D.

In the ELCD data sets [8], the system boundaries for the different materials surveyed are not absolutely identical, but they are sufficiently close, as we shall see in the Discussion. All of the data is for the production of materials from raw materials up until just before the stage of manufacture of the final product [8] including aluminium

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sheet and profile sections, mild steel sections and sheet, PET, S_PVC and HDPE granules before injection or blow moulding, and sections of spruce and pine timber as products from saw mill, before final shaping. The error due to exclusion of final shaping is not seen as significant, since the energy input involved in the final shaping is relatively small compared to the energy required for extraction and purification which lie within the survey system boundaries. This assumption will also be explored for soundness in the Discussion. Another, more significant difference in the data sets, is that the materials that are not recycled to an equal extent. Aluminium and mild steel for example are recycled to a significant extent, significantly affecting the inventory quantities for a standard kilogramme of each, compared to the scenario where all material is sourced from virgin resources. This difference is seen as not problematic, as the research aims to analyse the real implications of using one material as opposed to another which may, as in this case, involve the reality of recycling. The assumptions for obtaining the embodied energy for the different materials are in Appendix F to Appendix N.

In addition to the use of available LCA inventory data, practical information on the products surveyed was obtained from various sources. These include the actual weighing of 280 ml beverage cans used in Japan (Appendix A, Fig. 4), using a specific size for the house window frame (Fig. 5 in Appendix B), and obtaining the actual sizes of crates used to transport beverage bottles via online sources (Fig. 6 in Appendix C).

What follows is a discussion of how each indicator is evaluated. The first indicator, "emergy", or the embodied energy, is derived primarily using the ELCD data. Other information is used to determine this embodied energy, either through weighing or online references stating the mass of the material in a particular product. The highest processing temperature is derived from process information which is available from industry associations, research reports, product information websites and so on. This indicator is included as an indirect indicator of the energy burden of a process. One objective is to check to what extent a correlation can be seen between the highest processing temperature and the embodied energy. The relative annual use energy is derived using reasonable assumptions about the energy requirement when the product is used. This analysis is not carried out for instances where the use energy would be almost exactly similar, such as the PET and aluminium beverage bottle containers. This value is labelled "relative" because it is only with respect to the aspects being considered, such as the transport energy in the case of the beverage bottle transport crate. There may be other possible sources of use energy, such as the re-painting of surfaces where the beverage crates are transported or stored, which may be more susceptible to metal crates damage, as opposed to damage by wood and plastics, for example.

The network reliance is a measure of the dependence of the material production process (embodied energy), on the expansive and intensive energy networks present globally today. These are mainly the fossil fuel energy networks (oil, coal, and natural gas). Some other sources of energy are included in the definition of energy from energy networks. These include electricity of any origin that is transmitted over long distances, including electricity from wind generators and large hydro electricity. In the analysis, solar drying [26], which was used for the wood types included in the survey according to the ELCD data, and wood as a fuel, were considered as non-network sources of energy.

In order to effect a convenient graphical representation of the results, the values obtained for the indicators were converted into metrics that allowed for a clear star plot to be displayed. The modifications made to each indicator are shown in Table 2 below.

The calculation of the indicators was carried out in a separate spreadsheet document and the results presented in this paper.

2 Results

The results for the 280 ml beverage container are shown in Table 3.

The indicator plot for the beverage container is shown below in the star plot (Fig. 1) below.

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Table 2. Conversion of the indicators for the star plot.

Indicator	Calculated Units	Modification for Metric
Emergy	MJ	Normalise against material with lowest value
Temperature	K	Normalise against material with lowest value
Relative annual use energy	Decimal fraction	Remains same
Network reliance	%	Change % to a fraction, 100% = 1

Table 3. Technical indicators for a 280 ml beverage container.

	Indicator values		Metrics for star plot	
Indicator	PET	Aluminium	PET	Aluminium
Emergy (MJ)	2.02	1.61	1.25	1.00
Temperature (K)	553.40	1223.14	1.00	2.21
Relative annual use energy	1.00	1.00	1.00	1.00
Network reliance	99.70%	99.51%	1.00	1.00

The results show clearly that using the data source and the assumptions in this survey, PET requires 25% more energy to process than aluminium in the manufacture of a beverage can. During the aluminium manufacturing process, temperatures reached are much higher than those of the PET manufacturing process, at 1223 K versus 553 K respectively. The relative annual use energy is also roughly equal at 1, based on the assumption that the use energy is equal for materials when used as a beverage container. The reliance on energy networks is almost similar for both materials, at over 98% for PET, and over 99% for aluminium, and therefore the embodied energy is a good indicator of the relative burden of the two materials.

The results for a window frame for a house in Osaka, Japan are shown in Table 5 below.

Figure 2 below is the plot of the indicators for the window frame of the house in Osaka.

The results of the survey for the window frame of a house in Osaka, Japan show that out of the three materials selected, aluminium and suspension PVC perform quite similarly, while spruce timber shows a much lower energy burden on society. Aluminium and suspension PVC require 3.39 and 3.76 times as much embodied energy as spruce timber, which has an embodied energy of only 505 MJ for this application. As stated in the methodology, these embodied energy values include the energy contribution of the minority materials used to make the window frame in each case. Aluminium and PVC each have maximum processing temperatures in excess of 1100 K, while Spruce

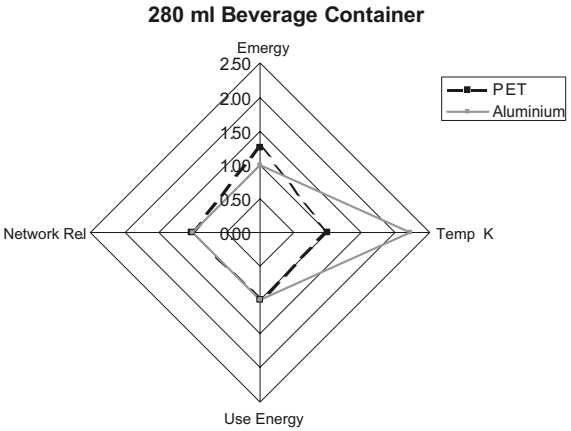


Fig. 1. Plot of technical indicators for 280 ml beverage container.

timber has a maximum processing temperature of about 340 K. The annual use energy for aluminium is 27% higher than that for PVC or Spruce timber, under the assumptions stated. The reliance on energy networks is approximately the same for both aluminium and PVC, at over 99%, while it is less than 4% for spruce timber, with the processing methods for which the data corresponds.

The results for a beverage bottle transport crate are shown in the Table 5 below.

The indicator plots for the beverage bottle crate are shown in Figure 3 below.

For the beverage bottle transport crate, the embodied energy requirement for PVC and HDPE are about 7.6 and 6.5 times the energy required for the material with the lowest amount, Pine wood (timber), which

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Table 4. Technical indicators for the window frame of a house in Osaka.

	Indicator values			Metrics for star plot		
Indicator	Aluminium	S_PVC	Spruce Wood	Aluminium	S_PVC	Spruce Wood
Emergy (MJ)	1708.27	1896.40	504.51	3.39	3.76	1.00
Temperature (K)	1223.14	1123.14	338.70	3.61	3.32	1.00
Relative annual use energy	54.17	42.77	42.77	1.27	1.00	1.00
Network reliance	99.23%	99.51%	3.94%	0.99	1.00	0.04

Table 5. Technical indicators for for beverage bottle transport create.

	Indicator values				Metrics for star plot			
Indicator	Pine timber	Al Profile	S_PVC	HDPE	Pine timber	Al Profile	S_PVC	HDPE
Emergy (MJ)	18.79	52.67	142.16	122.70	1.00	2.80	7.56	6.53
Temperature (K)	338.70	1223.14	1123.14	573.14	1.00	3.61	3.32	1.69
Relative annual use energy	13.84	7.26	18.82	12.77	1.91	1.00	2.59	1.76
Network reliance	3.67%	99.23%	99.51%	99.72%	0.04	0.99	1.00	1.00

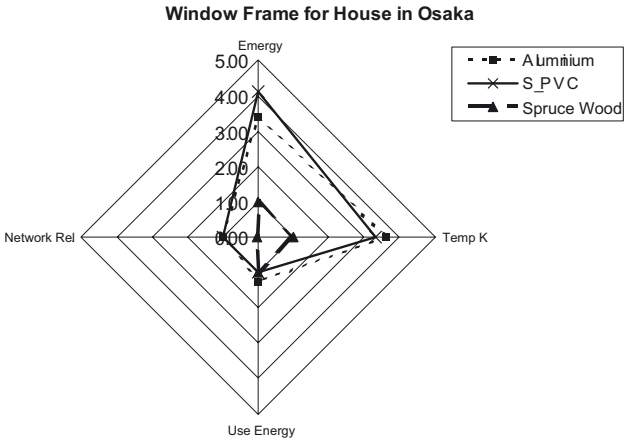


Fig. 2. Technical indicators for the window frame of a house in Osaka.

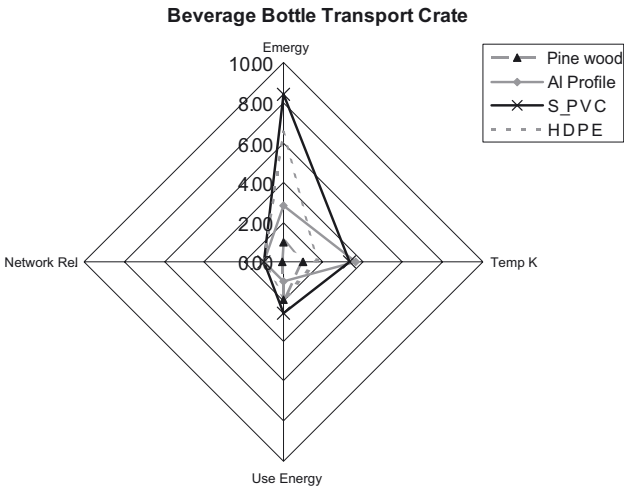


Fig. 3. Plot of technical indicators for a beverage bottle transport create.

requires about 19 MJ. Aluminium is between the extremes, with about 53 MJ, or 2.8 times the Pine Timber embodied energy. The lowest processing temperature is that for pine wood, at just below 340 K, while the HDPE value is about 1.7 times this value, in K, and both aluminium and PVC have values in excess of 3.3 times this pine wood value. Under the assumptions, the lowest annual use energy is the aluminium value, at 7.26 MJ, while HDPE and Pine Timber have values about 1.8 and 1.9 times the aluminium value respectively. PVC has a noticeably higher annual use energy at 2.6 times the aluminium value, or equal to almost 19 MJ per year. Similar to the case for the house window frame, the reliance on the energy network shows a wide gap for the materials used for the beverage bottle transport crate. Aluminium, PVC and HDPE have an over 99% reliance on energy networks, while Pine Timber has less than 3.67% reliance.

3 Discussion

3.1 Embodied energy network reliance

The main result of interest in the survey of the 280 ml beverage container is the embodied energy. The processing temperature has a wide difference between the two materials, but this does not cause a higher embodied energy for aluminium. The other indicators are practically the same for the two materials surveyed.

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Table 6. Calculating Network-Derived Embodied Energy for the house window frame.

Material	Aluminium	S_PVC	Spruce Wood
Embodied Energy MJ	1708.27	1896.40	504.51
Network Reliance	99.23%	99.51%	3.94%
Network-Derived Embodied Energy MJ	1695.12	1887.11	19.88
Network-Derived Embodied Energy Ratio	85.3	94.9	1

Table 7. Technical indicators for a beverage bottle transport crate.

Material	Pine wood	Al Profile	S_PVC	HDPE
Embodied Energy MJ	18.79	52.67	142.16	122.70
Network Reliance	3.67%	99.23%	99.51%	99.72%
Network-Derived Embodied Energy MJ	0.6896	52.26	141.5	122.34
Network-Derived Embodied Energy Ratio	1	75.8	205.2	177.4

Within the boundaries set for this survey, the results show that for the purpose of making a 280 ml beverage container, the use of PET requires an input of 25% more energy per container manufactured than if aluminium were used. The processing of both materials required energy from energy networks, where a very high proportion of the energy is fossil fuels. When considering number of beverage bottles manufactured per year in many countries, the difference in impact on the energy networks is significant. The advantage of using aluminium in line with the assumptions in this survey is only maintained if a high recycling rate, 79% [9], is maintained. It must be noted that a significant proportion of the embodied energy for the aluminium beverage can was due to waste when the blanks for the cans are cut from a flat sheet during a processing stage called the cupping process. The assumed waste was 14% in accordance with the higher limit stated by Hosford and Duncan [10]. Without this waste in the manufacture of the aluminium can manufacturing process, PET requires about 40% more energy than aluminium, if all other factors remain the same.

For the house window frame, the embodied energy results clearly show a higher burden on energy networks for aluminium and PVC as compared to spruce timber. The difference is at least a factor of 3.3 less for spruce timber versus each of the other two materials. If we factor the embodied energy figure by the network reliance value, then we find that the gap grows further. Table 6 below shows the embodied energy derived from energy networks, for the three materials. The "network-derived embodied energy" is the embodied energy multiplied by the network reliance percentage ratio. The "network-derived embodied energy ratio" is a comparison of the "network-derived embodied energy" amounts for the respective materials.

Table 6 shows the real implication of the spruce timber having a close to zero value for network reliance in the plot in Figure 2. It shows that the embodied energy for aluminium and PVC in the survey scenario requires about 85 times and 95 times more energy from networks than spruce timber does.

It is also clear from the results of the house window survey that the use energy can be a significant proportion of the energy associated with a material. In the case of Spruce timber, if the embodied energy were to be discounted over a 10 year lifespan, then the annual equivalent embodied energy and the annual use energy would be equal to within 10%.

The beverage bottle transport crate shows a similar phenomenon to the case of the house window frame. The equivalent analysis table for the beverage bottle transport crate is as shown in Table 7. The left hand column labels are the same as for Table 6.

Here, we can see that the ratios of energy sourced from energy networks, relative to pine wood, for profile aluminium, PVC and HDPE are approximately 76, 205 and 177 respectively.

As in the case of the house window frame, the use energy for the beverage bottle transport crate is also significant, relative to the embodied energy. For the case of pine wood, if we discount the embodied energy,

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then the annual use energy would be almost 75% of the annual equivalent embodied energy.

For the materials surveyed, the results showed that the energy input up to the point where the material is in its useful form, but before final shaping, is the vast majority of the energy (see examples in Appendix F and Appendix H). Very little energy is required for final shaping such as shaping the aluminium can, blow moulding the PET bottle, and shaping the house window frame out of wood.

4 The applicability of the indicators

Of the four indicators, the highest processing temperature indicator is the weakest indicator of impact on an energy system. The reason for this is that while processing temperature often implies a greater requirement for high quality energy, such as that obtained through energy networks, it is often possible to use technology to raise process temperatures to a high degree without substantially increasing overall requirement for energy from electricity or other networks. A case in point is the use of electric arc, laser and plasma-type heating instead of heating through electrical resistance, gas flame and so on. The second easiest indicator to control would likely be the relative annual use energy. Various interventions such as design weight decreases and changes in use mode can reduce this indicator. Embodied energy and use energy can be traded off in certain cases, whereby a material with a higher embodied energy may be better in the long run due to lower use energy during its lifespan. This was the case above with the pine wood versus the (lighter weight) aluminium for the beverage bottle transport crate above. Next, embodied energy can be changed through interventions such as process optimisations and material change. Decreasing the network reliance indicator requires more consideration since current industrial practice is highly dependent on the established (often global) energy networks. The advent of high output, standardised and capital intensive industrial processes since the start of the Industrial Revolution has generally been accompanied by a design assumption that energy is sourced from the global energy networks (including electricity, crude oil, natural gas, coal etc.), with little attention to local resources. Use of the network reliance indicator as defined here can encourage measures to reduce reliance on energy networks. This indicator requires deeper consideration since processing a material using (higher quality) energy from the energy networks as opposed to local sources may result in a better material in terms of lower overall system impacts.

The four technical indicators used can give a relatively quick indication of the impact of materials on an energy system. In cases where the advantage of one material above another is clear after evaluation using the four indicators, then they offer an alternative to life cycle assessment. Where the differences are not clear, an LCA process will be necessary to clarify whether differences in material energy system impact are more pronounced than LCA differences. The result could ease material selection.

4.1 Relevance to impacts on society

In the context of the three chosen social system impacts: opportunity costs to society, impact on equity in society and the administrative burden to society, the following is inferred. The results in this paper give an indication of the opportunity costs to society, mainly through the relative amount of energy which needs to be sourced from the existing expansive and intensive energy networks (Appendix O), for the purpose of processing and the using the material as part of a product. The case of spruce wood versus S_PVC and aluminium in the house window shows that there can be a large difference in the amount of network-sourced energy required to process one material as opposed to another (a maximum difference factor of 95 is observed), with no corresponding reduction in use energy for the material with the higher embodied energy. In order to quantify administrative burden, one would then have to link the material embodied energy to the amount of government

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legislation and the implementation of such legislation, as related to the establishment and maintenance of the supply networks for the energy required. Impact on equity is perhaps more difficult to evaluate. Quantifying it requires quantifying the amount by which various entities in the society (industries, commercial entities, private households and so on) benefit from the centralised energy networks. This information in turn allows quantification of any cross-subsidy among the various entities and, in instances where the cross subsidy seems unjustifiable in the overall social order, allows quantification of a contribution to inequity that can be allocated to a material-making process.

Apart from indicating burden on society, the network reliance indicator gives a measure of vulnerability to variations in network supplies. In the case of a manufacturing enterprise, vulnerability to variations in energy network prices, as well as lack of control over energy sources, can be very disruptive. The inclusion of local energy sources, some of which are renewable, can help improve security of energy supply. To be thorough in applying the indicators, the use energy of a material or product too should also be separated between network-sourced and non-network sourced energy.

4.2 Comparisons and fusion with other approaches

An LCIA process which considers the burden on energy networks as shown in this survey, is able to show the impacts on a social system. It is possible to formulate economic and environmental impact indicators which are also adjusted to focus on the opportunity costs to the social system, and environmental degradation as an opportunity cost. Materials flow analysis can be enhanced through the use of energy network burden indicators. For example, the deliberate replacement by a society, of one material by another for some reason, such as supply security, would need an analysis of changing energy patterns due to the processing of the new material.

The energy required for processes is often characterised in terms of renewable energy requirement as opposed to non-renewable energy use [11]. This approach has some similarities to the approach used in this paper, in so far as energy from non-network sources is often renewable. The difference is that the indicators used here would classify renewable energy sources from distant sources, such as long distance transmission of electricity from off-shore wind turbines, as energy from the energy networks, which invariably impose some burden to society.

Another known analysis approach is the evaluation of CO_2 emissions resulting from a process [12]. Such an approach has become widespread, and is generally technically robust in that it contains relatively little ambiguity. The results of such analysis enable entities in society to evaluate processes in relation to a widely accepted limit imposed by the biosphere. The approach is however distinguishable from the approach presented here, which focuses on the social system impact rather than look directly at the biosphere impact.

Other different approaches to the technical burden of a material have been proposed. One such approach is the total annual energy burden [13]. For a material, the annual energy burden E_a, due to the use of a material for a particular application can be expressed as follows:

$$E_a = E_p + E_u + E_d \tag{1}$$

where E_p is the total energy required for the production of the material (embodied energy), divided by its lifetime to give an annual burden, E_u is the equivalent annual energy due to the use of the material, and E_d is the annualised energy required for disposal of the material. Their sum E_a is the annual energy burden assuming continued use.

The above approach is more useful when calculating the gross energy demand in a country or within a defined system. It is particularly useful for semi-durable consumer goods with a relatively high embodied energy, which also have an annual use energy amount of at least approximately the same order of magnitude. These would be goods whose useful lifetime is longer than a year, including computers, refrigerators and other appliances, as well as transport vehicles. For the indicators presented here, the embodied energy and the annual use energy were

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separately shown and furthermore, the network reliance was evaluated. This approach is useful for fast moving consumer goods (FMCG) such as beverage cans, paper cups, chopsticks and so on, where the relationship between the embodied energy and the annual use energy can be critical to energy system sustainability. This analysis allows the determination of the relative energy burden of products between different materials and also in the types of energy inputs within one material. Strategically-targeted modifications could then be made in how a material is produced or used, in order to reduce a material's burden on the respective energy system. If, as is generally the case, the lifetime (in days, weeks, months) of the fast moving consumer goods is not the same for different materials being compared, then it is necessary to convert their lifetime impacts into an annualised average.

Bringing together the indicator approach from this survey with the approach consistent with Equation (1) above, Equation (1) can be modified so that each term looks at the energy supplied by energy networks, so that the annual network energy burden $E_a\, n_a$ can be expressed as:

$$E_a n_a = E_p n_p + E_u n_u + E_d n_d \qquad (2)$$

where E_p, E_u and E_d and have the same values as above, and the n_x coefficients are the respective network reliance values of the different types of energy, indicating the percentage of the respective energy that is sourced from energy networks.

5 Conclusions

Considering three types of social impact: opportunity cost, impact on equity and administrative burden, the four indicators applied allow a relatively quick method of evaluating the impact of materials as produced by a given method and used in a particular product. An LCA process may still be necessary depending on the results from the four indicators. Of the three social impact indicators, opportunity cost is the simplest to determine from the four indicators while impact on equity appears to be the most difficult.

The results above show that, for the same end use, the choice of material for a product can have very different impacts on the energy supply networks. This is illustrated especially in the analysis of the house window frame and the beverage bottle crate, where the wooden materials in each case showed a much lower burden to the energy supply networks: by a factor of 95 for the window frame.

Of the four indicators, the processing temperature indicator is the weakest indicator of energy system impact while network reliance is the strongest. While the maximum processing temperature of a material can give an indication of the embodied energy, the relationship is not a direct one as can be seen in the case of PET and aluminium, where the production of (lower processing temperature) PET does include a large number of steps (chemical processing), while the main contributor to the high temperature in the (lower embodied energy) processing of aluminium is during electrolysis. The maximum processing temperature does perhaps remain useful as a rough indicator of the ability to use energy sources other than the energy networks, such as local renewable energy and available waste heat.

The information derived in calculating the "network-derived embodied energy" in the Discussion of Results above indicates that the network reliance consideration can be an informative addition to the consideration of energy burden. It seems useful to extend the network reliance consideration to the annual use energy.

The results lead us to also conclude that perhaps much can be learned and improved by considering the relative contributions of the different phases of material processing to the total energy burden from the processing of that material. These phases are generally extraction (often mining), purification and final product manufacture. In this survey, extraction and purification have made up more than 95% of the energy required to deliver the material in product form. We have seen this for the plastics and aluminium (Appendix F and Appendix H).

Further, the results for the energy burden for pine and spruce show that taking advantage of natural processes which produce materials (wood production in this case), can have significant advantage in reducing

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Fig. 4. Samples of the Aluminium and PET beverage containers. (Source: original photograph.)

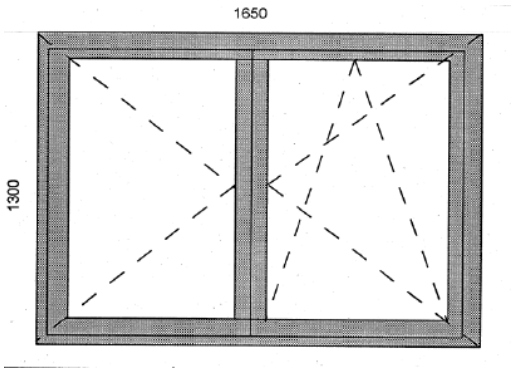


Fig. 5. Dimensions for Window frame for a house in Osaka (dimensions in mm). (Source [7].)



Fig. 6. A beverage bottle transport crate. (Source [14].)

society's energy burden. If a material made through a particular process has a lower impact on the energy system, then financial and regulatory incentives should be aligned to promote the lower environmental impact alternative.

Appendices

Appendix A: Specifications for beverage containers

The beverage container specifications are as follows:

Materials surveyed: Aluminium (from aluminium sheet) and PET (bottle grade).

Mass: 24 g for the PET bottle (excluding cap, which is made of a different material), 20 g for the aluminium bottle, including the aluminium cap.

Volume: 280 ml nominal specified beverage volume.

Transport: As an input to the use energy value, it is assumed that the filled and empty bottles are transported an average 100 km a week, for 50 weeks a year, totalling 5000 km per year, using a truck with a load capacity of 3 tons.

A sample of the beverage containers are shown in Figure 4.

Appendix B: Specifications for the window frame for a house in Osaka

The specifications for the window frame for a house in Osaka, Japan are as follows:

Length and height: are as specified in Figure 5.

The dimensions of the house window frame are shown in the Figure 5.

Appendix C: Beverage bottle transport crate

A sample of a beverage bottle transport crate (HDPE material) is show in Figure 6.

Appendix D: The processing outlines for the main materials in the survey

The following figures show the processing outlines of the main materials surveyed in this report.

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Table 8. Main materials. (Source: *k* values and material masses from [7].)

Main window frame material	Main other material used	K value (main material only) W/m^2K	Mass input Kg
Aluminium	Aluminium profile	1.9	28.69
	Aluminium sheet		0.67
PVC	S_PVC	1.5	27.55
	Steel section		14.58
Spruce Timber	Spruce Timber	1.5	37.64
	Aluminium profile		1.28
	Mild steel sheet		1.64

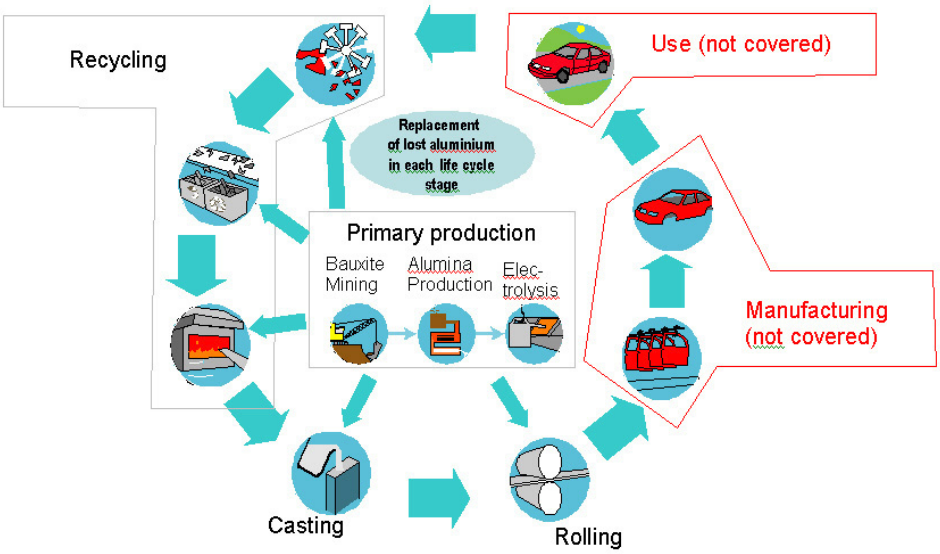


Fig. 7. The processing of sheet aluminium. (Source [9].)

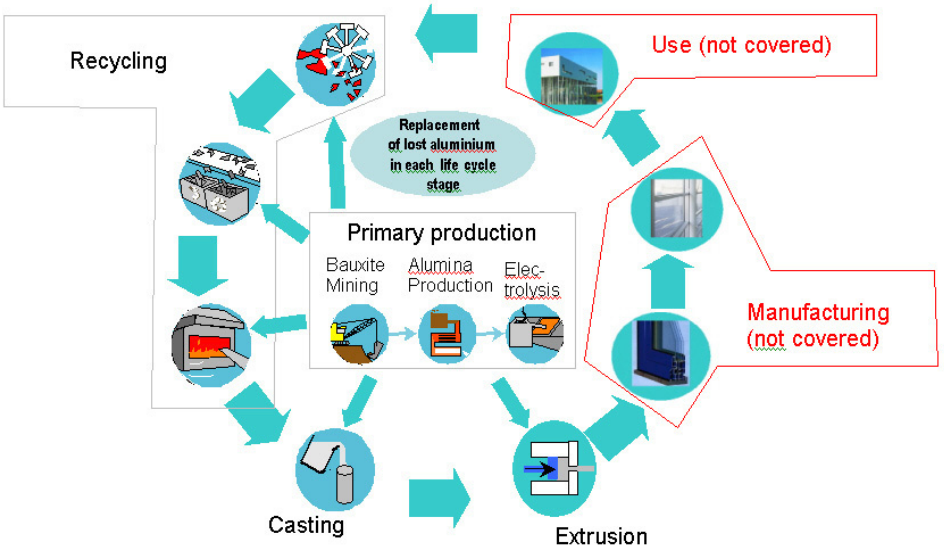


Fig. 8. The processing of aluminium extrusion. (Source [18].)

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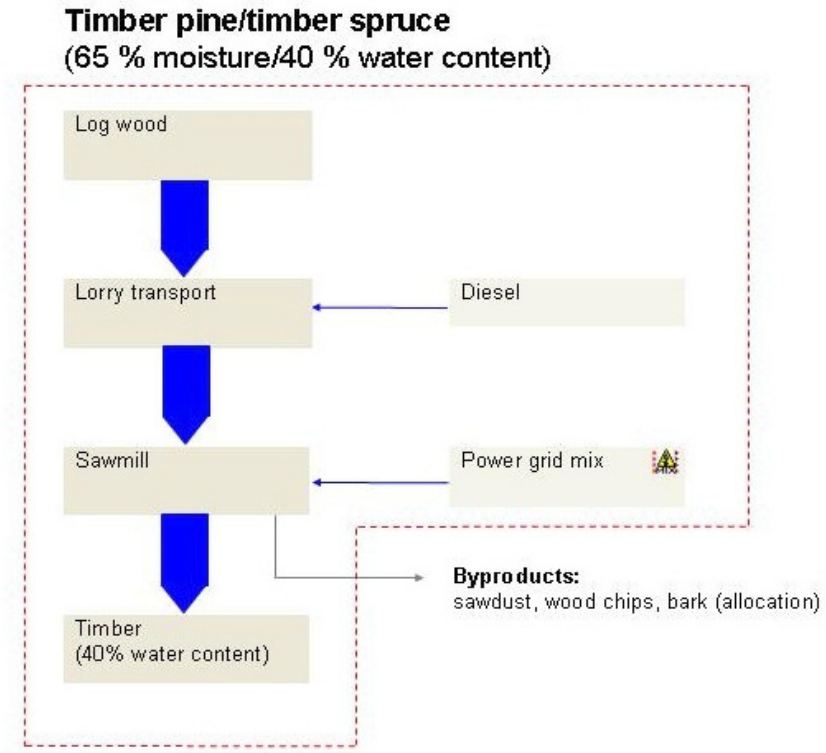


Fig. 9. The processing of pine timber (similar for spruce timber). (Source [15], for the timber drying process, see [26].)

Appendix E: Sample of the online ELCD data

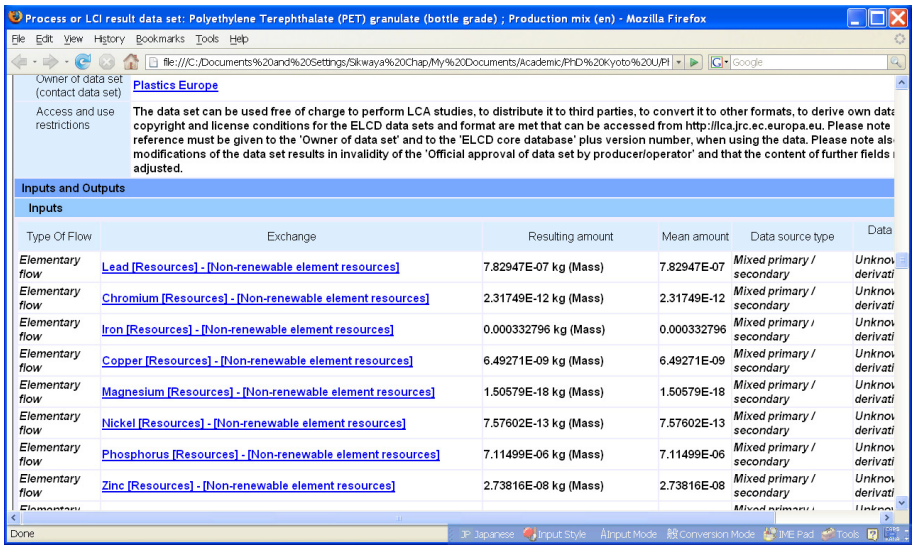


Fig. 10. A sample screenshot of the ELCD data (PET bottle grade sample). (Source [19].)

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Appendix F: Outline of properties and assumptions for Aluminium Sheet

Assumptions for aluminium sheet.

There are explanatory notes for calculations at the bottom of the assumptions.
The aluminium sheet analysis is based on a 79% recycled aluminium input for smelting into aluminium sheet [9]. The inventory analysis is from mining up until the production of aluminium sheet as shown in the outline Figure 7 of Table 8 above.
For the final shaping of the aluminium sheet into the beverage bottle, the high speed cold processes are assumed. The specific analysis is for an aluminium can rather than a bottle, but processes are considered similar enough. A 3 step process (cupping, body-making and necking) is assumed [16], at about 1 s each, 33 cans a second, at a conservatively overstated average electrical power input of 30 kw. These 3 steps requires a total an input of about 0.00 3MJ. This is followed by high-speed printing on the can body, followed by heat drying of the decoration [16], which requires another 0.0032 MJ. Adding together the energy for shaping can and for drying the decoration, we obtain 0.006 MJ. Converting this to primary energy, through dividing by 0.37 (37% conversion efficiency from fossil fuels to electricity), gives 0.016 MJ. The transportation of the can around the factory is assumed to total about 1 km in travel, and the worst efficiency mode considered, the forklift is selected. This energy is calculated at about 0.0035 MJ.
The waste of aluminium sheet material has an energy implication. About 14% of the aluminium sheet is not part of the final can, but is waste material from blank cutting [10]. This is 2.8 g of additional sheet aluminium per can. The additional primary energy for this material is 0.1959 MJ.
Therefore, the energy required to make and decorate the can body, transport the can material around the factory, and to make the wasted material, amounts to about 0.215 MJ. This is equivalent to about 15.4% of the embodied primary energy of the aluminium sheet material that is a final part of each can, before it is processed into a beverage can.
Notes:

- From ELCD, 69.97MJ of primary energy are required to make 1 kg aluminium sheet.
- The specific heat capacity of aluminium is taken as 0.87 kJ/kgK [17].
- The decoration drying temperature is 204 °C [16].

Appendix G: Outline of properties and assumptions for Aluminium Profiles

Assumptions for aluminium profile.

The aluminium profile analysis is based on an 88% recycled aluminium input for smelting into aluminium sheet [18]. The inventory analysis is from mining up until the production of aluminium sheet as shown in the outline Figure 9 of Appendix D above.
Notes:

- From ELCD, 57.91 MJ of primary energy are required to make 1 kg aluminium profile.
- The specific heat capacity of aluminium is taken as 0.87 kJ/kgK [17].

Appendix H: Outline of properties and assumptions for PET (Polyethylene teraphthalate) bottle grade

Assumptions for PET (polyethylene teraphthalate) bottle grade.

The analysis for PET is based primarily on the ELCD sourced LCA inventory data for PET resin [19]. The additional energy required for the final shaping of PET into the beverage bottle was estimated using assumptions and PET characteristics data.
The required steps for the production of the PET bottle from PET resin are: heating of resin, injection, blow moulding, cleaning the bottle mould and labelling the bottle. For the heating of the resin, heating is assumed to happen twice, once to make the initial form, and secondly to blow the form into a bottle. The primary energy requirement for the heating processes is about 0.01362 MJ. The non-heating energy required for the process of shaping the PET bottle is assumed to be of similar magnitude to that required for shaping the aluminium can, and is estimated at 0.02344 MJ. The total for the production of the bottle from PET resin is 0.03706 MJ, which is 1.87% of the energy required to make only the resin for the bottle.

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Notes:

- From ELCD, 82.66 MJ of primary energy are required to make 1 kg PET [19].
- The specific heat capacity of PET is taken as 1 kJ/kgK [20].
- The temperature for injection and blow moulding of PET is 125 °C, 10 degrees above the glass transition temperature [25].

Appendix I: Outline of properties and assumptions for S_PVC (Suspension PVC)

Assumptions for S_PVC (suspension polymerised PVC).

In this survey, energy required to make the PVC section from resin is assumed to mainly constitute the reheating energy for the resin.
Notes:

- From ELCD, 60.29 MJ of primary energy are required to make 1 kg S_PVC [8].
- The specific heat capacity of S_PVC is taken as 1 kJ/kgK [22].
- The temperature for injection and blow moulding of S_PVC is 97 °C (requires 10 °C above the glass transition temperature Tg [21]), Tg is listed in [23].

Appendix J: Outline of properties and assumptions for HDPE (High Density Polyethylene)

Assumptions for HDPE (high density polyethylene).

In this survey, energy required to make the HDPE final form from resin is assumed to mainly constitute the reheating energy for the resin.
Notes:

- From ELCD, 76.69 MJ of primary energy are required to make 1 kg HDPE [8].
- The specific heat capacity of HDPE is taken as 1.9 kJ/kgK [24].
- The temperature for injection and blow moulding of HDPE is 230 °C [25].

Appendix K: Outline of properties and assumptions for Pine Timber

Assumptions for Pine Timber.

The solar drying for the pine timber in this survey is assumed to be direct solar heating in a simple building designed to trap solar energy for the purpose of drying the timber. The details have been outlined by some authors [26].

Appendix L: Outline of properties and assumptions for Spruce timber

Assumptions for Spruce timber.

The solar drying for the spruce timber, similar to the pine timber in this survey, is assumed to be direct solar heating in a relatively simple building designed to trap solar energy for the purpose of drying the timber. The details have been outlined by some authors [26].

Appendix M: Outline of properties and assumptions for Mild Steel Coil (sheet)

Mild Steel Coil is used as a compliment in the house window frame made primarily from Spruce timber, and as such we are only interested in its embodied energy, for the sake of this survey.

Appendix N: Outline of properties and assumptions for Mild Steel Section

Mild Steel Section is used as a compliment in the house window frame made primarily from "S PVC" (Suspension Polymerised PVC), and as such we are only interested in its embodied energy, for the sake of this survey.

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Appendix O: Quote on energy networks from Debeir et al.

Expansion of the Capitalist Energy System: The Age of Networks.

The essential link between coal-energy and transport was revealed as new uses for coal were found, locally, regionally then nationally. Energy production was in response to the almost insatiable demand created by European industrialization, a demand so great that energy supplies had to be shifted from their extraction sites to the many new consumption sites. Newer energy forms had to meet the same criterion of transportability. As a result, most gas, electricity and oil production companies were also energy transport companies. They created vast centralized distribution networks whose broad expanse tended to free the energy supply from local constraints and make it available worldwide. But eventually, they also reversed the demand-supply relation which had characterized early industrialization. In twentieth-century capitalism, energy production acquired unprecedented elasticity through widespread recourse to non-renewable fossil fuel and advances in the means of transport: henceforth, energy supply would tend to anticipate demand. All the great energy networks shared certain common features: they created a new market for energy, they supplied technical systems that could drive machines, and generated new needs. The primacy of production over demand, characteristic of the capitalist energy system, was thus established.

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