Computers and Chemical Engineering 91 (2016) 93–103

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Towards sustainable production and consumption: A novel DEcision-Support Framework IntegRating Economic, Environmental and Social Sustainability (DESIRES)

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ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form 17 March 2016
Accepted 20 March 2016
Available online 22 March 2016

Keywords:
Decision-support framework
Energy
Life cycle sustainability assessment
Sustainable production and consumption
Systems approach
System optimisation

ABSTRACT

The idea of sustainable production and consumption is becoming a widely-accepted societal goal worldwide. However, its implementation is slow and the world continues to speed down an unsustainable path. One of the difficulties is the sheer complexity of production and consumption systems that would need to be re-engineered in a more sustainable way as well as the number of sustainability constraints that have to be considered and satisfied simultaneously. This paper argues that bringing about sustainable production and consumption requires a systems approach underpinned by life cycle thinking as well as an integration of economic, environmental and social aspects. In an attempt to aid this process, a novel decision-support framework DESIRES has been developed comprising a suite of tools, including scenario analysis, life cycle costing, life cycle assessment, social sustainability assessment, system optimisation and multi-attribute decision analysis. An application of the framework is illustrated by a case study related to energy.

1. Introduction

It is becoming increasingly apparent that the lifestyles and practices of modern society cannot be sustained indefinitely, with growing scientific evidence showing that we are exceeding the Earth's capacity with respect to resource use and environmental pollution (IPCC, 2013; UNEP, 2012). One of the many challenges of moving towards sustainable production and consumption is finding out which options are sustainable and balancing a plethora of disparate economic, environmental and social aspects. The challenge is exacerbated by the complexity of production and consumption systems as well as a large number of different stakeholder groups, often with conflicting interests. It is also often unclear what sustainability criteria are relevant for which alternatives. An additional difficulty is related to the need to consider both quantitative and qualitative criteria, often based on imprecise (fuzzy) or subjective information. However, probably the greatest challenge is that sustainability problems are "wicked" problems which are intractable and highly resistant to resolution (Rittel and Webber, 1973; Azapagic and Perdan, 2014). Among other characteristics, wicked problems are typically ill-defined and have no well-described potential solutions. Examples of wicked problems include climate change, energy provision and waste disposal. Take, for instance, the issue of climate change: there is still no universal agreement about 'the problem' or 'the solution'. This is due to the problem being highly complex, involving various stakeholders, from individuals to national government to international bodies, with different perspectives and goals. Furthermore, as our knowledge about climate change develops, 'the problem' also changes. Various solutions to address the problem of climate change have been proposed but, as there is no possibility of testing them by trial and error, they may lead to unintended consequences (Azapagic and Perdan, 2014).

Different approaches have been proposed for dealing with wicked problems (e.g. Roberts, 2000; Brown et al., 2010). This paper argues that the best way is adopting a systems approach and considering simultaneously all three aspects of sustainable development – economic, environmental and social – on a life cycle basis. The main reason for this is that such an approach treats sustainability issues as complex systems, and instead of focusing just on 'cause and effect', recognises their complexity and interrelationships, acknowledging that technological solutions must be considered in a wider social, environmental, economic, regulatory, political and ethical framework (Azapagic and Perdan, 2014).

In an attempt to facilitate the process of better understanding and solving wicked sustainability problems and helping towards

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http://dx.doi.org/10.1016/j.compchemeng.2016.03.017

sustainable production and consumption, this paper proposes a decision-support framework which is underpinned by a systems, life cycle approach that integrates all three aspects of sustainable development. The framework, called DESIRES (DEcision Support IntegRating Economic Environmental and Social Sustainability), is outlined in the next section, followed in Section 3 by its application to a decision problem related to identifying sustainable electricity options for the future.

2. An overview of DESIRES

The DESIRES framework is outlined in Fig. 1. Following the usual approach in decision analysis (see e.g. Belton and Stewart, 2002), the framework is divided into three stages: problem structuring; problem analysis; and problem resolution. Each stage involves several steps as described in the next sections.

2.1. Problem structuring

2.1.1. Stakeholders and decision-makers

As mentioned earlier, decision problems related to sustainability are typically ill-defined – decision-makers often approach them assuming that they know what the problem is but, in reality, that is rarely the case. This is particularly complicated by the diversity of stakeholders, with each group or even individual having a different view as to what the problem may be. Therefore, the aim of the problem structuring stage is to aid the decision-making process by helping stakeholders and decision-makers to define the problem through discourse and deliberation. For that reason, engaging stakeholders and understanding their point of view is the first and probably the most important step in a decision-making process (step 1a in Fig. 1). This is particularly important in cases where the stakeholders are not the decision-makers but need to be consulted on a decision-making problem. Depending on the problem, stakeholders may be representatives from industry, government, non-governmental organisations (NGOs), consumer groups and citizens.

One of the first tasks in defining the decision problem is to determine its goal and scope. For example, the goal may be to identify the most sustainable design option for a new manufacturing plant, or to define a sustainable energy consumption pattern, or to identify the best policy options for tackling climate change. Depending on the goal, and following the life cycle approach, the scope will typically be from 'cradle to grave', encompassing all relevant activities from extraction of raw materials to end-of-life waste management.

2.1.2. Identification of options and/or scenarios

Once the goal and scope have been defined, the stakeholders and decision-makers can proceed to identify options and/or scenarios to be considered, which will subsequently be evaluated on their sustainability to help identify the most sustainable solution(s) (step 1b). This can involve technological, consumption, policy, behavioural and/or other options, as appropriate for the type and goal of the decision problem. Scenario analysis can also be used as a useful tool to explore a range of possible and, in some cases, extreme futures, to find out what will be needed to achieve the goal of the study.

2.1.3. Identification of sustainability indicators and decision criteria

Since the sustainability of options and scenarios is evaluated on economic, environmental and social aspects, the next step (1c) is for the stakeholders and decision-makers to identify key sustainability issues of interest to them. These will then need to be translated into measurable sustainability indicators to be used as decision criteria. For example, if one of the identified issues is air pollution, the indicators to measure it could include emissions of various air pollutants and related human health impacts. Given the need for a life cycle approach, tools such as life cycle costing (LCC), life cycle assessment (LCA) and social life cycle assessment (SLCA) can be used to guide the choice of economic, environmental and social sustainability indicators, respectively, based on the identified sustainability issues. An advantage of using the indicators considered in these tools is that they are quantitative (measurable) and well defined. However, not all the indicators will be relevant so they should be selected in collaboration with the stakeholders and decision-makers, also ensuring that they can understand them easily. Perhaps one of the greatest challenges in selecting the indicators is to keep their number small enough to be manageable in the decision-making process while at the same time addressing all

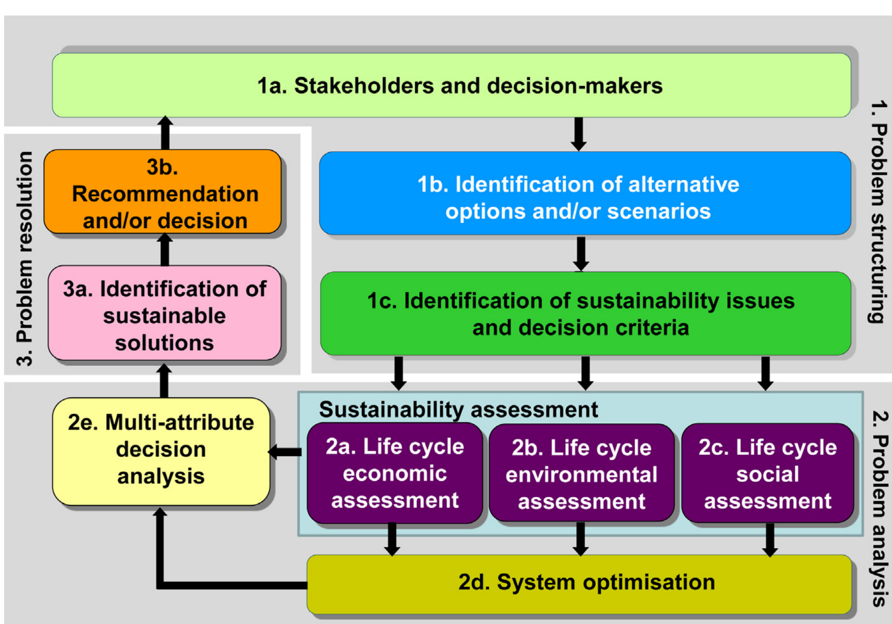


Fig. 1. DESIRES: a decision-support framework for identifying sustainable production and consumption options.

the identified sustainability issues. The sustainability indicators are discussed further below.

2.2. Problem analysis

The second stage of DESIRES – problem analysis – involves sustainability assessment of the options identified during the problem structuring stage, system optimisation and multi-attribute decision analysis. These are discussed in turn in the next sections.

2.2.1. Sustainability assessment

Given that the sustainability assessment is on a life cycle basis, LCC, LCA and SLCA are used as tools to estimate economic, environmental and social indicators (steps 2a–c in Fig. 1) as described below.

2.2.1.1. Life cycle costing. Following the LCC methodology proposed by Hunkeler et al. (2008) and Swarr et al. (2011), the total life cycle cost T_{LCC} of a plant or product can be estimated as:

$$T_{LCC} = \sum_{n=1}^{N} c_n X_n \tag{1}$$

where c_n represents unit cost of life cycle activity n. For example, the total LCC of a product will include the costs of raw materials and energy, production and packaging costs, transport and end-of-life management. For a manufacturing plant, it includes costs of construction, operation and decommissioning of the plant.

The concept of life cycle costs is related closely to the more commonly used total annualised costs. The latter is essentially the life cycle cost equalised over the lifespan of the product or (more commonly) plant, expressed per year and estimated as follows (Gujba et al., 2010):

$$T_{AC} = \sum ACC + \sum FC + \sum VC \tag{2}$$

where T_{AC} is total annualised cost and ACC, FC and VC are annualised capital, fixed and variable costs, respectively. Like life cycle costs, total annualised cost may include decommissioning costs, but these are typically classified as capital expenditure and are included within annualised capital rather than as a separate life cycle stage.

In addition to T_{AC}, the concept of levelised costs is also used for some applications, particularly for estimating costs of electricity generation. Since this is relevant to the case study considered later in the paper, its definition is included here. Like LCC, it includes the full costs of building, operating and decommissioning an asset. However, in this case, the total cost is expressed per unit of electricity generated, normally as follows (IEA, 2010; Stamford and Azapagic, 2014):

$$LC = \frac{\sum_{t=1}^{T} (C_t + M_t + F_t)/(1+r)^t}{\sum_{t=1}^{T} E_t/(1+r)^t} \tag{3}$$

where C_t, M_t and F_t represent the capital, operation/maintenance and fuel costs, respectively, incurred in year t. E_t is the total amount of electricity generated in year t and r represents the discount rate. It should be noted that LCC and total annualised cost normally do not consider discounting, whereas levelised cost is most often discounted.

2.2.1.2. Life cycle assessment. Life cycle environmental impacts can be estimated in LCA as follows (Azapagic, 1999a):

$$E_k = \sum_{j=1}^{J} e_{k,j} B_j \quad k = 1, 2, \ldots, K \tag{4}$$

where E_k is environmental impact k, B_j is environmental burden j causing the impact and $e_{k,j}$ the relative contribution of burden j to impact k. Environmental burdens represent materials and energy consumption as well as emissions to air, water and soil. For example, if global warming potential (GWP) is E_k, then the life cycle emissions of carbon dioxide (CO_2) would be one of the burdens B_j with the relative contribution $e_{k,j}$ to the GWP of 1 kg CO_2 eq./kg CO_2. The environmental burdens are calculated as follows:

$$B_j = \sum_{n=1}^{N} b_{j,n} x_n \quad j = 1, 2, \ldots J \tag{5}$$

where $b_{j,n}$ is the environmental burden j per unit life cycle activity n and x_n is the level of that activity. Using the same example as above, if CO_2 is emitted from combustion of a fuel, $b_{j,n}$ would represent its emission per unit of fuel (e.g. kg CO_2 per kg or MJ of fuel), with the amount of fuel representing the level of activity x_n (kg or MJ). Typically, over a hundred environmental burdens and more than 10 impacts are considered in LCA.

Unlike LCC, for which there is no internationally agreed methodology, LCA is standardised by the ISO 14040 and 14044 standards (ISO, 2006a,b).

2.2.1.3. Social life cycle assessment. SLCA follows the LCA approach but, instead of environmental impacts, it evaluates different social aspects in the life cycle of the options of interest to stakeholders. As yet, there is no international standard for SLCA, but according to the methodology proposed by UNEP (2009), over 150 social impacts could be considered in SLCA, both quantitative and qualitative. Examples of the former include number of jobs provided, number of worker injuries and health impacts while qualitative indicators include issues such as child labour, corruption and cultural heritage. The quantitative impacts can be estimated as follows:

$$S_m = \sum_{n=1}^{N} s_{m,n} x_n \quad m = 1, 2, \ldots, M \tag{6}$$

where S_m is a social impact m and $s_{m,n}$ the impact per unit life cycle activity x_n. For example, if S_m is the number of jobs provided by producing a product, then $s_{m,n}$ is the number of jobs generated per unit output of each activity x_n in the life cycle.

Qualitative impacts can either be left in the original, descriptive, form or converted to quantitative indicators; for instance, using a scale from 1 to 10 to indicate how 'positive' or 'negative' the impact from one option is, relative to the other options.

2.2.2. System optimisation and multi-attribute decision analysis

The sustainability indicators quantified during the sustainability assessment are then used as decision criteria in the next stages of the decision-making process (steps 2d and 2e in Fig. 1). Depending on stakeholders' and decision-makers' interests and the type of the decision problem, normally a large number of decision criteria will be involved, usually with some alternatives being better for some but worse for others. To help deal with this complex information and identify the most sustainable option(s), multi-criteria decision analysis (MCDA) can be used, whereby stakeholders are required to articulate their preferences for different sustainability criteria.

Elicitation of preferences is probably the most difficult part of the decision-making process. In addition to expressing their own preferences, each stakeholder and decision-maker has to understand the preferences of the other participants. A further difficulty is that preferences are often not fully formed or they are non-existent. Therefore, the main challenge is to help the participants learn about their own but also about the preferences of the other stakeholders to reach a compromise solution (Azapagic and Perdan, 2005).

MCDA tools used for these purposes include multi-objective system optimisation (step 2d in Fig. 1) and multi-attribute decision analysis (2e). In theory, both types of method can deal with a large number of criteria, but in practice, they will be limited by various methodological and computational issues as well as the inability of a human brain to relate to more than a handful of decision criteria at a time (Belton and Stewart, 2002). Multi-objective optimisation can be carried out with the preferences elicited *a priori*, in which case the criteria are aggregated into one objective, reducing the problem to single-objective optimisation. Alternatively, the preferences can be elicited after optimisation, in which case the results are fed into the multi-attribute decision analysis (2e). While single-objective optimisation eases the computational burden, multi-objective optimisation is often more useful as it helps decision-makers to see clearly the trade-offs between different Pareto-optimum solutions, which in turn helps them to elicit their preferences in a more informed manner.

A multi-objective optimisation problem that considers simultaneously economic, environmental and social sustainability objectives can be formulated as follows:

$$\min \quad \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}) = [f_1 f_2 \ldots f_p] \tag{7}$$

$$\begin{aligned} \text{s.t.} \quad & h(\boldsymbol{x}, \boldsymbol{y}) = 0 \\ & g(\boldsymbol{x}, \boldsymbol{y}) \le 0 \\ & \boldsymbol{x} \in \boldsymbol{X} \subseteq R^n \\ & \boldsymbol{y} \in \boldsymbol{Y} \subseteq Z^q \end{aligned} \tag{8}$$

where $\boldsymbol{f}$ is a vector of economic, environmental and social objective functions; $h(\boldsymbol{x},\boldsymbol{y}) = 0$ and $g(\boldsymbol{x},\boldsymbol{y}) \le 0$ are equality and inequality constraints, and $\boldsymbol{x}$ and $\boldsymbol{y}$ are the vectors of continuous and integer variables, respectively.

Multi-objective optimisation is widely used in chemical engineering, but in terms of application to sustainability problems, it has so far largely focused on economic and environmental aspects (e.g. Azapagic and Clift, 1999b; Hugo et al., 2003; Čuček et al., 2012), with social criteria starting to be considered only very recently (see e.g. Santibañez-Aguilar et al., 2014). Most authors use linear or mixed-integer linear programming (MILP) to formulate and solve multi-objective optimisation problems, although stochastic methods are also gaining momentum to take into account the uncertainty inherent in sustainability problems (e.g. Grossmann and Guillén-Gosálbez, 2010; Zeballos et al., 2014; Geraili and Romagnoli, 2015).

Selecting objective functions to optimise on out of the plethora of sustainability indicators is an important step as that will determine the ultimate findings and recommendations from the study. Typically, the objective functions will be chosen by decision-makers, based on the input from the stakeholders in step 1c and informed by the findings in steps 2a–c (see Fig. 1). For example, the LCA results may indicate that some environmental impacts are not as important as originally thought by the stakeholders as their values are low. Furthermore, some impacts will be closely linked so that optimising on one would optimise on the others. This will help to reduce the number of objective functions, minimising the computational burden and aiding the decision-making process. However, care must be taken that this reductionist approach does not result in excluding some of the objectives that could influence the optimisation outcomes. To aid this process, Guillén-Gosálbez (2011) and Copado-Mendez et al. (2014) proposed an MILP method demonstrating how the number of objective functions could be reduced in environmental applications by eliminating redundant criteria from the optimisation model.

The output of multi-objective optimisation will be a range of Pareto optimum solutions and typically trade-offs between the objectives will be necessary to identify the best compromise solution. For instance, if the system is optimised on three objectives – one economic, one environmental and one social – the resulting Pareto optimum does not necessarily correspond to their respective optima obtained if the system is optimised on each objective separately. However, the Pareto optimum does mean that the best possible options have been identified when the aim is to improve all three objectives simultaneously.

Depending on the number of objectives considered, understanding the trade-offs and identifying the best option can be challenging, particularly for four or more objectives. Graphical representation of the results can help, but that becomes difficult beyond three dimensions. Therefore, to choose the best compromise solution out of a number of optimum alternatives, some articulation of preferences will be necessary. To assist with this, the results of multi-objective optimisation can be fed into multi-attribute decision analysis (MADA). Alternatively, optimisation can be skipped and the results of sustainability assessment used directly in MADA (see Fig. 1). Examples of MADA methods include multi-attribute value theory (MAVT), the analytic hierarchy process (AHP) and compromise programming (for a review see e.g. Azapagic and Perdan, 2005). Regardless of the method, the output of MADA will be a sustainability score for each of the options considered, obtained by aggregating the decision criteria based on preferences. This allows stakeholders and decision makers to compare the options easily, considering a single criterion rather than a large number of decision criteria.

2.3. Problem resolution

In the third and final stage of the decision-making process, the stakeholders and/or decision-makers use the results from the problem analysis stage to identify the most sustainable option (step 3a in Fig. 1). If the outcome of the decision-making process is agreeable to the participants, a decision or recommendations can be made (3b). However, if the outcome is not acceptable, the process can be repeated in an iterative way to stimulate further learning about the decision problem and ensure that subsequent decisions are taken with a full awareness of possible consequences. Thus, DESIRES can be used in an iterative manner to suit the type of the problem and stakeholders. It can also be used in a modular fashion, with the type and extent of sustainability assessment chosen depending on the problem and the goal of the decision-making process.

The proposed framework is generic and applicable to different sustainability decision-making problems involving sustainable production and/or consumption. Depending on the 'owner' of the decision problem, it can be 'driven' by different stakeholders and/or decision-makers or by researchers in collaboration with these two groups. An example application of DESIRES is illustrated in the next section, related to the identification of sustainable options for future electricity supply in the UK, based on the data reported in Stamford and Azapagic (2014). In this case, the process is driven by the researchers (authors of this paper) in collaboration with different stakeholders and decision-makers.

3. Applying DESIRES

3.1. Problem structuring

3.1.1. Stakeholders and decision-makers

The goal of the decision problem considered here is to evaluate the sustainability of different future technologies and scenarios for electricity generation in the UK and identify options that would bring the highest economic, environmental and social benefits. The outcomes of the analysis are intended to be used to make recommendations to the industry and government. The scope of the

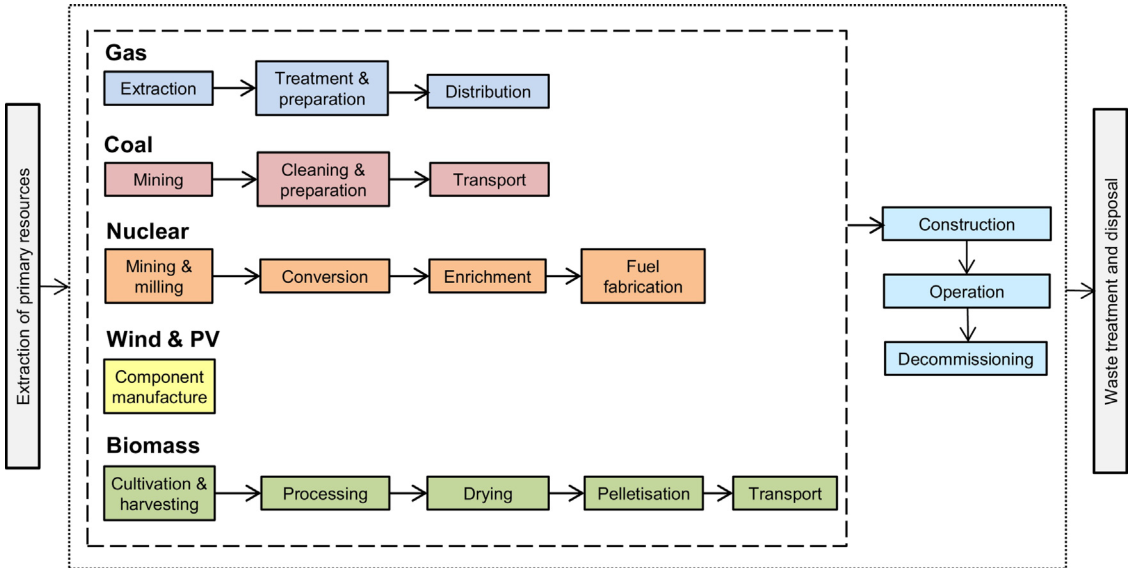


Fig. 2. The life cycle of electricity technologies from 'cradle to grave'.

analysis is from 'cradle to grave' and the time horizon extends up to the year 2070.

To enable consideration of both production and consumption aspects associated with electricity, the stakeholder groups consulted include energy companies, government, research organisations, NGOs and consumers. The consultation process involved face-to-face interviews with 32 individuals from the industry (nuclear, fossil and renewables), NGOs, government bodies and academia. In this decision problem, they are considered expert stakeholders. In addition, over 600 consumers were consulted through online surveys developed for the purposes of addressing this decision problem. Their input has been used to inform the next steps of the framework, as discussed below.

3.1.2. Identification of options and scenarios

The following electricity generation options are considered, expected to play a major role in a future UK electricity mix (DECC, 2011): coal with and without carbon capture and storage (CCS), natural gas, nuclear, solar photovoltaics (PV), wind and biomass. As shown in Fig. 2, the system boundaries for all the technologies comprise the construction and decommissioning of power plants, extraction, processing and transport of fuels (if relevant), generation of electricity and waste management.

Four future scenarios have been formulated in consultation with expert stakeholders to examine the sustainability implications of different electricity mixes; the scenarios are summarised in Table 1. All scenarios are driven by the need to reduce greenhouse gas (GHG) emissions. Achieving the UK's legally-binding target of reducing GHG emissions by 80% by 2050 on 1990 levels (DECC, 2012) will require a complete decarbonisation of the UK electricity mix (UKERC, 2009). This is considered in scenarios 100%-1 and 100%-2 (Table 1). The other two scenarios consider a case whereby the GHG targets are not achieved and the electricity mix is decarbonised only by 65%. The scenarios also assume different penetration of the electricity technologies, as given in Table 1.

Table 1
Definition of scenarios.

Scenario	Coal CCS and nuclear	Electricity mix
65%-1	Coal CCS, no new nuclear build	68% fossil and 32% renewables
65%-2	Coal CCS, new nuclear build	37% of fossil, 30% of nuclear and 33% renewables
100%-1	No coal CCS, no new nuclear build	100% renewables
100%-2	No coal CCS, new nuclear build	50% of nuclear and 50% of renewables

Adapted from Stamford and Azapagic (2014).

3.1.3. Identification of sustainability issues and decision criteria

Sustainability issues and decision criteria have been identified through an extensive consultation with expert stakeholders. In total, 32 individuals took part in the consultation process representing 24 different organisations in industry, government and academia. Face-to-face semi-structured interviews were conducted lasting up to 2 h. As a result of this process, 19 economic, environmental and social sustainability issues were selected (Table 2) and translated into 36 indicators (see Appendix) to be used as decision criteria. Note that in this case, economic indicators also include various technical aspects (termed 'techno-economic'). The indicators were chosen through stakeholder engagement, literature review and new indicator development by the authors of this paper. Throughout the process, the indicators were refined and guided by the following criteria:

- relevance to the subject at hand: in this case, electricity generation;
- completeness: they should address all the identified sustainability issues;
- no double-counting: no two indicators should address the exact same issue;

Table 2
Sustainability issues considered by different stakeholders (based on Stamford and Azapagic, 2014).

Techno-economic	Environmental	Social
Operability	Material recyclability	Employment
Technological lock-in resistance	Water ecotoxicity	Human health impacts
Immediacy	Global warming	Large accident risk
Levelised cost of generation	Ozone layer depletion	Energy security
Cost variability	Acidification	Nuclear proliferation
	Eutrophication	Intergenerational equity
	Photochemical smog	
	Land use and quality	

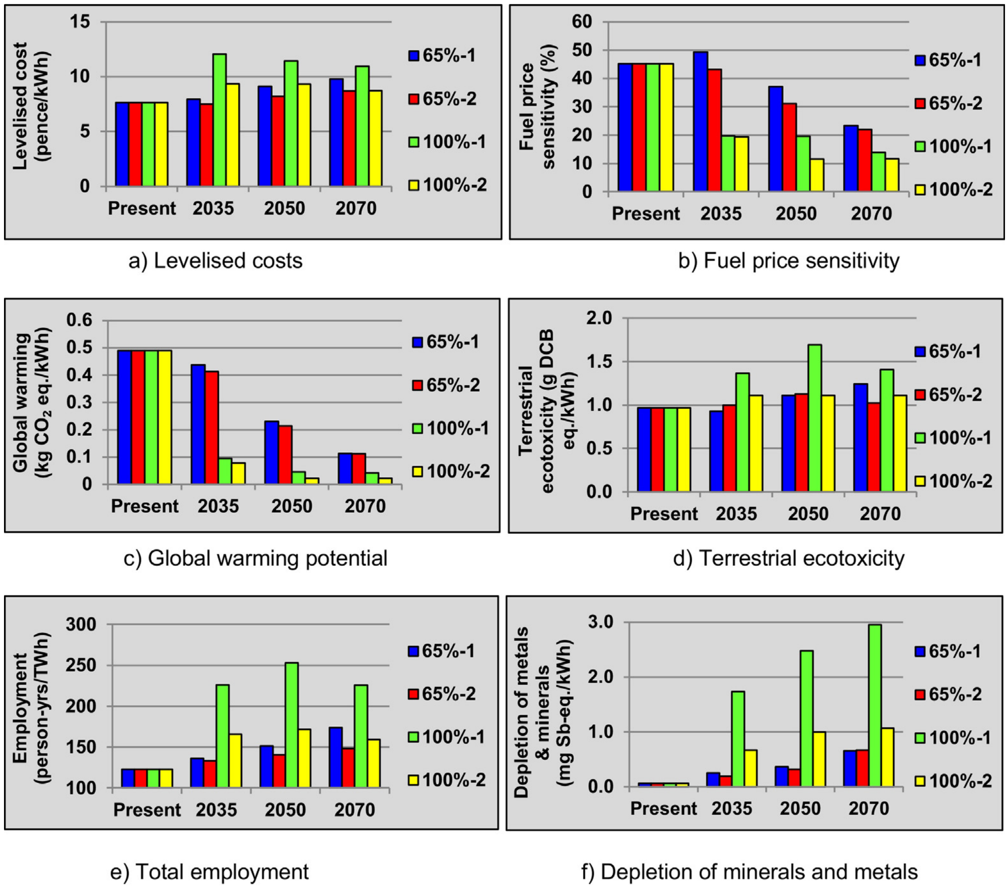


Fig. 3. Selective results of the sustainability assessment of the scenarios considered in the decision problem (based on data from Stamford and Azapagic, 2014). [Figures (a) and (b): examples of the techno-economic indicators related to issues of levelised cost of generation and cost variability in Table 2. Figures (c) and (d): examples of environmental indicators related to the issues of global warming and land quality in Table 2. Figures (e) and (f): examples of social sustainability indicators related to the issues of provision of employment and intergenerational equity in Table 2. For the definition of the indicators, see Appendix.]

- clarity of value preference: it should be clear if lower or higher values of indicators are preferred (i.e. better);
- measurability: indicators should be quantifiable; and
- practicality: they should be feasible, given constraints on time and data availability.

Each indicator addresses a particular sustainability issue on a life cycle basis, from 'cradle to grave'. For example, employment considers provision of total employment along the whole supply chain for each technology, including mining, fuel processing, plant construction, operation and decommissioning. Similarly, intergenerational equity refers to depletion of non-renewable resources across the life cycles of different options, which if used up by the current generation will not be available for future generations to draw on. By implication, although the focus is on electricity in the UK, the sustainability issues span a number of other countries owing to the globalised nature of supply chains.

3.2. Problem analysis

3.2.1. Sustainability assessment

To assess the sustainability of different electricity technologies and scenarios on a life cycle basis, LCA, LCC and SLCA have been carried out using the Scenario Sustainability Assessment Tool (SSAT) v2.1, developed for the purposes of this work. SSAT, which can be downloaded for free from www.springsustainability.org/?page=tools, is an interactive tool enabling stakeholders to define their own electricity scenarios and examine the related sustainability implications. It has an integral life cycle database and enables sustainability assessment on the 36 techno-economic, environmental and social indicators mentioned above and detailed in Appendix. The assumptions and data underlying SSAT are drawn from a great variety of sources; for details, see Stamford and Azapagic (2014).

The results of the scenario analysis are given in Fig. 3. For the purposes of the illustration of DESIRES, only a limited number of indicators are shown. For example, for all the scenarios the levelised costs would go up in the future relative to the present day, with scenario 100%-1 being the worst and 65%-2 and 100%-2 the least expensive options (Fig. 3a). However, the sensitivity to fuel prices reduces significantly over the period for all the scenarios because of the lower contribution of fossil fuels than at present (Fig. 3b). Furthermore, all the scenarios would have lower life cycle environmental impacts than the UK grid today, including GWP (Fig. 3c). The exception is terrestrial ecotoxicity (Fig. 3d) which would go up for all the scenarios. For the social impacts, some scenarios are better than today but others are worse. For instance, the employment in the supply chain would increase across the scenarios but so would the depletion of minerals and metals, affecting intergenerational equity.

Given the breadth of data and assumptions required, as well as the long timeframe spanned by the analysis, it is important to consider the related uncertainties. A quantitative, probability-based analysis was not possible owing to a lack of data; instead, a pedigree matrix-based assessment of data quality typically used in LCA has been performed for each technology in the model. The assessment evaluated each data point against seven criteria: specificity with regard to time, geography and technology, completeness of data, quality of data source, auditability and validation. While the scenarios themselves were not evaluated, the overall reliability of results for each technology was estimated to be quite high and was very similar across technologies (within 3%); for further details, see Stamford (2012).

It should be noted that some uncertainties are inherent within future scenarios. In this case, the development of technologies cannot be known with certainty *ex ante* and other aspects, which fall outside the system boundary considered here, may become more important in future under the systems view adopted by the framework. Specifically, increasing penetration of renewable and nuclear technologies is likely to require changes to grid characteristics including the addition of supply-side management and energy storage technologies. However, lack of data prevents inclusion of these phenomena at the present time.

Therefore, as the results show, the sustainability of the scenarios differs for different indicators, making it difficult to identify the most sustainable option. The next section shows how MCDA can help towards that, first considering system optimisation and then multi-attribute decision analysis.

3.2.2. System optimisation

Instead of fixing the electricity mix in different scenarios as in the previous step of DESIRES, in this step system optimisation has been carried out to allow the model to choose an optimum electricity mix depending on the objective function and the carbon reduction targets (for the latter, see Table 1). MILP has been used to formulate and solve the problem, a detailed description of which can be found in Barteczko-Hibbert et al. (2014). Here, for an illustration, only selective results are considered for two objective functions: total life cycle costs and GWP (Fig. 4). For each objective function, the values of the remaining 35 sustainability indicators have been estimated during optimisation. Note that these results are not directly comparable to those obtained in the sustainability assessment discussed in Section 3.2.1. As mentioned earlier, this is due to the electricity mixes in the scenarios being determined by the optimisation model subject to constraints rather than fixed *a priori* as was the case in the previous step. That means that the electricity mixes obtained through optimisation are different from those specified in Section 3.2.1, which in turn leads to different values of sustainability indicators. Note also that, to reduce the computational burden, optimisation extends to the year 2060 rather than 2070.

The results in Fig. 4a (left) indicate that optimising on the total life cycle costs favours scenarios 65% but the carbon targets are missed by a large margin (Fig. 4b left). On the other hand, optimising on the total GWP leads to negative overall emissions of GHG (Fig. 4b right) but the costs are much higher than in cost optimisation (Fig. 4a right). The results for the other environmental and social impacts are mixed. For example, cost optimisation yields

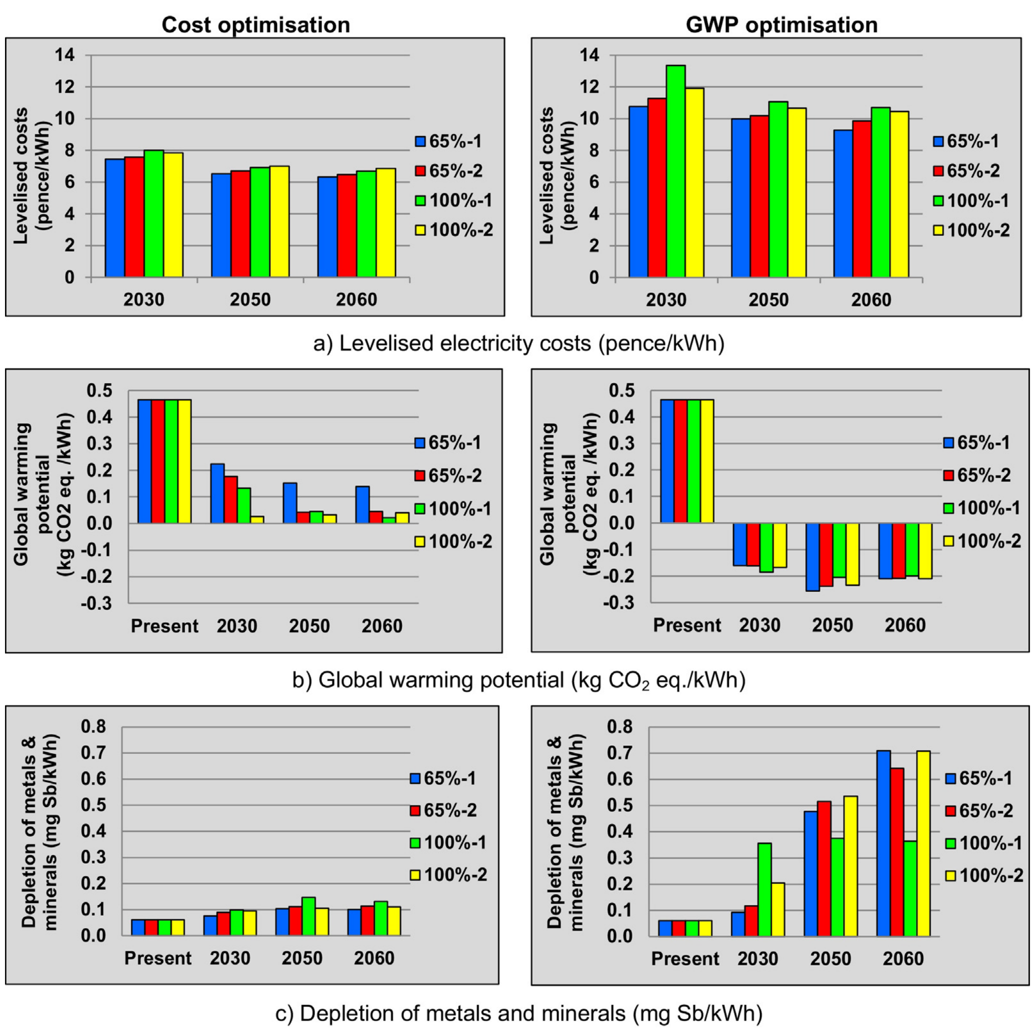


Fig. 4. Selective results of scenario optimisation on the total life cycle costs (left) and global warming potential (right) (based on data from Barteczko-Hibbert et al., 2014). [The figures on the left represent the results obtained by optimising on the total life cycle costs and on the right the results obtained by optimising on global warming potential. For each objective function, the results are shown for (a) levelised electricity costs; (b) global warming potential; (c) depletion of metals and minerals.]

much lower depletion of metals and minerals than optimisation on GWP, with scenarios 65%-1 being the best option in the former and, together with 100%-2, the worst option in the latter case by 2060 (Fig. 4c).

Thus, choosing the most sustainable option is not easy and some elicitation of preferences will be necessary through MADA to facilitate decision-making. This is discussed in the next section.

3.2.3. Multi-attribute decision analysis

As mentioned in Section 2.2.2 and indicated in Fig. 1, MADA can be applied either directly after the sustainability assessment or after system optimisation. As an illustration of the application of this part of DESIRES, we consider the former.

Both expert stakeholders and the UK public were consulted on their preferences for different decision criteria. Two different MADA methods have been used for these purposes, depending on the number of decision criteria involved. For preferences on the sustainability aspects (economic, environmental and social), AHP has been applied as this method is suitable for a smaller number of decision criteria – stakeholders make pairwise comparisons across all the criteria, indicating which one is more important than another and by how much (Saaty, 1980). The weights of importance are assigned using an integer 9-point scale, with a score of 1 assigned if both criteria considered at a time are equally important and 9 if one of the criteria is extremely more important than the other, with the intermediate scores reflecting different levels of importance. As the number of criteria increases, the number of pairwise comparisons increases exponentially, making the process long and drawn-out, also often leading to inconsistencies in the pairwise comparisons. Thus, to elicit preferences for the 36 sustainability indicators, MAVT was used which is more suited for a larger set of decision criteria (Keeney and Raiffa, 1976). In this method, stakeholders place a score of 100 on the most important indicator within the sustainability aspects they are assessing (techno-economic, environmental and social), with each other indicator having a lower score to reflect their relative importance with respect to the most important indicator.

On average, the expert stakeholders identified world fuel reserves, GHG emissions and long-term radioactive waste management as the top three most important indicators to consider when assessing the sustainability of electricity options. In addition, they showed relative agreement on the importance of costs. Overall, they rated techno-economic aspects as the most important and social aspects the least important (Youds, 2013).

By contrast, on average, the public rated the environmental aspects as the most important, followed by the social. When asked which specific sustainability issues were most important to them in distinguishing among different electricity options, the respondents ranked water eco-toxicity the most important, followed by terrestrial eco-toxicity and GHG emissions. Thus, only the latter was identified by both stakeholder groups as one of the most important issues. Perhaps surprisingly, the public considered the cost of electricity least important. This could be explained by the fact that consumers do not see on their bills a difference in costs between different technologies, only the total cost of electricity. For further details on preference elicitation, see Youds (2013).

The preferences for the sustainability aspects and indicators have then been aggregated to identify the preferred scenarios, considered most sustainable by the stakeholders. The MAVT method has also been applied for this purpose using Web-HIPRE software (Mustajoki and Hämäläinen, 2000).

The results are discussed in the next two sections, starting with a simplified approach whereby all the sustainability aspects (techno-economic, environmental and social) and indicators are assumed to be equally important. This is followed by consideration of different preferences as elicited during the stakeholder consultation process.

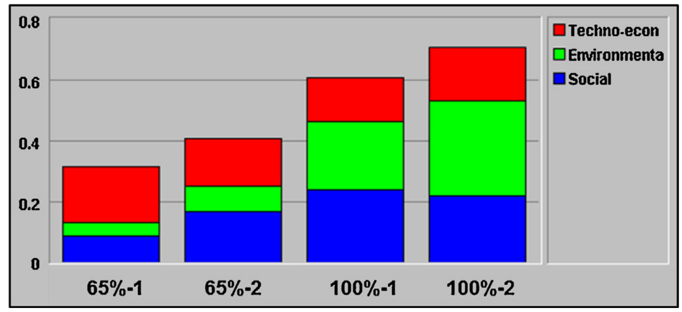


Fig. 5. Sustainability ranking of the scenarios in 2070 with equal weights for all sustainability aspects and indicators. [The higher the score, the more sustainable the option].

3.2.3.1. Equal weighting. Assuming an equal importance of all three sustainability aspects and 36 indicators and using the results of the sustainability assessment presented in Section 3.2.1, the obtained sustainability scores for each scenario are displayed in Fig. 5. Under these conditions, scenario 100%-2 is overall the most sustainable option (with the highest score of 0.7), followed by 100%-1 (with 0.61). Scenario 65%-2 is ranked third with a score of 0.41 while scenario 65%-1 is the least sustainable, scoring overall only 0.32.

The results in Fig. 5 also suggest that scenario 100%-2 is environmentally most sustainable (with a score of 0.31). It is also the second best option for social sustainability (scoring 0.22), after 100%-1 (0.24). On the other hand, scenario 65%-1 has the best score for the techno-economic aspects (0.18), but is the worst option for the social and environmental aspects (0.09 and 0.04, respectively). As can be seen from the sensitivity analysis in Fig. 6, the ranking of the scenarios is robust over a range of different weights for the different sustainability aspects. The ranking would only change if the weighting on the techno-economic aspect changed from the current 0.33 to 0.98. In that case, scenario 65%-1 would become the best option while 100%-1 would be relegated to second place and 100%-1 would be considered the least sustainable.

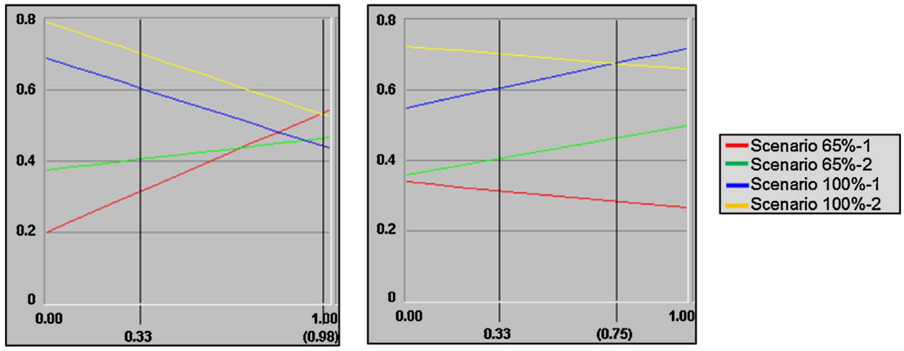
Similarly, if social sustainability were to be considered much more important than the other two aspects, with its weight of importance increasing from the current 0.33 to 0.75, the rank of scenarios 100%-1 and 100%-2 would reverse so that the former would become the preferred option; the rank of the other two scenarios would remain unchanged. For the environmental aspect, the rank order does not change with the weighting.

3.2.3.2. Different stakeholder preferences. This section considers first the expert and then public preferences elicited during the stakeholder consultation process.

i) Expert stakeholder preferences

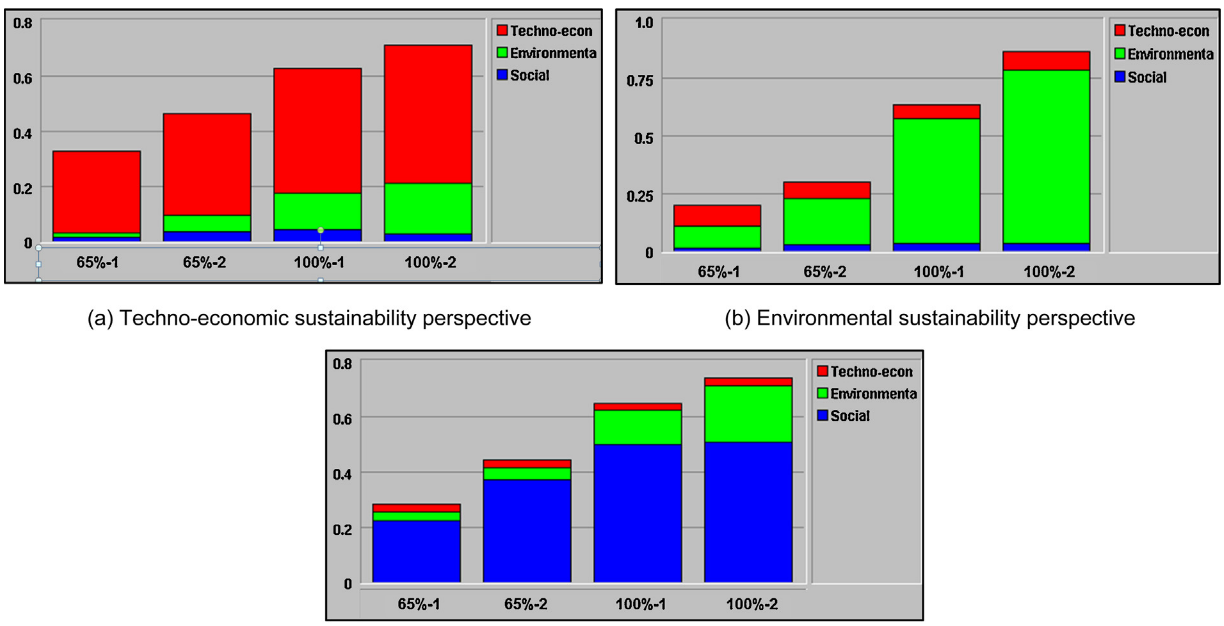
To explore how different expert stakeholder preferences affect the outcomes, rather than consider the average findings from the expert stakeholder analysis discussed in Section 3.2.3, three extreme cases are discussed here instead. The first considers a strong preference for the techno-economic aspect, the second has an environmental focus and the third a strong bias for social sustainability. The weights used for these three cases are summarised in Table 3, based on the extreme opinions expressed by some expert stakeholders during the consultation process.

Assuming a techno-economic bias, scenario 100%-2 is the preferred option, with an overall score of 0.71, followed by 100%-1 with 0.63; scenario 65%-1 is the least sustainable, scoring in total 0.33 (Fig. 7). This outcome is the same as for the equal weighting of the sustainability aspects discussed in Section 3.2.3.1. The ranking also remains the same for the environmental and social



(a) Techno-economic aspects (b) Social aspects

Fig. 6. Sensitivity analysis for equal weights for all three sustainability aspects (techno-economic, environmental and social). [The results refer to 2070. The vertical line originating at the value 0.33 on the *x*-axis represents the weight placed on the techno-economic and social aspects of sustainability. The vertical line at 0.98 (a) and 0.75 (b) represents the weight that would need to be placed on the techno-economic and social aspects, respectively, to cause a change in the scenario ranking.]



(a) Techno-economic sustainability perspective (b) Environmental sustainability perspective

(c) Social sustainability perspective

Fig. 7. Sustainability ranking of the scenarios in 2070 assuming different perspectives of expert stakeholders.

sustainability perspectives; the only change is in the total sustainability scores (see Fig. 7). The reason for 100%-2 being the best option for all three perspectives is a good performance on the majority of the sustainability indicators (see Section 3.2.1 for some examples and Stamford and Azapagic (2014) for further details).

Table 3
Weights of importance for the sustainability aspects for expert stakeholders and the public.

	Weights of importance for sustainability aspects		
	Techno-economic	Environmental	Social
Expert stakeholders[a]			
Techno-economic perspective	0.75	0.19	0.06
Environmental perspective	0.15	0.80	0.05
Social perspective	0.06	0.20	0.74
Public[b]	0.21	0.55	0.24

[a] The weights represent preferences assuming a strong bias for one of the sustainability aspects.
[b] The weights have been averaged across the sample.

ii) Public preferences

Public preferences have been averaged across the sample to derive a mean weight of importance for different sustainability aspects (Table 3). As indicated in Fig. 8, with a score of 0.77, scenario 100%-2 is the most sustainable option, followed by 100%-1 with 0.62. Scenario 65%-1, which has a score of 0.25,

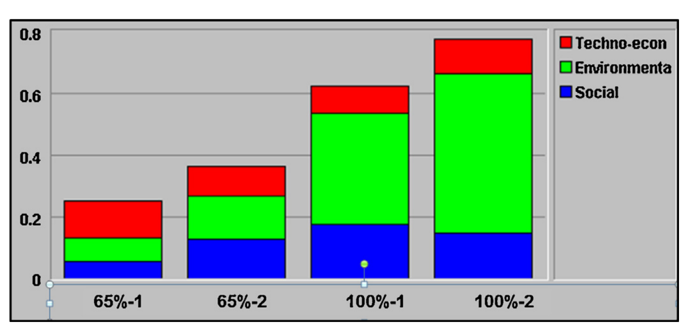


Fig. 8. Sustainability ranking of the scenarios in 2070 considering public preferences.

is the worst option. This outcome, which is the same as for the expert stakeholder preferences, is not surprising because of a large bias towards the environmental aspect expressed by the public, for which scenario 100%-2 performs well. Scenario 100%-1 also scores well owing to its good environmental performance compared to scenarios 65%-1 and 65%-2.

Thus, in summary, the weighting placed on different sustainability aspects and indicators does not change the ranking of the scenarios, with 100%-2 being the most sustainable and 65%-1 the worst option. Therefore, the MADA results can be considered robust with little sensitivity to the change in the weights of importance.

3.3. Problem resolution

Finally, the MADA results can be used to make a decision or recommendations. In this case, scenario 100%-2 is identified as the most sustainable by both expert stakeholders and the public, despite the difference in their preferences for the sustainability aspects and indicators. Since the outcome of the decision-making process appears to be agreeable to all the stakeholders, a decision or a recommendation can be made without the need for additional iterations through the DESIRES framework.

4. Conclusions

This paper has argued that bringing about sustainable production and consumption requires a systems and life cycle approach, taking into account the economic, environmental and social concerns of different stakeholders. In an attempt to facilitate this process, a novel decision-support framework DESIRES has been developed incorporating such an approach. DESIRES comprises a range of tools, including scenario analysis, life cycle costing, life cycle assessment, social sustainability assessment, system optimisation and multi-attribute analysis. Application of the framework has been illustrated by an example related to future electricity supply in the UK, with the aim of identifying the most sustainable electricity mix. The example shows how following the structured approach inherent to DESIRES can facilitate stakeholder engagement throughout the decision process and help reach a consensus despite very different preferences of different stakeholders. This approach is particularly valuable as it allows each group of stakeholders to learn more not only about their own sustainability preferences but also to understand the opinions of others, helping towards consensus building. Furthermore, by integrating different sustainability considerations, stakeholders and decision makers can see easily the trade-offs between different aspects, allowing them to make more informed decisions. In this way, DESIRES can facilitate decision-making by helping decision makers to understand better the decision problem and the consequences of their decision for sustainable production and consumption.

Acknowledgements

This work was carried out as part of the SPRIng project (www.springsustainability.org), funded by the UK Engineering and Physical Sciences Research Council (Grant no. EP/F001444/1). The authors gratefully acknowledge this funding.

Appendix. Sustainability indicators (decision criteria) identified by expert stakeholders (after Stamford and Azapagic, 2014).

Aspects	Issues	Indicators	Units
Techno-economic	Operability	1. Capacity factor (power output as a percentage of the maximum possible output)	%
		2. Availability factor (percentage of time a plant is available to produce electricity)	%
		3. Technical dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summed rank
		4. Economic dispatchability (ratio of capital cost to total levelised generation cost)	%
		5. Lifetime of global fuel reserves at current extraction rates	Years
	Technological lock-in resistance	6. Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or H_2 production) and operational lifetime	$Years^{-1}$
	Immediacy	7. Time to plant start-up from start of construction	Months
	Levelised cost of generation	8. Capital costs	£/MWh
		9. Operation and maintenance costs	£/MWh
		10. Fuel costs	£/MWh
		11. Total levelised cost	£/MWh
	Cost variability	12. Fuel price sensitivity (ratio of fuel cost to total levelised generation cost)	%
Environmental	Material recyclability	13. Recyclability of input materials	%
	Water eco-toxicity	14. Freshwater eco-toxicity potential	kg 1,4 DCB[a] eq./kWh
		15. Marine eco-toxicity potential	kg 1,4 DCB[a] eq./kWh
	Global warming	16. Global warming potential	kg CO_2 eq./kWh
	Ozone layer depletion	17. Ozone depletion potential	kg CFC-11 eq./kWh
	Acidification	18. Acidification potential	kg SO_2 eq./kWh
	Eutrophication	19. Eutrophication potential	kg PO_4^{3-} eq./kWh
	Photochemical smog	20. Photochemical smog creation potential	kg C_2H_4 eq./kWh
	Land use & quality	21. Land occupation (area occupied over time)	m^2 year/kWh
		22. Terrestrial eco-toxicity potential	kg 1,4 DCB[a] eq./kWh

Aspects	Issues	Indicators	Units
	Employment	23. Direct employment	Person-years/TWh
		24. Total employment (direct + indirect)	Person-years/TWh
	Human health impacts	25. Worker injuries	No. of injuries/TWh
		26. Human toxicity potential (excluding radiation)	kg 1,4 DCB[a] eq./kWh
		27. Total human health impacts from radiation (workers and population)	DALY[b]/kWh
Social	Large accident risk	28. Fatalities due to large accidents	No. of fatalities/PWh
	Energy security	29. Amount of imported fossil fuel potentially avoided	toe/kWh
		30. Diversity of fuel supply mix	Score (0–1)
		31. Fuel storage capabilities (energy density)	GJ/m^3
	Nuclear proliferation	32. Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0–3)
	Intergenerational equity	33. Use of abiotic resources (elements)	kg Sb eq./kWh
		34. Use of abiotic resources (fossil fuels)	MJ/kWh
		35. Volume of radioactive waste to be stored	m^3/TWh
		36. Volume of liquid CO_2 to be stored	m^3/TWh

[a] 1,4-dichlorobenzene.
[b] disability-adjusted life years.

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